Synergies and trade-offs between climate mitigation and poverty alleviation for East Africa's dairy sector

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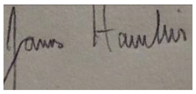
Abstract

Throughout East Africa, cattle play important roles in livelihoods of the rural poor and in supporting urban food security. As a result of low productivity, the dairy sector emits as much as 20 times more greenhouse gas (GHG) emissions per unit product than high income countries, while also acting as a leading driver of emissions from land use change. Productivity improvements may contribute to domestic food security and poverty alleviation jointly with GHG reductions for national climate targets. Yet the multi-functional roles cattle play within livelihoods imply mitigation strategies must be designed with care. Using household survey data from Kenya and Tanzania and a system modelling framework, this thesis evaluates options to better align country dairy policy initiatives with GHG targets under nationally determined contributions (NDCs). The thesis includes an empirical chapter (3) informing of variability in GHG emissions and dairy production practices across Kenya and Tanzania to inform mitigation interventions. Two model chapters then assess respectively the potential of feeding efficiency gains (chapter 4) and genetic gains combined with improved feeding (chapter 5) to contribute to GHG reductions consistent with development targets envisaged by the 'dairy roadmap' (part of the 2016 'Livestock Master Plan'). Feeding efficiency gains alone have negligible potential to meet climate targets consistent with growth in milk production (chapter 3). Instead, realising milk production targets with absolute reductions in GHG emissions will depend on reaching ambitious breed adoption targets (chapter 4). Realising such targets could increase milk production to 70% and 100% of the national target with respectively 29.6 ± 13.4% (95% CI) and 13.8 ± 17.1% GHG reductions relative to the baseline. Cost-benefit accounting indicates improved breeds would have net positive welfare impacts, increasing income on average by 195 to 261 USD capita^{-1} year^{-1} for producers. Since genetic gains are a central feature of Tanzania's dairy roadmap, the findings demonstrate the likely congruence between climate mitigation and national dairy development initiatives in East Africa, suggesting that improved breeds can deliver both climate and livelihood benefits within high agro-ecologic potential systems of East Africa.

Declaration

I declare that the thesis presented is my own work, except where references are made to other work and that it has not been submitted, in whole or in part, in any previous application or award for a higher degree elsewhere. Contributions by other researchers are properly acknowledged.

Recoverable Signature

X 

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Statement of authorship

The thesis is intended to result in three published journal articles; chapters 3, 4 and 5. Chapter 3 in addition to describing a typology of dairy producers is meant to provide general contextual understanding of the subject matter and to inform the discussion chapter (6). Chapters 4 and 5 conduct scenario analysis using the household suvey as well as auxiliary data sources. The decision of using *LivSim* for these chapters was determined by M.C. Rufino as a requirement for this PhD. The parameterization and scenario definitions used in *LivSim* was conducted entirely by the author of this thesis. The references and supplementary information for each chapter in this thesis are included immediately succeeding the chapter. This format helps ensure that each of the analytic chapters (3, 4, and 5) can be presented 'stand alone'.

Chapter 1 provides a general introduction and outlines the objectives of the thesis.

Chapter 2 comprises the literature review.

Chapter 3 describes the survey data and typology and will be submitted for publication.

J.H. was responsible for contributing to the design of the household survey in coordination with Esther Kihoro and Vera Vernooij. M.C.R. and C.T. contributed to the research methods and editing of the chapter.

Chapter 4 is published in *Scientific Reports* as:

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J.H. was responsible for contributing to the design of the household survey, coded the LCA and land footprint modelling in Python, and drafted the paper. G.Y. aided in the development of the spatial modelling and contributed to drafting the paper. G.C.S. contributed to project management, design and execution of the survey, and minor edits to the paper. M.Z. aided in the design and troubleshooting of the livestock simulations. M.C.R. contributed to design and management of the study, advised on the livestock simulations and agricultural/environmental modelling, and edited the paper.

Chapter 5 is intended for submission for publication.

J.H. was responsible for contributing to the design of the household survey, and developed the model framework used in this chapter. Adam M. Komarek contributed to the framework for income accounting and advised on the overall economics content of the chapter. M.C.R contributed to the scenario design, chapter formatting and editing. C.T. advised on the economics and made editorial contributions to the chapter along with G.C.S.

Chapter 6 is a general discussion and not intended for publication.

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1 Introduction

1.1 Background

For many countries in sub-Saharan Africa, and East Africa in particular, the dairy sector plays an important role in rural livelihoods, rural and urban nutrition security, and agricultural and economic development. Staple crops and pulses have historically been the mainstay of calorie intake throughout the region. Increasing intake of protein and micro-nutrients provided in dairy products would play an important role in improving nutrition security (FAO 2013; WHO and FAO 2003). The majority of milk is produced by smallholder and agropastoral farm-households (ADB 2014). In Kenya and Tanzania, in particular, approximately two thirds of rural households own cattle (NBS, 2013, GOK, 2013), relying on them for nutrition and income diversification, roles in farming (soil nutrients, draught power) and for financial and insurance roles (Udo *et al*. 2011), since livestock of all sorts constitute a store of value.

Research has demonstrated that increasing production in the dairy sector can act as a potent vehicle for poverty alleviation. Udo *et al.* (2011) found, among alternative livestock (beef cattle, small ruminants, poultry, and pigs), increasing income through greater production and sale of milk had the highest benefit-to-cost ratio. Using a dynamic multi-market model for East and Central Africa, Omamo *et al*. (2006) found that production growth in the dairy sector contributes more to GDP growth than other agricultural sub-sectors. The dairy sector, thus, represents an attractive avenue for private and public development agencies to promote rural poverty alleviation and economic development in the region.

The Kenyan and Tanzanian governments want to increase milk production to contribute to agricultural development and national food security (Michael *et al*. 2018, GOK 2013). Methods to achieve this include commercialization of milk production, coordinated development of dai supply chains, modernization of the regulatory environment related to milk quality and safety, solicitation of private investment, promotion of exports, and human skills development (URT 2015; GOK 2010). Further, increased demand and changing consumption patterns, growing population, growing household incomes, and growing demand abroad (providing opportunity to export milk and dairy products) are also expected to drive production growth in coming years (MMP 2020).

Climate change mitigation policy in the East African context

In 1994, the United Nations Framework Convention on Climate Change (UNFCCC) was established with the stated purpose of:

> *'stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system'* (UNFCCC 1994).

Today, near universal participation in the UNFCCC exists. Under the Durban platform, established in 2011 (UNFCCC, 2021) countries participating in the UNFCCC, including those in East Africa, are legally obliged to submit NDCs (Nationally Determined Contributions). The NDCs put forth by countries are commitments to greenhouse gas (GHG) emission reductions in the context of their own national circumstances, capabilities, and priorities. In addition to NDCs, there exist other policy mechanisms allowing countries in East Africa to receive financial assistance from the international community for mitigating GHG emissions. Some examples include REDD+ (Reducing Emissions from Deforestation and Forest Degradation), NAMAs (Nationally Appropriate Mitigation Actions), the Clean Development Mechanism (CDM, 2014), the Green Climate Fund, and the World Bank's Climate Business Innovation Network.

In 2017, Kenya adopted a NAMA for its dairy sector to contribute to the country's NDC target of 30% GHG mitigation by 2030 (GOK 2018). The NAMA's overarching strategy is to enhance productivity through better feeding, improved breeds and greater attention to animal husbandry, in order to fulfill the national milk production target while at the same time reducing GHG emission intensities (GOK 2017). The Tanzanian government has not as yet made any firm commitments to GHG mitigation. However, the dairy roadmap, as part of the national 'Livestock Master Plan' (Michael *et al*. 2018) shares common elements with Kenya's dairy NAMA, and thus has inherent potential to contribute to Tanzania's NDC. Tanzania's NDC targets emissions reductions of 10 to 20% by 2030 relative to 'Business as usual' (URT 2017).

1.2 Low emissions development in the dairy sector

The question of whether low-income countries (LICs) should contribute to climate change mitigation has been a topic of debate (e.g. Lamb and Steinberger 2017, Jacob and Steckel, 2013). Historically, GHG emissions have disproportionately been generated by high income, industrialized countries (Matthews *et al.* 2014). One could thus raise an obvious moral objection to making LICs bear the costs of reducing GHG emissions. This position, however, overlooks the potential role of international climate finance when invested in low emissions development (LED) to both support economic development and reduce GHG emissions for LICs. Development finance invested in productivity enhancing practices of technologies can, at least in principle, lead to 'co-benefits' in the form of climate mitigation as a result of the effect of productivity gains in reducing GHG emissions (e.g. Gerber *et al*. 2011, Herrero *et al*. 2013, Havlik *et al*. 2014). Opportunities for 'double' or 'triple' wins (the latter generally implying the additional element of 'adaptation' to climate change) are borne out by studies including Valin *et al*. (2013), Mottet *et al*. (2015), Tilman *et al*. (2011), and Weindl *et al*. (2015). These studies have demonstrated quantitatively the potential for reducing GHG emissions in absolute terms, increasing food availability (ie. milk), and in the case of Weindl *et al*., also increasing adaptation to climate extremes.

While possibilities for double or triple wins may exist, two generalized problems inhibit broad generalizations that productivity gains are a 'silver bullet' for LED:

> i) The 'rebound effect' (Lambin *et al.* 2011). Productivity gains, *via* market-mediated feedbacks, lead to greater production and consumption of the product in question. Demand for animal source foods, such as milk and dairy products, tend to be highly income and price elastic. Demand or supply rebounds can therefore be sufficient to negate emissions savings from improved productivity (Valin *et al*. 2014, 2013).
>
> ii) The multi-functional roles provided by ruminants to rural sub-Saharan Africa households. Farming households in these regions rely on multiple functions of cattle: nutrient cycling, store of capital, among others. Oosting, Udo, and Viets (2014) demonstrated that the multi-functional roles provided by cattle are maximized with large herds at low productivity levels, implying a fundamental trade-off between GHG mitigation and farmer livelihoods, including resilience to economic risk and climate shocks (Oosting, Udo, and Viets, 2014). For many agro-pastoral or smallholder households, productivity enhancing practices and technologies are thus either not feasible, or involve hard tradeoffs and therefore risks to livelihoods.

As mentioned above, growing dairy production is central to both Kenya's and Tanzania's national agricultural policy (GOK 2013, Michael *et al*. 2018). These initiatives reflect the acknowledged importance of domestic food production not only for food security in rural and urban settings, but also as a contributor to income growth among farming households, acting as a pathway out of poverty through increases in marketed surpluses employment generation in the rural economy. In Kenya approximately 20% of the population or 10 million people suffer from chronic food insecurity and poor nutrition (Lokuruka 2020). In Tanzania approximately 40% of children under five suffer from malnutrition and stunting (Lokuruka 2020). Policy programs striving to improve efficiency and/or increase production within respective dairy sectors can thus have substantial consequences by improving food security both for rural and urban households, or by acting as a pathway out of poverty for rural households. Harmonization of climate mitigation with domestic political agendas therefore depends on knowledge of the potential for reducing GHG emissions alongside achieving broader gains in food/nutrition security, incomes of rural producers, and polocy objectives more broadly. Exploring the synergies which do exist, and better understanding the tradeoffs can help facilitate decision makers to act on climate mitigation, while contributing to human development.

1.3 Main research aims and objectives

The aim of the thesis is to guide the design of LED frameworks for the dairy sector in the East Africa region. This involves identifying promising avenues for GHG mitigation which have a high level of overlap with development priorities, to minimise tradeoffs. This may help identify research and investment priorities in the dairy sector, and help design policy, institutional, and governance frameworks, including the implementation of climate policies (NDCs or otherwise).

The thesis uses a combination of methods including collection and analysis of household survey data, and biophysical and economic modelling, to explore future scenarios and their impact on production, GHG emissions and associated welfare implications for dairy producers. An integrated approach is required to analyse both the potential for GHG mitigation, and the financial and food security impacts of particular mitigation strategies, thus guiding LED interventions in the dairy sector.

While such tools can demonstrate the feasibility of future pathways, they are poorly suited to account for the behavior of cattle rearing households. Therefore, this thesis devotes a chapter to a qualitative *ex post* assessment of the diversity in dairy farming households in mid to high potential systems of Kenya and Tanzania (i.e. high mitigation potential systems), and the inter-linkages between livelihood orientations, resource endowments, and the animal husbandry practices and technologies that influence the level of GHG emissions. In the concluding chapter this qualitative assessment is discussed to explore the enabling conditions influencing practice and technology adoption, in order to show how LED pathways can be realised in practice.

The main objective of this thesis is:

To identify promising avenues for GHG mitigation that contribute to rural poverty alleviation among dairy producing households in East Africa, and the potential contribution of the sector to both national development objectives and mitigation under NDCs.

To accomplish this, household survey data is linked with livestock production system modelling to address the following knowledge gaps:

1. *Practices and technologies with high promise for reducing dairy GHG emissions while positively contributing to livelihoods of dairy producers (Chapters 3 and 6),*
2. *The contribution of improved feeding practices on sectoral GHG emissions, including from land use change (Chapter 4)*
3. *The contribution of improved breeds on sectoral GHG emissions, including from land use change (Chapter 5)*
4. *The potential for emissions reductions under sectoral development pathways involving growth in dairy production consistent with targets defined under national policies (Chapter 5), and*
5. The *potential for co-benefits between the sectoral development scenarios with welfare improvements for dairy producing households (Chapter 5).*

1.4 Chapter outline

The remaining chapters of this thesis involve a synthesis of key literature (Chapter 2) followed by an empirical chapter (Chapter 3) based on a large household survey (GLS 2019) conducted in south/central Kenya and the southern highlands and coastal regions of Tanzania. This is followed by two modelling chapters applied to the same regions of Tanzania (Chapters 4 and 5).

Chapter 2 synthesizes the most relevant literature on the drivers of variation in GHG intensity, on GHG quantification protocols, and of the expected tradeoffs and synergies associated with different mitigation pathways. This literature review informed the scenario analysis (mitigation interventions and adoption pathways), the design of the GHG quantification framework in Chapter 4, and quantitative welfare indicators used in Chapters 3 and 5.

Chapter 3 describes the methods used to conduct the household survey in Kenya and Tanzania and develops a household typology to explore the consequences of different mitigation interventions, and inform modelling assessments in the later chapters. The analysis of household diversity is used to identify mitigation interventions to consider in chapters 4 and 5 and to frame the qualitative assessment of enabling conditions in chapter 6.

Chapter 4 develops a model to assess sectoral mitigation pathways in the dairy sector of Tanzania's southern highlands and coastal regions. This chapter describes a framework linking the simulation model *LivSim* with a land footprint indicator, in order to quantify the role of feeding practice improvements on both direct dairy sector GHG emissions, and indirect emissions from land use change. This chapter describes and validates this framework by assessing the role of changes to feeding practices on the land footprint and GHG emissions. This framework is then used to conduct more policy relevant scenarios in Chapter 5 and with additional outcome indicators.

Chapter 5 extends the modelling framework of chapter 4 to assess the role of cattle genetic gains in meeting milk production targets consistent with the national targets defined under Tanzania's Livestock Master Plan. The welfare impacts of these scenarios are accounted for using income computations, which are then used to inform of potential co-benefits and tradeoffs of realizing sectoral development goals.

Chapter 6 summarizes the main findings and implications of the thesis and identifies topics for future research.

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2 Review of farm and regional model studies

2.1 Introduction

The chapter reviews studies assessing GHG emissions among smallholder and agropastoral dairy producers, across production systems, and of alternative mitigation strategies, within the East Africa region. There are three elements which the literature review seeks to consider:

(i) ***Understanding drivers of variation in GHG intensity***: Meeting national climate targets depends on alignment of policy interventions with spatial and farm heterogeneity in GHG emissions intensities. Thus understanding drivers of variation in GHG intensities and mitigation potential across production systems and farms within them is an essential pre-requisite to designing national climate mitigation frameworks.

(ii) ***Quantifying GHG emissions in prospective analyses***: Due to thediffuse, non-point source nature of GHG emissions from dairy production systems, alternative quantification methods may involve highly variable levels of uncertainty and accuracy in representation of factors driving GHG emissions (*e.g.* such as from land use change). Understanding the variety of approaches used and their individidual strenghths and weaknesses is thus important to capture the full GHG impact of any proposed intervention.

(iii) ***Harmonizing mitigation with broader societal objectives***: Promoting increased food security and income generation among farming households is in general a central feature of government policy in the agricultural sectors for countries in East Africa. Interventions to reduce GHG emissions must therefore be congruent with the livelihoods of dairy farming households. Understanding the variety of methods used to account for livelihood impacts of mitigation interventions in historical or forward looking (*ex ante*) analyses is therefore required.

The following review provides an overview of the state of knowledge pertaining to (a) key drivers of variation in emissions intensities across systems and at farm level, based on household livelihood strategies and resource endowments, (b) protocols for GHG emission quantification from dairy production systems, which include direct and indirect emissions (eg. from land use and land use change, LUC), and (c) synergies and tradeoffs with other broader objectives, given by government and development policy. The review is divided into studies done at farm-household level (farm studies) and those done at regional levels (national or sub-national, multi-country, or continental regional studies). For the latter, studies include those focusing on East Africa, but also higher levels, such as continental sub-Saharan Africa, and global studies.

2.2 Farm-level studies

Table 1 summarizes eight farm-household level studies quantifying GHG emissions for dairy production in the East Africa region. Four involve *ex post* empirical analyses of GHG emissions, livelihood (income and food security) and productivity indicators, and evaluation of these measures based on variation in farm-household characteristics (Hammond *et al*. 2017, *Udo et al*. 2011, Henderson *et al*. 2015), factors exogenous to the household (Henderson *et al.* 2015), and of different emission allocation methods (Weiler *et al 2014*., Udo *et al*. 2011). The other four involve *ex ante* simulation modelling to assess changes in select GHG emissions, productivity, and livelihood indicators relative to a baseline. Of these latter four, two involve strictly biophysical simulations: Bryan *et al.* and Seebauer *et al. (2014)* while the other two -- Shikuku *et al.* (2017) and Paul *et al.* (2018), -- evaluate the GHG and livelihood impacts, on income and food security respectively, of particular policy interventions in Tanzania and Rwanda.

Empirical studies

Udo *et al*. (2017) compare the carbon footprints from mixed crop-livestock dairy farms in Kenya under two alternative allocation methods: allocation to milk and meat, and allocation to all economic benefits derived from cattle (milk, meat, manure as fertilizer, insurance and financing). This is conducted for both free graze and zero-graze farms. The authors find that when the additional economic benefits provided by cattle are accounted for, there is nearly no difference in emissions intensities (CO_2eq per shilling milk) across farms. Weiler *et al*. (2014) comes to similar findings. Both these studies propose that the practices and technologies that reduce GHG emissions from milk production are likely to involve risks to livelihoods, arising from the multi-functional roles cattle provide for rural livelihoods: manure, draught power, insurance, and store of capital in the absence of formal financial services.

In addition to conducting simple carbon footprint calculations, Henderson *et al*. (2015) and Hammond *et al*. (2017) explore an added dimension of livelihood strategies, assets, and market integration for cattle rearing households. Both these studies find that higher market orientation (farm level) and market access (site level) are negatively correlated with GHG intensity, although these findings are not necessarily always statistically significant. Both studies also find that higher off-farm income is associated with higher GHG intensity, and Henderson *et al*. (2016) additionally find in some cases a negative, statistically significant relationship between asset endowment (both farm assets such as ploughs, irrigation systems, and household assets such as stoves, motorcycles) and GHG intensity.

Simulation model studies

Bryan *et al*. (2013) and Seebauer *et al*. (2014) quantified the potential for improved feeding and land management practices to reduce GHG emissions among smallholder farming systems. Bryan *et al*. (2013) considered nutrient management practices (residue retention, inorganic fertilizer application), and water conservation, and Seebauer *et al.* (2014) considered residue management, composting, cover crops, and agroforestry. These studies demonstrate that these management changes can reduce GHG emissions per unit of land, while increasing milk production up to 36%. However, they do not find conclusive evidence of potential to reduce GHG emissions per unit milk. Policy assessment studies provide an added dimension in predicting adoption from government policies aimed at supporting intensification, as well as the impacts at farm level on food security and income, considering the tradeoffs associated with adoption. Shikuku *et al*. (2016) studied improved feeding plus improved breeds and Paul *et al*. (2018) additionally consider improved crop management (access to seeds and inorganic fertilizer). Both Paul *et al.* (2018) and Shikuku *et al*. (2016) find that adoption of improved cows has greater poverty alleviation effects than other strategies involving only improved feeding and/or crop management. While this reduces emission intensity (Shikuku *et al. 2016)* emissions are found to rise in absolute terms. These studies additionally note that not all households have adequate resources to adopt improved cattle, and work is needed to understand barriers to adoption of improved cattle.

From the above studies, two points are highlighted with relevance for the design of mitigation scenarios and understanding tradeoffs associated with emission reductions. (i) For many dairy producing households producing within the efficiency frontier (using the terminology of Henderson *et al.* 2016), adopting more efficient practices and technologies may lead to improved food security and household income. However, as noted by Udo *et al*. (2017), smallholder farmers are risk averse and adopting efficiency-enhancing practices will involve costs. Because cattle serve multi-functional roles in livelihoods, adoption of emission reducing practices and technologies is not likely to occur unless farmers have at least some degree of market orientation in production. Therefore, adoption of new practices is critically dependent on both good market access as well as an enabling policy environment which facilitates access to capital and inputs and services. (ii) The majority of studies conducting *ex ante* assessment find that scenarios lead to higher absolute total emissions. In most cases this is because of the nature of the scenarios evaluated, such as those in which production increases in absolute terms, albeit with higher productivity and lower emissions intensity. In this respect, farm level studies have limited capacity to inform policy on national mitigation targets because (a) at sector level, increased production will result in lower prices and hence in turn a feedback effect which disincentivizes more production, and (b) as noted by Seebauer *et al. (2014)* there exist opportunities outside the farm to mitigate emissions. Land use change and land degradation, both of which are significant emissions sources from dairy production, are not typically considered in farm level studies.

Table 2.1 Summary of farm level studies on GHG emissions, technology and practices, productivity, and welfare indicators for sites across East Africa

Main author; region studied	**Framework, scenarios**	**GHG accounting**	**Main Findings**
	***Ex post* – farm types and allocation procedures**		
Udo *et al.* (2016); farms in Kenya highlands	Case study involving comparison of grazing, zero-graze, large, and very large farms. Compare emissions intensity using a physical allocation method to milk and meat, and to all outputs than can be quantified economically (milk, meat, increase in herd size, manure, insurance value of stock, and financing value).	Farm gate life cycle assessment; enteric fermentation (CH_4), manure (CH_4 and N_2O), soil N inputs (N_2O), feed production (CO_2)	Grazing and zero-graze smallholder farms are found to have emissions intensities of 1.8 and 1.3 kg CO_2eq kg^{-1} milk respectively, slightly higher than the larger farms. When considering all economic benefits, no differences in emissions intensity are found. The problems associated with adopting improved feed are attributed to low cost effectiveness at farm level, and high-risk aversion.
Weiler *et al.* (2014); Kaptumo, Kenya	Quantification of life cycle greenhouse gas emissions in three types of allocation systems: (1) economic; per unit milk, meat, manure as fertiliser, cattle as a mean of financing and insurance, (2) food allocation; per unit milk and meat, and (3) livelihood allocation; relative to the importance of cattle in livelihoods.	Life cycle assessment; enteric fermentation (CH_4), manure (CH_4 and N_2O), feed production (CO_2, CH_4, N_2O)	The carbon footprint of milk decreases as additional functions of dairy cattle are considered. The food allocation carbon footprint is 2.0 kg CO_2eq kg^{-1} milk. With economic allocation, the carbon footprint is 1.6 kg CO_2eq kg^{-1} milk.; with livelihood allocation, it is 1.1 kg CO_2eq kg^{-1} milk. Measures aimed at reducing GHG emissions per unit milk and/or meat may neglect livelihood functions of dairy cattle for households.

	***Ex post* – farm types and market interactions**		
Hammond *et al*. (2017); Lushoto, Tanzania	Inform the targeting of interventions based on variation in spectrum of agricultural production and market integration, nutrition, food security, poverty and GHG emissions. Group farms according to herd size and land area, resulting in two farm types: 'large' and 'small'. Appraise the role of three farming strategies on climate smartness: intensification, diversification, market orientation.	IPCC methodology (tier 1); enteric fermentation (CH_4), manure (CH_4 and N_2O), soil N inputs (N_2O)	The climate smartness of different farm strategies is clearly determined by an interaction between the characteristics of the farm household and the farm strategy. In general strategies that enabled production intensification contributed more towards the goals of climate smart agriculture on smaller farms, whereas increased market orientation was more successful on larger farms.
Henderson *et al.* (2017); Sites in Kenya, Tanzania, Uganda, Ethiopia	Conduct efficiency frontier analysis combined with farm gate GHG emissions accounting for smallholder mixed crop-livestock farms. Compare farm attributes, including market orientation, asset endowments, and off farm income (%) to technical efficiency.	IPCC methodology (Tier 1); enteric fermentation (CH_4), manure (CH_4 and N_2O), soil N inputs (N_2O)	Percentage possible increase in output between 28 and 167% across sites. Emissions intensities range from 11 to 40* kg CO_2eq kg^{-1} milk . Emissions intensities decline with yield gaps. Strong and statistically significant relationship between market integration and efficiency, emissions intensity. Find wealth positively correlated with efficiency, but also off farm income.
	***Ex ante* – adoption under policy scenarios**		
Shikuku *et al*. (2016) Intensive, zero-graze systems in Lushoto, Tanzania	Multi-dimensional trade-off analysis and impact assessment tool (MD-TOA) is used to assess income and GHG outcomes with improved livestock feeding and breeds. Improved livestock feeding involved higher intake of Napier grass, maize bran, and sunflower cake relative to local grass and maize residues. Breed improvement involved replacement of local with cross bred cows.	Enteric Fermentation (CH_4) (Ruminant)	Quantity and quality of feed intake were related to economic benefits; only quality improvements led to declines in methane emissions intensity. Methane emissions intensity ranged from 24 to 27 kg CO_2eq kg^{-1} milk. Food security increased relatively more under improved feeding practices with local

			cows; income increased relatively more with improved cows.
Paul *et al.* (2017) Smallholders in Rwanda	*Ex ante* impact evaluation of crop and livestock intensification policies on food availability and GHGs. Scenarios included improved breeds, improved feeding, improved crop and feed management.	IPCC methodology (tier 1); enteric fermentation (CH_4), manure (CH_4 and N_2O), soil N inputs (N_2O)	All scenarios increased food availability and increased net greenhouse gas emissions per household.
		***Ex ante* – practice adoption**	
Bryan *et al*. (2011); central Kenya	Simulation analyses of improved feeding and soil management practices on select GHGs and farm profitability. A variety of supplement regimes in addition to basal forage (diet scenarios). Use of organic soil fertility management and hybrid seeds (soil management).	Enteric fermentation (CH_4) (Ruminant); Soil carbon stock changes (CO_2) from improved soil fertility management (Century)	Practices studied increased soil carbon sequestration, reduced methane emissions intensity, and increased profit. Ten out of the 14 feeding strategies increased total emissions. Baseline emissions and mitigation were highly variable across sites, especially between arid and humid regions (up to a 5 fold difference).
Seebauer *et al*. (2014) Smallholder mixed crop-livestock farms in Kenya	Assess emission profiles of four farm clusters representing baseline 2009 conditions with the year 2011 where adoption of sustainable land management practices occurred. The sustainable land management practices included residue application, composting, cover crops, and agroforestry.	Enteric fermentation (CH_4), manure (CH_4 and N_2O), soil N inputs (N_2O), carbon stock changes (CO_2) in soil organic carbon and woody residues. Burning crop residues.	An estimated net mitigation of 4 to 6.5 tCO_2 ha^{-1} yr^{-1}, with significantly different mitigation potential based on the farm type.

*Calculated using a milk protein content of 4.5%

Table 2.2: Review of literature on analyses of the dynamics between land use, productivity, and greenhouse gas emissions from dairy production systems at global, continent or national scale

Main author; region studied	**Model framework**	**GHG accounting**	**Key findings**
		Sub-national	
Brandt *et al.* (2018); central and west Kenya	Coupled *LivSim* with a GHG accounting framework, including land use change emissions from croplands. Scenarios included improved feeding practices, differentiating feed conservation, higher forage availability, and concentrates and grains supplementation.	Life cycle assessment; enteric fermentation (CH_4), manure (CH_4 and N_2O), soils (N_2O), feed processing/transport (CO_2), and carbon stock changes (CO_2) in soil organic carbon from cropland conversion.	Potential for reducing emissions intensity up to 31% while leading to 41% of the milk production target.
Brandt *et al.* (2020); central and west Kenya	Extended Brandt *et al.* (2018) to include the impacts on C loss from forest disturbance. Extended the scenario analysis to include maize crop yield gains.	Same as Brandt *et al.* (2018) plus C losses (CO_2) from forest disturbance	Milk yields increase by 44-51%. Maximum reduction in emissions intensity of 33% and absolute emissions by 2.5%.
Notenbaert *et al.* (2020); Tanga region of Tanzania	Couple the 'CLEANED'* framework with an economic feasibility model to assess four intervention scenarios on GHG emissions and income at value chain (VC) level. Scenarios include genetic improvement, improved feeding, animal health, and a package combining all interventions.	Life cycle assessment; enteric fermentation (CH_4), manure (CH_4, N_2O), and managed soils (N_2O).	An overall rise in GHG emissions is expected, with a maximum of 53% increase associated with an 89% increase in milk supply at VC level.

		Regional	
Gerssen-Gondelaach *et al.* (2017); sub-Saharan Africa	Analysis of literature, as well as Herrero *et al.* (2013) and GLOBIOM to compare GHG impacts of two intensification strategies: (1) intensification of pasture-based systems, and (2) converting from pasture-based to mixed and/or industrial systems.	Life cycle assessment; enteric fermentation (CH_4), manure (CH_4 and N_2O), soils (N_2O), natural land, grassland, and cropland conversion (CO_2)	Intensification of pasture-based systems can obtain significant farm gate emissions reductions (>50%). Land use change mitigation is considered to be the most important mitigation strategy. Emissions from land use change make up between 45-65% of total emissions for pasture, industrial, and mixed systems.
Havlik *et al.* (2014); sub-Saharan Africa	GLOBIOM; consider transitions towards more efficient systems, from grazing to mixed, to industrial systems, in relation to GHG emissions. Consider emissions to 2030 under three scenarios: (a) system transitions, (b) growth in production with constant land use, and (c) system transitions under C taxes.	Life cycle assessment; enteric fermentation (CH_4), manure (CH_4 and N_2O), soils (N_2O), natural land conversion (CO_2)	Scenario (a), (b), and (c) involve total emissions of 1380, 1405, and -25 Mt CO_2eq y^{-1} emissions respectively.
Havlik *et al.* (2012); Africa	GLOBIOM; simulate growth in crop yields on the structure of production systems, crop and grassland expansion, and GHG emissions. These results are compared to emissions reductions pathways without crop yield growth.	Life cycle assessment; enteric fermentation (CH_4), manure (CH_4 and N_2O), soils (N_2O), natural land conversion (CO_2)	Scenarios involving higher crop productivity improvements relative to baseline Land use change, contributes ~ 50% of all emissions, regardless of scenario, due to emissions from conversion of natural land and forestry. For each scenario, total emissions were inversely proportional to the rate of growth in the crop sector.

Henderson *et al.*. (2015); sub-Saharan Africa	Link GLEAM to the soil C models Century and Daycent to calculate soil C emissions, N_2O emissions, and forage removal under differing grazing management scenarios. Scenarios include improved grazing management, sowing legumes, and N fertilization.	Grazing lands only -- CO_2 – soil stock changes from grazing lands (Century and Daycent) N_2O – grazing lands (Century and Daycent)	The practices were estimated to reduce emissions by up to 379 metric megatons of CO_2 equivalent emissions per year. Two thirds of this was possible at a carbon price of 20 US dollars per metric ton of CO_2 equivalent emissions. Improved grazing management is particularly effective in South Africa.
Herrero *et al.* (2013); sub-Saharan Africa	Spatially disaggregated analysis of biomass use, production, feed efficiency, excretion, and greenhouse gas emissions.	Enteric fermentation (CH_4), manure (CH_4 and N_2O)	Increasing feed efficiency is a crucial aspect of meeting the objectives of increasing ruminant milk production and reducing greenhouse gas emissions.
Mottet *et al.* (2015); East Africa, mixed crop-livestock systems	GLEAM; spatially explicit biophysical model of livestock supply chain. High level of detail on herd production functions. Distinguishes between grazing and mixed systems. Strategies for mitigation considered are improved feed quality and herd management.	Life cycle assessment; enteric fermentation (CH_4), manure (CH_4) and N_2O), feed production and transport (CO_2), Forest conversion for soybean only	For mixed dairy production in East Africa, there is the potential for increasing output between 6-18%. Mitigation potential of 10–24% from baseline with constant output, and 5–10 % with expanded production. Mitigation of 6–14 and 4-10% from improved quality diets and improved herd management respectively.
Popp *et al.* (2010); sub-Saharan Africa	MAGPIE; a spatially explicit land use model is used to assess future emissions scenarios by combining region specific socioeconomic data, including population, income, food demand, and production costs, with crop yields.	Enteric fermentation (CH_4), manure (CH_4 and N_2O), Agricultural Soils (N_2O)	Demand, especially for meat and milk, is a pivotal factor explaining different emission pathways. Technological mitigation options are not as effective as demand side measures in reducing emissions.

Thornton and Herrero (2010); sub-Saharan Africa	Consider a range of mitigation options in mixed and rangeland based systems, considering the extent of adoption potential in each system. Scenarios include adoption of improved pastures, intensifying diets, changes in land use, and adoption of improved breeds.	Enteric fermentation (CH_4), soil carbon emissions/sequestration from land management change (CO_2)	The ordering of the mitigation potential of different practices from highest to lowest are: reversing rangeland degradation, agroforestry, improved pasture species and residue digestibility, improved breeds, and grain supplementation.
Valin *et al.* (2013); sub-Saharan Africa	GLOBIOM; assess four crop and ruminant yield scenarios and three productivity pathways (representing different strategies for closing yield gaps) (CONV) compared to a stalled yield growth scenario (SLOW). Yield increases in crops (CONV-C) are considered separately from yield increases in livestock (CONV-L).	Life cycle assessment; enteric fermentation (CH_4), manure (CH_4 and N_2O), soils (N_2O), natural land conversion (CO_2)	CONV-L is the lowest emissions pathway, followed by CONV, and CONV-C. SLOW results in highest emissions. Demand growth resulting from productivity changes reduces emissions savings.
		Global	
Gerber *et al.* (2011); Global	GLEAM; assess cradle to farm gate emissions with changes in productivity.	Life cycle assessment; enteric fermentation (CH_4), manure (CH_4) and N_2O), soil N inputs (N_2O), feed production and transport (CO_2)	GHG emissions per cow increase with increasing milk yield; emissions intensities decline.

* Comprehensive Livestock Environmental Assessment for improved Nutrition, a secured Environment and sustainable Development.

2.3 Regional studies

Table 2 summarizes key findings of thirteen high level spatially explicit model studies involving GHG emissions quantification, productivity indicators, and land occupation for livestock production systems (hereafter, LPS) that span the East or sub-Saharan Africa region.

The focus areas include three studies at sub-national level, nine multi-country or continental (sub-Saharan Africa as a region), and one global study. With the exception of Herrero *et al.* (2013), all studies involve dynamic biophysical modelling of emissions intensities and efficiency indicators across LPS under forward looking scenarios. All studies consider the major direct livestock GHG emissions sources: enteric fermentation and manure. But coverage of emissions from feed production, and particularly with respect to land use and LUC differs widely. Six studies conduct either life cycle (Notenbaert *et al*. 2020, Gerber *et al 2013*, Mottet *et al 2015.*, Popp *et al. 2010*) or comparable methods quantifying GHG emissions per unit product (without allocating emissions between co-products) (Brandt *et al.*, Herrero *et al. 2013*). Seven consider land use and LUC emissions/removals either in combination with other non-CO_2 emissions (Brandt *et al*. 2018, 2020, Gerssen-Gondelaach *et al. 2017*, Havlik *et al*. 2014, 2012, Valin *et al. 2013*, Thornton and Herrero 2010) or in isolation (Henderson *et al. 2015*).

Regional variation in emissions intensity

Herrero *et al*. (2013) quantifies GHG emissions across production systems finding that emissions intensities per unit of milk vary by as much as a factor of five between the most and least productive systems. This variation is a result primarily of variation in diet qualities, ie. digestibility and crude protein content of feeds, resulting in large differences in feed conversion efficiency, land and herd productivity.

Gerber et al. (2013), the only global study, demonstrate that regional variation in productivity is a key determinant of GHG emissions intensities. They find that total GHG emissions per cow increase with increasing productivity but that emissions per unit of milk decline. The authors suggest that because of low livestock productivity in developing country regions, improving productivity is a promising approach for reducing emissions intensities while improving food availability, meeting the likely growth in demand in coming decades.

Summary of multi-country model studies

Using GLEAM (Global Livestock Environmental Assessment Model), Mottet *et al.* (2015) find that herd productivity is a key factor allowing for emissions reductions from dairy within East Africa's mixed crop-livestock systems. With increased productivity per cow and a decline in total cow population, allowing total milk production to remain constant, emissions decline in absolute terms by 10-24%. With increased productivity per cow and constant cow numbers, leading to growth in milk production up to 18%, absolute emissions decline by 5-10%. While these findings are notable in that they include the impact of improved feeding practices on herd composition (the proportion of cows in the herd), a limitation is the omission of emissions from LUC.

Studies using GLOBIOM (the Global Biosphere Model) are notable in their degree of rigour in calculating indirect GHG emissions from LUC. Havlik *et al.* (2012) examine dynamics of crop yield gains in land sparing, directly from crop yield increases and indirectly from greater use of crop-based feeds in livestock diets. This study finds a negative relationship between crop yields and total livestock GHG emissions, primarily as a result of reduced CO_2 emissions from conversion of native ecosystems. Havlik *et al.* (2014) further the analysis to consider livestock production system transitions – defined as a transition from grazing to mixed crop livestock systems by greater production and feeding of crop-based feeds. For the sub-Saharan Africa region, system transitions are found to lead to reductions in total emissions relative to a counterfactual 'fixed' production system scenario by 1.8% by the year 2030. Valin *et al.* (2013) conducted an analysis of the food security impacts of alternative crop and livestock productivity scenarios. Livestock scenarios included improved feeding and improved husbandry resulting in reduced mortality. The authors found that combinations of crop and livestock productivity gains delivered reductions in total emissions by as much as 15% for the Africa region.

While GLOBIOM studies involve regional aggregation of emissions estimates, the results are nonetheless insightful for sub-national climate mitigation initiatives for countries in East Africa. Among each of these studies, avoided LUC is a pivotal element for emissions reductions pathways. Gerssen-Gondelaach *et al*. (2017), the only study to consider dairy production systems as distinct from agriculture more broadly, estimate that LUC contributed between 45 to 65 % of total dairy GHG emissions in Africa throughout the period 2009 to 2017. Havlik *et al*. (2014) suggest that mitigation policies targeting avoided LUC are 5 to 10 times more efficient than those targeting direct livestock emissions alone.

Grazing management

Thornton and Herrero (2010) and Henderson *et al*. (2015) both account for improved forage management in relation to partial GHG budgets in the sub-Saharan Africa region. Scenarios considered included improved grazing management (resulting in higher soil carbon in grazing lands), legume sowing, and N fertilization. While nearly all scenarios simulated reduced GHG emissions intensities, higher CH_4 emissions from higher dietary forage intake often offset reduced emissions from land management.

The role of demand growth on emissions outcomes

Popp *et al*. (2010) and Valin *et al*. (2013) both explicitly account for interactions between demand shifts and productivity gains in relation to potential livestock mitigation in future scenarios. Popp *et al*. consider the potential of better herd management, breeding, and feeding practices as principal strategies for mitigating non-CO_2 emissions. Both these studies conclude that future growth in demand for milk and meat is a central factor influencing emissions outcomes, with plausible increases in demand for livestock products able to negate any mitigation resulting from improved productivity. Valin *et al*. (2013) predict that with a 50% increase in demand elasticity for livestock products over the baseline assumption, emissions would increase by between 27 to 42% by 2050, despite crop and livestock productivity gains. Popp *et al.* (2010) predict that only with a decadal reduction in meat consumption by 25% can emissions be reduced in absolute terms by 2055; increases in consumption of livestock products by contrast lead to up to 36% higher emissions even under scenarios where emissions intensities decline.

Country level studies

Brandt *et al.* (2018, 2020) and Notenbaert *et al.* (2020) represent the only studies which, by virtue of their sub-national focus, could be used for policy making at the national level for emissions reductions in the dairy sector. Brandt *et al*. (2018) simulate GHG effects of changes in feeding practices and feed crop yields in Kenya. The authors found feeding practices were important for realizing potential milk yields, however no evidence was found for potential to mitigate emissions in absolute terms. Notenbaert *et al*. (2020) assess the GHG and income effects of a range of scenarios in Tanzania. The authors calculate the gross profits of feeding, cattle genetic, and health interventions when adopted in isolation and combined for smallholder and agro-pastoral dairy producers. Gross profits were calculated based on milk revenue minus the associated costs of adoption. All interventions increased gross profits 5 years after the initial investment. While Notenbaert *et al*. (2020) demonstrate that the practices considered are economically viable for producers, a limitation is that the role of LUC was entirely overlooked in their analysis.

2.4 Key insights from farm and regional studies

From the studies reviewed emissions intensities are found to vary by as much as factors of 3.5 for household level studies (Henderson *et al.* 2016) and by as much as a factor of 5 for regional level studies (Herrero *et al.* 2013). Variability in emissions intensities is driven by both agro-ecology (Herrero *et al.* 2013), where pastoral production systems in arid regions emit as much as 5 times more GHGs per unit product than crop-livestock systems in tropical systems. Regional and farm variability in market access and participation are key socioeconomic drivers of uptake of low emissions practices/technologies across regions and households, and farm level emissions intensity (Henderson *et al.* 2016, Hammond *et al.* 2017). As noted by many studies, productivity of the dairy herd is a key factor leading to emissions intensity reductions in prospective analyses and in variability in emissions intensities acrss farms and regions. Hence this will be a key aspect for reducing GHG emissions consistent with higher calorie availability from milk and dairy products, a key requirement if mitigation is to be consistent with broader political agendas.

The results of GLOBIOM studies imply that a significant component of dairy GHG mitigation lies in reduced CO_2 emissions as a result of avoided LUC. To date, however, only Brandt *et al*. (2018) and (2020) have included LUC in a country level study of the dairy sector. However, these findings are limited in that only the LUC impacts of intervention scenarios are considered, and the authors do not establish a baseline for LUC from which emission reductions can be considered. Notenbaert *et al.* (2020), a study which integrates a life cycle assessment with income accounting to study the welfare impacts on dairy producers, is notable as the only study which evaluates the economic viability to producers from adopting emissions reducing practices. However, their study which omits LUC and thus misrepresents the magnitude of GHG emissions from dairy production, cannot therefore readily inform national climate policy in Tanzania, or elsewhere.

Relevance for climate policy in Tanzania’s dairy sector

The ‘dairy roadmap’, as part of Tanzania’s Livestock Master Plan (Michael *et al.* 2018), prioritizes productivity gains in the dairy sector to reduce dependence on dairy imports. Key aspects of the 'dairy roadmap' include improved (*B. taurus*) genetics, improved feeding, and inclusive dairy value chains (Michael *et al.* 2018). Replacing imports with domestically produced milk offers the opportunity to increase gross revenue for the dairy sector, making adoption of new technology and practices more financially feasible for producers. According to FAO statistics, both Kenya and Tanzania are effectively self-sufficient in raw and minimally processed dairy products. Trade in fresh milk makes up a small percentage of total domestic consumption, less than 2% for Kenya and less than 1% for Tanzania. However, in processed and value-added products such as cheese, butter and yoghurt, the countries are more highly reliant on imports, with imports comprising up to 50% of domestic consumption (FAO 2021).

Based on existing literature the roadmap initiatives can be expected to lead to reductions in GHG intensities. Notenbaert *et al.* (2020) document the potential for reduced emissions intensities and improved profits for producers in the Tanga region, considering the types of interventions that are part of the roadmap. However, as noted earlier, the authors omitted the role of LUC in their analysis. Presumably, the magnitude of emissions reductions estimated by Notenbaert *et al.* (2020) was underestimated. It remains unclear, however, whether the initiatives under the dairy roadmap could result in emissions reductions consistent with Tanzania's NDC target of 10 to 20% reduction relative to business as usual by 2030 (URT 2017).

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3 Mitigation targets in East Africa's dairy sector: practices and household diversity

Abstract

The dairy sector in sub-Saharan Africa has significant potential to reduce its carbon footprint *via* improved efficiency. A key constraint to more widespread inclusion of the sector in nationally determined contributions (NDCs) has to do with knowledge gaps on how to scale low emissions practices across households of diverse assets and livelihood strategies. Using a large household survey dataset, this study evaluates which would be the appropriate practices to reduce emissions for dairy households in mid to high potential systems of Kenya and Tanzania. Households are stratified based on predominant breed of cattle owned; local (*Bos indicus*) or improved (*Bos taurus*). Factor reduction and clustering are then applied to each stratum to group households into discrete types to understand existing low emissions practices and their relationships with livelihood strategies and assets. The result is a functional typology with 3 main livelihood features x 2 breed types, for 6 distinct household types in total. These types are distinguished by their main livelihood strategy, for which three are identified: (i) dairy specialization, (ii) diversified farming, and (iii) off-farm orientation. Indicators are then examined depicting livelihood strategies, assets, dairy-related greenhouse gas emissions, and current input use and practices. This study finds that households specialized in dairy production are more likely to benefit from and therefore adopt low emission practices that result in productivity gains. These households represent ideal candidates for targeting interventions for climate mitigation. The characterisation of diversity in greenhouse gas emissions, livelihoods, and farm assets in this study can be used to design of climate mitigation frameworks in the East African dairy sector which maximise synergies with the welfare of rural dairy producers.

3.1 Introduction

Dairy cattle play meaningful roles in food security and income diversification among smallholder and agropastoral households in East Africa (Rufino *et al.* 2013a). However, the dairy sector in this region is characterised by poor environmental performance, as a result of the subsistence nature of production, poorly developed marketing infrastructure, and small average land holdings (and therefore poor economies of scale) (ADB 2010). As a consequence, the sector contributes several times more greenhouse gas emissions (GHG) per unit of milk than in high- and middle-income countries (Herrero *et al.* 2013). Ongoing demographic and development trends are expected to result in further increases in consumption of milk and dairy products in coming decades (MMP 2020), posing a risk for the natural resource base and climate if this demand is not met sustainably. 'Sustainable intensification' has been advocated as means of meeting future consumption growth with reduced climatic impact (Herrero *et al* 2016). Modelling studies such as Notenbaert *et al.* (2020) and Mottet *et al*. (2015) have suggested productivity gains in dairy supply chains can both reduce GHG emissions intensities while contributing to food availability and producer incomes, the main priorities for agricultural development policies. To meet dairy GHG mitigation targets as part of nationally determined contributions, a plausible approach is thus to design policies to incentivize or finance farm level adoption of low emissions technologies and management practices; these would enable reduced greenhouse gas emissions while enhancing welfare through higher marketable surpluses. Realising these outcomes however depends on the effective design of policies, a topic which remains under-studied and poorly understood (Herrero *et al.* 2016).

There exist several technologies and practices commonly proposed for reducing GHG emissions intensities in smallholder and agropastoral dairy production systems in the tropics. Among others, these include (a) provision of nutrient-dense forages or concentrates in place of lower quality feeds (Caro *et al.* 2017), (b) selection for high yielding breeds (De Haas *et al.* 2017), (c) preventive health measures and improved reproduction management (Macleod *et al.* 2018, Hristov *et al.* 2013), and (d) efficient manure handling practices (Forabosco *et al.* 2013). *Ex ante* studies modelling adoption of such low emissions practices by farm households have demonstrated productive synergies when they are adopted simultaneously. For example, adopting crossbreds (*Bos taurus x Bos indicus*) combined with improved feeding practices was found by Paul *et al.* (2018) and Shikuku *et al*. (2016) to lead to greater mitigation and welfare benefits than when any one is adopted in isolation. However, these studies and others (including Notenbaert *et al*. 2017) which aim to guide development of GHG mitigation policies generally treat households in broad groupings that neglect the inherent variability in livelihood strategies and resource endowments which influence household propensity to adopt new practices. Therefore, at present knowledge gaps persist on how practices and technologies for low emissions dairy can be best targeted to support uptake of these practices among diverse households.

Kenya's dairy sector ranks among the most productive in East Africa, and also has the lowest greenhouse gas emissions per unit milk. Greenhouse gas emissions intensities at national level are 3.8 kg CO_2eq per kg milk, compared to 19.9 and 24.5 kg CO_2eq per kg in Tanzania and Ethiopia, respectively (FAO New Zealand, 2017a,b, 2019). Moreover, Kenya is the first country in all of Africa to implement a climate mitigation policy in its dairy sector as part of its nationally determined contribution (NDC) (GOK 2018). While Kenya has stipulated priority interventions to meet its target emissions level, upscaling these practices among dairy producers remains an acknowledged constraint in realizing climate mitigation targets (Mbae *et al.* 2020). To date, Kihoro *et al.* (2021), focusing on Tanzania, is the only study to explicitly characterise the diversity in farm households to guide the design of low emissions dairy interventions in the East Africa region. Kihoro *et al.* presented important insights into producer practices, livelihoods and asset bases, however no explicit formulation of variation in greenhouse gas emissions intensities was made. Emissions intensities between production systems based on local *versus* improved cattle in Kenya and Tanzania differ by factors of 3.5 to 10.0 (FAO New Zealand 2017, 2019). Explicitly categorizing households based on variation in emissions intensities, and the relation of such to existing practices and socioeconomic characteristics, may provide more clarity for how best to design interventions and how these can contribute to mitigation targets.

The aim of this study is to provide empirical evidence to guide the design of policy interventions for low emissions dairy development in the East Africa region assessing their congruence with the livelihood objectives of rural dairy households. The objectives of this research are defined as:

1. To develop a household typology of dairy producers to understand differential adoption of low emissions dairy production practices, and
2. To guide the development of policy frameworks for climate change mitigation in the dairy sector considering the variability in:
   a) livelihood strategies,
   b) resource endowments,
   c) dairy greenhouse gas emissions intensities and herd productivity, and

d) input use and dairy practices

This study involved collection of a large household survey throughout mid to high potential agro-ecological systems of Kenya and Tanzania (Figure 3.1). To investigate the linkage between household diversity and GHG emissions intensities, dairy households are stratified by the breed of cattle owned. Few households own both local and improved cattle (less than 5% and 14% in Kenya and Tanzania respectively). This allows for grouping of households based on the breed which forms the largest percentage of the herd. This results in two strata based on the predominant cattle breed, local indigenous cattle (stratum 1), and improved cattle (stratum 2). Factor reduction and clustering analysis are then applied to the two strata, resulting in a consistent typology of dairy producers across districts. 'Consistency' in the context of this paper implies that the ordinal ranking of clustering variables among household types is the same for each site. Next, the four indicator categories are contrasted across regions, strata, and household types and the chapter then discusses the implications for targeting and designing mitigation policy frameworks that are congruent with livelihood objectives of dairy producers in Kenya and Tanzania.

3.2 Methods

3.2.1 Survey design

A survey of dairy producing farm-households was conducted between November 2017 and August 2018, hereafter referred to as GLS (2019) (the 'Greening Livestock Survey'). In the context of this paper a household is defined as a collection of individuals dwelling in the same place, and the associated land owned by the occupants. All households survey owned at least one dairy cow (*Bos indicus* or *Bos taurus*, or crosses thereof). GLS (2019) surveyed 1,900 smallholder dairy producing households using a stratified random sampling protocol across six sites: two in south and central Kenya, Nandi and Murang'a (Fig. 3.1a) and four in southern and coastal Tanzania: Njombe, Mufindi, Rungwe (southern highlands region) as well as Mvomero district, Morogoro region (Fig. 3.1b). Random sampling was conducted at hierchical levels: within each site, wards and villages were selected randomly. After a village was identified, enumerators would select households randomly from within the village. These sites represent a transect ranging from mid to high potential agro-ecological systems, and from low to high market quality (defined as the reliability and attractiveness of procurement systems for inputs and for selling milk, based on Duncan *et al.* 2013) (Table 3.1). In Mvomero the focus was only on the northern region, therefore in this study, the localities surveyed are referred to as 'sites'; neither one is meant to be representative of the broader administrative unit.

Survey questionnaire

Local enumerators conducted the survey using the Open data kit platform (ODK 2020). The enumerators visited the homestead and interviewed household members, either the household head or other farm labourers or household members. The questionnaire took between 1.5 to 2.5 hours to complete. The survey template involved a structured questionnaire which was based loosely on 'IMPACTlite' (Rufino *et al*. 2013b). The main survey modules included: household member composition and activities (family members and their employment on and off-farm), land holdings and allocation, cattle holdings by breed and cohort, and entries/exits of cattle into the herd, feeding practices including the amount of individual feeds fed to cattle, the cohorts of cattle receiving feed rations and grazing, and the grazing practices including land uses and tenure, crop production including inputs used, cash income and expenses, additional household income and food production activities, farm and off-farm income, and household participation in markets and the associated input and offtake arrangements. The data quality checking, analysis, variable transformation and typology construction as described in the following sections were conducted using the R statistical computing program (R Core Team 2021). The quality verification was based on manual inspection of individual variables used in the typology and indicator analysis. Variables which were deemed to not normally exceed a certain value, such as the quantity of feed provided per TLU, received arbitrary thresholds demarcating a reasonable outlier range. A household was then removed from the dataset based on the condition of a variable being between outside of this range.

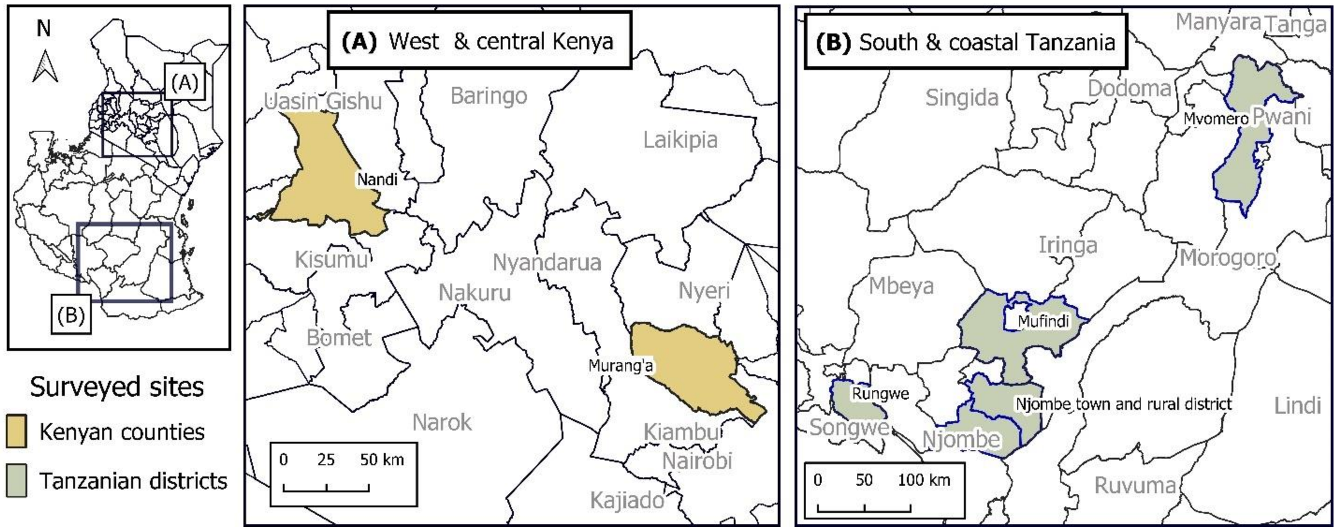

Figure 3.1: Location of survey sites. A. Surveyed counties (shaded in beige) in west and central Kenya. B. Surveyed districts in south and coastal Tanzania (shaded in grey).

Table 3.1: Main agro-ecological, farming, and milk selling characteristics across counties (Kenya) and districts (Tanzania) included in study. Production systems include mixed, crop-livestock production systems, arid (MRA), tropical (MRT), and humid (MRH). EADD denotes the East African Dairy Development.

	Kenya		Tanzania			
	Murang’a	*Nandi*	*Mufindi*	*Mvomero*	*Njombe*	*Rungwe*
	Agro-ecology & production systems					
Production systems[2]	MRA	MRT	MRT MRA	MRH MRA	MRT	MRH
Rainfall[1] (mm yr^{-1})	~1,200	1,200-2,000	500-1,600	600-1,000	600-1,600	900-2,700
Feeding practices	Zero-graze	Fenced, tethered, or free grazing	Grazing/ semi-graze		Zero graze/ semi-graze	
	Mostly on privately owned native grasslands		Free grazing in communal grasslands (native pastures) and croplands in dry season			Same but with swamp/river bank grazing
	Herd characteristics					
Herd size (heads ± SD)	4.6 ± 3.6	2.7 ± 1.8	11.4 ± 10.9	27.1 ± 49.4	4.5 ± 4.1	3.5 ± 2.4
Improved cattle (% of site sample)	85.7%	89.6%	16.8%	10.5%	58.2%	68.4%
	Market characteristics and population density					
Dairy market quality	Good 0 EADD hubs Multiple processors Close to Nairobi	Good 3 EADD hubs Multiple processors	Moderate 1 EADD hub No processors	Poor 0 EADD hubs 1 Processor	Good 3 EADD hubs Multiple processors	Good Multiple processors Close to Mbeya
Human Population density[1] (# km^{-2})	459	366	41	55	43	215

[1] Regional socioeconomic profiles (CGM 2018, CGN 2018, ISP, 2013; NSP, 2016; MRR 2007, NBS 2017)
[2] Based on the classification of Robinson *et al.* (2011)
All other values provided by survey (GLS 2019).

3.2.2 Typology construction (Figure 3.2)

The typology is constructed by applying sequentially principal components analysis (PCA) followed by non-hierarchical clustering analysis (CA) by each stratum of households for each site. PCA is a technique that reduces a large set of inter-dependent variables to a smaller set of orthogonal (uncorrelated) variables which, in combination, explain a high proportion of overall variance in the data (van der Maaten *et al.* 2009). This allows identification of key variables driving variation in livelihoods and resource endowments, thus providing a basis for understanding differential adoption patterns. In this study, variables included in the PCA depict structural (assets and resources) and functional (livelihood strategies) characteristics. This method allows specific variables to be identified which are most influential in understanding adoption of low emissions dairy practices by diverse households.

Factors influencing adoption of low emissions dairy production practices

This study considers four categories of constraints hypothesized to influence uptake of improved cattle, improved feeding, and other changes to husbandry practices. These potential constraints are used to guide the variables used in the PCA, by depicting variability in severity of constraints, and to select the indicators used to evaluate these constraints (section 3.2.3 below).

<u>Land and labour resources</u>: For cattle to produce more milk, higher quality diets are required, to be achieved by cultivation of forages with higher nutrient density, and/or feed conservation to maintain nutrient quality during the dry season when natural grazing is scarce. Cultivating forages and applying feed conservation techniques generally are labour intensive activities, necessitating more household or hired labour than reliance on natural grazing alone (Maleko *et al*. 2018). Further, especially for some sites such as Rungwe and Murang'a, where population density is highest (Table 3.3), land resources are scarce. Competition for land between forages and food crops therefore implies that availability of arable land is a limiting factor in improving availability of high-quality feeds (Maleko *et al*. 2018). Because improved breeds especially require higher quality diets (King *et al*. 2006), scarcity of land and labour are likely to influence the household's capacity to adopt improved breeds (unless high quality forage can be purchased at affordable prices).

<u>Financial resources</u>: High prices associated with purchasing improved cows or heifers are a major hindrance to their adoption (Shikuku *et al*. 2016, Abdulai and Huffman 2005, Chawala *et*

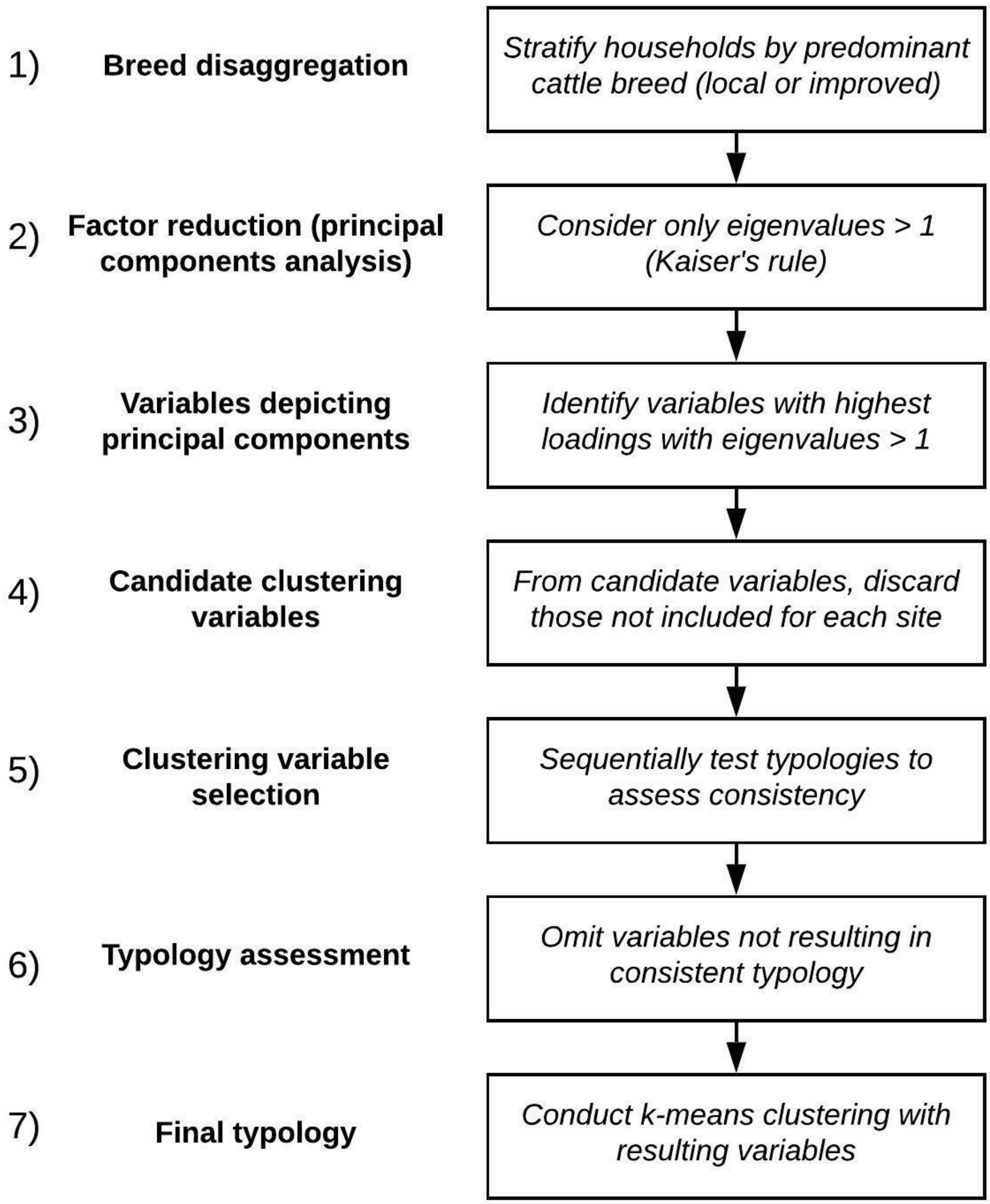

Figure 3.2: Decision framework used to construct the household typology. Households are first statified by predominant cattle breed (local and improved). Factor reduction and k-means clustering are then used to identify discrete household types for each district.

al. 2016). Prices of improved cattle are often $800 USD or more per head in the region than an equivalent local animal (Makokha *et al.* 2013). In regions where artificial insemination (AI) is available at low cost however this hindrance may largely be overcome. Ojango *et al.* (2016) report AI (for improved semen) to be available for as low as $70 USD in parts of Kenya and Tanzania. Nonetheless improved cattle have higher disease susceptibility (Mwai *et al.* 2015) and greater nutrition requirements, and therefore rely on high levels of external inputs and services necessitating cash expenditures throughout their productive lives. Costs associated with animal husbandry inputs, such as preventive health measures and purchasing feeds, also represent a constraint to improving animal husbandry among local and improved cattle.

Knowledge and technical capacity: Efficient and environmentally sound dairy production necessitates technical know-how in animal husbandry, feed cultivation, and manure handling practices. Rural households in East Africa generally have inadequate knowledge to implement these techniques (Orodho 2005). For improved breeds especially, due to the need for improved nutrition, there is a greater requirement for efficient feed production, processing, and formulation techniques, as well as animal husbandry techniques in reproduction and health. Moreover, because intensive dairy production is focused on market engagement to sustain continued resource inputs, expertise in marketing milk and securing inputs is required. Education levels of farmers, experience in dairy farming, measured *via* years of selling milk, and skill levels, approximated with participation in extension, have thus been observed as independent factors influencing adoption of improved cattle and other improved dairy production practices (Abdulai and Huffman 2005, Gerber 2007, Edirisinge and Holloway 2015, Dehinenet *et al*. 2014, Didanna *et al.* 2018, Staal *et al.* 2002).

Market access: Access to and affordability of inputs and services have been found to be major factors affecting uptake of improved cattle, improved feeding, and other animal husbandry inputs in the East Africa region (Van der Lee *et al.* 2018, Duncan *et al*. 2013). This relates to both access to services and inputs as well as access to markets for selling milk, and the associated terms of participation (Staal *et al.* 2002). Proximity to major urban areas, quality of infrastructure, as well as the presence of agri-businesses and dairy cooperatives providing inputs and services will therefore influence uptake.

Clustering variable selection

In addition to the structural variables depicting these constraints, 7 functional variables are included to capture for each household the degree of market orientation, income sources, orientation in crop production (food *versus* cash crops, sale *versus* consumption), and the degree of diversification in livelihood activities (Table 3.4). As this typology is constructed at site level, for which market access characteristics are broadly homogeneous (Table 3.3), market access is not explicitly included as a variable in the PCA or clustering.

Variables are first checked for their correlation by using the Bartlett's sphericity test, because either highly correlated or uncorrelated variables may not be suitable for PCA. Some variables are standardized and reported as fractions or percentages of the maximum observed values in the dataset to allow comparability. The PCA is conducted using the Factominer package (Le and Husson, 2008). PCA is run, for each site to evaluate similarities and deviations in principal components (PCs). Only PCs whose eigenvalues were greater than one are retained, following Kaiser's rule (Kaiser 1960). Of the resulting PCs, only variables with high loadings (>.65) are considered. Additionally, variables are selected by sequentially testing different typologies to verify that the resulting clusters are consistent across sites. This is necessary because the clustering is performed at site level, and not all variables selected from PCA have consistent correlations across sites. While there are in general consistent relationships between the orientational variables across sites, these variables do not consistently correlate with structural variables, such as herd size. Therefore, these variables are discarded and only those with consistent correlations across sites are used.

Cluster analysis is performed using the k-means algorithm (Hartigan and Wong 1979). The number of clusters is decided based on the marginal reduction in the within cluster sum of squared differences, the so called 'elbow method', which results in three household types at each site for each stratum. In cases when the clustering analysis resulted in households falling into 'fuzzy' domains, these cases are examined and re-allocated to a new group, based on the broad characteristics of the resulting typology. Based on the data quality assessment described above, a sub-set of 551 households is removed from the dataset. The resultant sample sizes for each site are 219 (Nandi), 289 (Murang'a), 134 (Mvomero), 145 (Mufindi), 260 (Rungwe) and 301 (Njombe).

3.2.3 Indicators

Livelihood strategies and resource endowments

The livelihood strategy of households is depicted using the orientation of the household, market *versus* subsistence, using two indicators: (1) the ratio of sales to total production (production side) (2) the monetary value of sales to total income (consumption side). These indicators depict the relative reliance of the household on market transactions, for production and consumption, similar to well-known indicators of commercialization used by von Braun *et al.* (1994). Indicators are either directly derived from a question in the survey or were calculated by linking survey data with auxiliary data sources. Production orientation is disaggregated into milk and all other agricultural goods produced by the homestead. For consumption orientation, cash and imputed incomes (the market value of produce consumed domestically) are estimated based on income sources and calculated annual expenses from the crop and dairy enterprises (see supplementary information for more details).

For resource endowments, variables are selected depicting the endowment of the factors influencing constraints to adoption described in section 3.2.2 (Table 3.2). One variable is used to characterise each of land and labour endowments. Total household income per adult equivalent is used to depict financial resources of the household. Years selling milk and education of the household head are used to depict two aspects of human capital: experience in commercial dairy production and overall level of human capital (i.e. education level).

Table 3.2: Variables used in principal components analysis

Variable name	Variable type	Factor category	References
Cropland* (hectares)	Structural	Land & labour	Maleko *et al.* (2018)
Household labour* (man-day yr^{-1})			
Land with title deed* (ha)		Financial (proxies for wealth)	Chawala *et al.* (2016) Abdulai and Huffman (2005)
Cattle numbers (#)			
Education level* (household head) (yrs of schooling)		Knowledge	Abdulai and Huffman (2005), Gerber (2007), Edirisinge and Holloway (2015), Dehinenet *et al.* (2014), Didanna *et al.* (2018), Staal *et al.* (2002)
Dairy experience* (yrs selling milk)			
Fraction of milk sold (%)	Functional	Market orientation	--
Income from milk (%)		Income reliance	Dehinenet *et al.* (2014), Didanna *et al.* (2018)
Off-farm income (%)			
Crop land for home produced food (%)		Crop production orientation	--
Land for cash crops (%)			--
Number of crops grown		Diversification	--
Number of livestock activities			--

* Variables which are standardized

Dairy greenhouse gas emissions and herd productivity

GHG emissions are calculated for each household from the survey and auxiliary data sources following the IPCC methodology (IPCC 2006). Methane (CH_4) and nitrous oxide (N_2O) emissions from enteric fermentation and manure are calculated by estimating feed intake from the survey, and using IPCC (2006) equations to estimate emissions based on dietary properties. Nitrous oxide emissions from soils are estimated based on the crop and grassland areas for feed cultivation and grazing, calculated based on the feed compositions of diets and yields. These are combined with emission factors representing embodied CO_2 emissions from processing, manufacturing and transportation of feed and fertilizer inputs, hereafter referred to as 'Fossil energy CO_2'. Global warming potentials of 28 kg CO_2eq kg CH_4^{-1} and 265 kg CO_2eq kg N_2O^{-1} are used (IPCC 2013). The fat and protein content of milk from local and improved cows is specified based on Rege *et al.* (2001), taking values of 3.5 fat and 4.1% protein for local and 4 fat and 5.5% protein for improved. Milk production is then converted to fat and protein corrected milk (FPCM), which is milk production standardized to 4% fat and 3.3% protein (IDF 2010). Emissions are expressed as an intensity and per unit livestock owned per household. Emissions intensities are calculated by dividing carbon dioxide equivalent (CO_2e) emissions by kg of FPCM produced per household per year. Emissions per livestock unit are calculated by dividing annual CO_2e emissions by tropical livestock units (TLU) owned by the household, each TLU being equivalent to 250 kg liveweight. In addition to these two GHG emissions indicators, productivity of the dairy herd is quantified based on the annual milk production from the herd in relation to the total herd size in TLUs. Live weights for local and improved cattle in the region are derived from literature sources (Table S2). GHG emissions and the herd productivity indicator reported are based on the average values for each household type at each site. A comprehensive description of the GHG estimation methods is provided in supplementary information 3.2.

Dairy input use and practices

Profiles of input use and dairy production practices across household types seek to reflect the intensity of adoption practices relating to the main components of dairy modernization and climate mitigation initiatives for both Kenya and Tanzania, which focus on feeding, genetics, reproductive practices, preventive health measures, and manure management (GOK 2018, GOK 2017, Michael et al. 2018, URT 2017). Expenses for the dairy enterprise are calculated as the sum of cash expenses on feed purchases, reproductive inputs and services, replacement animals, reproduction inputs, preventive health inputs, and other miscellaneous expenses. Intensity of expenditure on these inputs is calculated by dividing input use (USD per year) by TLUs per household.

The practice profiles consider: i) quality of cattle diets and severity of seasonal feed shortfalls, ii) reproductive practices, iii) use of preventive health inputs and services, and iv) manure management (Table 3.4). Diet qualities are evaluated by quantifying intake levels of improved forages, concentrates and by-products in place of grazed biomass, cut and carry pasture and crop residues (see Table S1 for details). The adoption of feed conservation is evaluated based on the frequency with which respondents report silage or hay making out of forages on farm. Severity of feed shortfalls are based on the reported months of feed scarcity per year. Reproductive practices include the use of artificial insemination (AI). Animal health practices included vaccines, anti-tick and deworming treatments. Manure storage and management practices are reported based on the presence of a manure storage system (i.e. a structure with a roof, floor or cover) covering of manure heaps, and the frequency with which manure is applied on fields. Field application frequency is based on the percentage of households reporting having spread manure on their fields at least once every 3 months.

3.2.4 Statistical analysis

Equality of means tests are performed to assess the ‘distinctiveness’ in select indicator variables across the six sites, the resultant household types from the typology, and between households rearing local and improved cattle (stratum 1 and stratum 2 households respectively). These tests evaluate (a) the importance of ‘site effect’ in influencing variability in a given indicator, (b) the typology’s effectiveness in differentiating households with a given indicator and (c) the role of breed ownership, local or improved, in differentiating households with a given indicator. These statistical tests are performed for the resource endowment indicators, greenhouse gas emissions intensities, and the low emissions practices. The statistical significance in difference in means across household sites and household types is evaluated by conducting a one-way analysis of variance (ANOVA). The statistical significance of difference in breed ownership wis assessed using a chi-squared test based on the household’s attribution to either strata 1 (local cattle) or strata 2 (improved cattle). In both tests, the null hypothesis is equality of means; rejection of the null implies a statistically significant difference in the given indicator between sites, household types, or strata.

Table 3.3: Indicators used to depict variability in household types.

Indicator category	Indicator	Variables and unit	Source
Livelihood strategies	Market orientation, production	% of milk sold	Calculated as fraction of sales to total production x 100
		% other agricultural goods sold	
	Market orientation, consumption	Fraction of total income from cash and home consumed goods	Calculated from total cash income and value of farm produce consumed following Rufino *et al.* (2013a)
Resource endowments	Land ownership	Available cropland (ha)	Survey questionnaire
	Household labour	Household size (#)	
	Dairy farming knowledge	Years selling milk	
		Participation in extension (boolean)	
	Capital endowment	Total income per adult equivalent (USD yr^{-1})	Calculated as total cash income and value of farm produce consumed following Rufino *et al.* (2013a)
Dairy environmental performance	Dairy carbon footprint	Greenhouse gas emissions as intensity and per livestock unit	Survey questionnaire and supplementary data (see SI 3.2)
	Dairy herd productivity	Milk produced per livestock unit (tons yr^{-1} TLU^{-1})	Survey questionnaire
Dairy practices and input use	Intensity of input use	Input use intensity on select inputs (USD TLU^{-1} yr^{-1})	Survey questionnaire
	Select low emissions dairy practices (see Table 3.4)		

Table 3.4: Indicators of intensity of adoption of select low emissions dairy practices

Indicator category	Indicator	Variables and unit	Source
Feeding	Diet quality	% offered from individual feed groups	Calculated from survey based on feeding practices and feed seasonality parameters (see SI 3.2)
	Feed conservation	Feed conservation (boolean)	Survey questionnaire
Reproduction	Artificial insemination (boolean)		
Animal health	Intensity of adoption of preventive health measures	Vaccines administered (boolean)	
		De-worming treatments administered (boolean)	
		Anti-tick treatments administered (boolean)	
Manure management	Manure technologies and practices	Manure managed (boolean)	
		Manure storage system (boolean)	
		Field application bi-seasonal or less (boolean)	

3.3 Results

Determinants of farm types

Between 4 to 6 principal components (PC) have eigenvalues greater than 1 across sites (Table 3.5). The total variance explained by these principal components (PCs) is in 8 cases between 60% and 70% and in 4 cases greater than 70%. In general, there is high consistency in the main principal components across sites, however their ordering differed across scales. The variables which most often have high correlations with major PCs are (and the number of PCs with which they correlated): cash crop area (8), dairy income (6), number of livestock activities (6), off farm income (6), arable land (6), and dairy market orientation (6). Out of these six variables with highest explanatory power, the first 4 are chosen as the basis for the clustering analysis. By selecting these variables with highest explained variation across all six sites, the typology built has the advantage that it results in a relatively consistent grouping of households across sites. Thus, the resulting typology has the benefit in allowing broad categorization of livelihood strategies and indicators of resource endowments within sites. The result is a functional typology with three primary livelihood strategies, *Ls* 1, 2, and 3, (*Livelihood strategy*) pertaining to the two household strata. Table 8 summarizes the main household characteristics.

3.3.1 Household types and main livelihood features

The proportion of household types attributed to stratum 1 and 2 is correlated to the proportion of each cattle type across districts (Table 3.3), Herd characteristics, % Improved cattle. The two Kenyan sites as well as the Tanzanian districts of Rungwe and Njombe have a higher proportion of stratum 2 households, which own a higher proportion of improved breeds. In Mufindi and Mvomero districts, local cattle are more prevalent, more households own local cattle, and in relatively larger herds (Fig. 3.3).

Livelihood strategy 1: Dairy specialists

Ls 1 Loc makes up between 1.2 (Rungwe) to 18.4% (Mvomero) of households per site. *Ls 1 Imp* makes up between 1.5 (Mufindi) to 30.1 % (Nandi). Among the *Dairy specialists*, income from dairy forms a moderate proportion (20-70%) of total cash income for the household (Fig. 3.4). For *Ls 1 Loc* in some regions, dairy income is a substantial proportion (as much as 80%) of cash income (Rungwe, Mvomero, Mufindi, Nandi). In Njombe and Murang'a there is relatively less distinction in income from dairy compared to other sources. For *Ls 1 Imp* dairy income is predominantly at least one third of total cash income. However, Nandi forms an exception to this, for which income sources are more highly diversified between farming (including cash crops) and off farm activities. These households are moderately to highly market oriented in dairy as shown by the percentage of milk sold (Fig. 3.5a). There are no consistent observations between household types and non-dairy market (Fig. 3.5b) orientation, nor the relative importance of cash versus imputed income (Fig. 3.5c).

Table 3.5: Variables corresponding to major principal components (PCs) run for each site and strata. Parentheses indicate loadings (%) within PCs. Variables selected to use in clustering to derive household types are indicated in **bold**.

Country, site, strata	***Kenya***				***Tanzania***							
	Murang'a		*Nandi*		*Mufindi*		*Mvomero*		*Njombe*		*Rungwe*	
	1	2	1	2	1	2	1	2	1	2	1	2
PC 1	Titled land (77.9)	Arable land (77.5)	**Cash crops** (ha) (74.0)	Arable land (71.8)	**Cash crop hectares** (71.8)	# crop activities (69.5)	**Dairy income** (66.7)	Arable land (77.1)	**Cash crops** (ha) (72.1)	Herd size (71.51)	Food crop area (68.4)	Labour endowment (65.1)
PC 2	**Dairy income** (65.14)	**Off farm income** (82.09)	**Off farm income** (69.11)	Cash crop hectares (69.8)	**Off farm income** (69.6)	Arable land (74.12)	**Cash crops** (ha) (60.9)	Years selling milk (83.91)	Years selling milk (78.95)	**Dairy income** (67.07)	Titled land (60.95)	Fraction sold (59.66)
PC 3	Food crop area (64.3)	Fraction sold (57.7)	Fraction sold (77.6)	Years schooling (59.0)	**Dairy income** (69.0)	**Dairy income** (78.5)	**Off farm income** (64.5)	**Cash crops** (ha) (74.4)	Education household head (64.2)	**Cash crops** (ha) (69.6)	Arable land (73.5)	**Off farm income** (65.2)
PC 4	**Cash crops** (ha) (53.9)	# livestock activities (70.3)	Years schooling (58.2)	Fraction sold (61.9)	Herd size (74.0)	**# livestock activities** (71.4)	Food crop area (73.2)	**# livestock activities** (62.0)	**# livestock activities** (82.6)	**# livestock activities** (58.94)	# crop activities (53.3)	# crop activities (82.0)
PC 5	# livestock activities (62.0)	Fraction sold (47.5)	--	**# livestock activities** (69.5)	Years schooling (59.5)	Titled land (67.8)	Arable land (50.9)	**Dairy income** (59.3)	**Off farm income** ((51.7)	Food crop area (63.5)	Herd size (59.9)	Years selling milk (65.1)
PC 6	--	--	--	--	Titled land (73.7)	--	--	--	--	Fraction sold (59.6)	--	**Cash crops** (ha) (52.56)
[1]Cum. variance (%)	73.3	63.4	74.1	64.1	62.3	74.6	62.7	73.1	69.5	62.8	61.5	63.8

[1] Of principal components with eigenvalues > 1

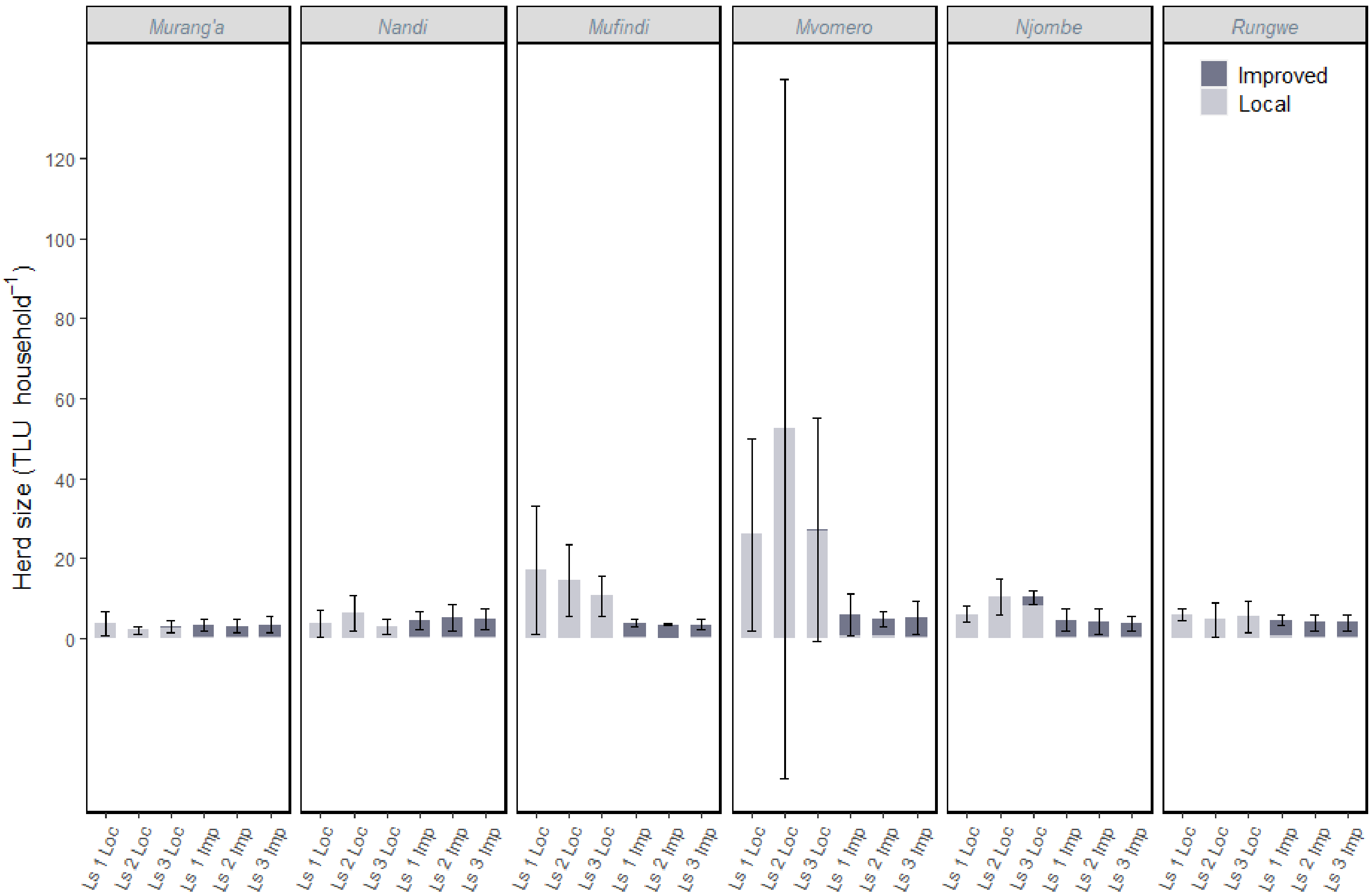

Figure 3.3: Herd size per household across sites and household types. Error bars denote standard deviation. Household types are a result of disaggregation of households into three distinct livelihood strategies: Dairy specialists (Ls 1), Farm reliant (Ls 2), and Off-farm reliant (Ls 3), and two strata differing based on predominant cattle breed owned: Loc (local) and Imp (improved). Herd size in TLU (tropical livestock units) is determined by standardizing herd size to 250 kg of live cattle weight.

Table 3.6: Main distinguishing features of the household typology

Household type*	Livelihood strategy	Predominant breed	Description
Ls 1 Loc	#1 -- Dairy specialists	Local	Income from dairy forms a relatively large contribution to household income, and the household is relatively specialized in this activity (relatively less total livestock activities). Generally more market oriented in dairy than other types (Fig. 3.5a).
Ls 1 Imp		Improved	
Ls 2 Loc	#2 – Diversified farmers	Local	Generally more diversified in livestock activities than dairy specialists, but still highly dependent on farming for food production and cash income (little off farm income).
Ls 2 Imp		Improved	
Ls 3 Loc	#3 – Off farm reliant	Local	Characterised by having the highest proportion of off farm income (Fig. 3.4). Usually the household head is among the most educated among types (Table 3.7) although the clustering is not based on this.
Ls 3 Imp		Improved	

Source: Typology described herein
* *Ls* = Livelihood strategy

Livelihood strategy 2: Diversified farmers

Ls 2 Loc includes between 3.5 (Njombe) to over 32.1% (Mvomero) of the households across sites. *Ls 2 Imp* makes up from 5.3 (Mvomero) to 39.8% (Nandi) of the households. The distinguishing feature of *Diversified farmers* is that livelihoods are highly reliant on the farm enterprise, and they have relatively few off-farm sources of income. Unlike livelihood strategy 1 however, which is relatively highly dependent on dairy, these types are more diversified between livestock production (dairy and other ruminants, poultry), cash cropping, and subsistence cropping (Fig. 4). A lower fraction (27-54%) of milk production is for the market (Fig. 5a) compared to livelihood strategy 1 (37-72%). Diversified famers have more variation in the degree of commercial orientation overall, however. For *Ls 2 Loc* market orientation for non-dairy goods is typically around 50% (Figure 5b). For this household type there is more variation in the degree of market and subsistence orientation, implying this household type includes both commercial crop farmers (and non-dairy livestock, especially in Mufindi, Njombe, and Nandi) as well as subsistence farmers (Fig. 5b). For *Ls 2 Imp*, commercial orientation overall is high, at 60% or higher for all sites, especially the Kenyan sites (Figure 5b). For *Ls 2 Imp* cash income is 67% of total household income (sum of cash and imputed income) (Fig. 5c). For *Ls 1 Loc* households, they are relatively more reliant on home produced food, with the exception of those in Njombe.

Livelihood strategy 3: Off farm reliant

Ls 3 Loc (local cattle variant) makes up between 1.9 (Nandi) and 45.5% (Mufindi) of households across sites. *Ls 3 Imp* (improved cattle variant) makes up between 2.3 (Mufindi) and 38.8% (Murang'a) of households across sites. *Off farm reliant* has the highest ratio (24-80%) of off-farm to total household income among all types for each site (Fig. 3.4). *Off farm reliant* has moderate market orientation on average in dairy (64%). Market orientation in other farm products ranges from 52 to 78%. For *Ls 3 Imp* dairy market orientation is moderate to high (70-82%) (Fig 3.5a). Market orientation in other goods was moderate to high on average (Fig. 3.5b) (52-78%). As site variability in off farm income varies significantly, so too does the relative proportion of this income source among types. Especially for *Ls 3 Loc* in Njombe, it is low (26%) relative to other sites and types.

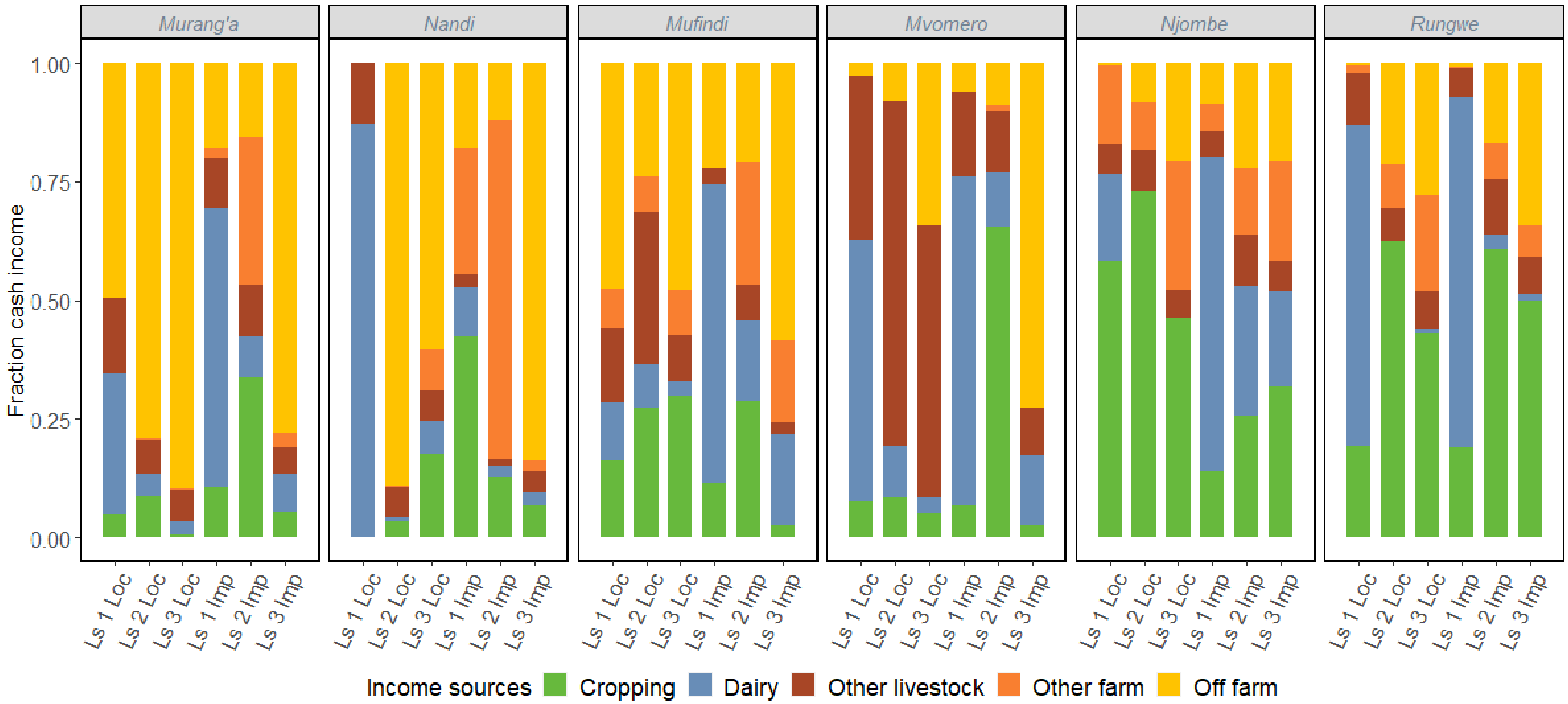

Figure 3.4: Income sources across survey sites and household types. Survey sites include two counties in west and central Kenya, Murang'a and Nandi, three districts in the Tanzanian southern highlands, Mufindi, Mvomero, and Njombe, and one district in coastal region of Tanzania, Mvomero. Household types are a result of disaggregation into three distinct livelihood strategies: Dairy specialists (1), Farm reliant (2), and Off-farm reliant (3), and two strata differing based on predominant cattle breed owned: Loc (local) and Imp (improved).

Figure 3.5: Indicators of livelihood strategies across sites and household types. Panels show percentage of milk (a) and other goods sold (b) and % cash to total income (c). All values shown are boxplots, and the points on each plot represent mean values.

Resource endowments

The analysis of endowment indicators across household types and sites is shown in Table 3.7. Experience selling milk and education level of the household head are the most important differences in both household types and between households in stratum 1. Experience selling milk is statistically significantly different across both household types and strata for four out of 6 sites. Years of schooling is significant at 3 sites for household type and 4 for household strata. Both experience selling milk and years of schooling are on average higher among strata 2 households. Labour endowment is also statistically significant in discerning household types and strata at two sites (Murang’a and Mufindi). Cropland area is statistically significant in discerning household types in Nandi and Mvomero. Interestingly income is not significantly different at any sites. However, for all indicators there are statistically significant differences across sites (bottom row, Table 3.7). This latter finding suggests site variability is a larger driver in these endowment indicators than household variability within a single site. The site level indicators reveal that the two Kenyan counties have a significantly longer history of selling milk relative to the Tanzanian sites, with averages of 12 years or more in Kenya *versus* less than 7 in Tanzania.

Table 3.7: Diversity in endowments of land, labour, financial and human capital factors (experience, education). Results of tests for differences in means (ANOVA, chi-squared tests) (type; household types, breed; adoption of improved breeds, site; survey site).

Site, livelihood strategy, breed			**n**	**Arable land** (ha)	**Labour endowment** (man-days yr^{-1})	**Income** (USD ae^{-1} yr^{-1})	**Experience selling milk** (yr)	**Household head schooling** (yr)
Murang'a	1	Local	9	0.8 ± 0.6	2.3 ± 1.3	443 ± 470	12.0 ± 18.3	8.4 ± 1.3
	2		12	1.2 ± 1.3	1.0 ± 1.9	801 ± 788	4.5 ± 10.5	1.3 ± 2.0
	3		12	0.8 ± 0.6	2.2 ± 1.3	1339 ± 872	7.2 ± 10.0	9.0 ± 2.5
	1	Improved	49	0.9 ± 0.6	2.4 ± 1.6	885 ± 830	23.8 ± 15.6	6.4 ± 4.6
	2		95	1.0 ± 0.7	2.0 ± 1.2	2149 ± 2029	19.7 ± 16.4	8.7 ± 4.3
	3		112	1.0 ± 1.0	2.8 ± 1.5	1517 ± 1331	14.3 ± 14	9.5 ± 4.1
	Site mean			1.0 ± 0.8	2.4 ± 1.5	1547 ± 1568	16.9 ± 15.7	8.3 ± 4.4
	p-value (type)			ns	< 0.005	ns	ns	ns
	p-value (breed)			ns	< 0.05	ns	< 0.05	< 0.05
Nandi	1	Loc	4	3.3 ± 2.2	3.5 ± 1.9	284 ± 143	2.5 ± 4.4	6.0 ± 4.0
	2		12	3.1 ± 2.3	2.6 ± 1.1	852 ± 827	2.5 ± 6.6	8.8 ± 4.9
	3		4	1.1 ± 0.7	3.0 ± 0.8	317 ± 211	0.0 ± 0.0	8.0 ± 4.6
	1	Improved	66	2.7 ± 2.8	3.0 ± 1.6	1583 ± 1645	15.1 ± 14.5	8.0 ± 4.4
	2		87	2.0 ± 1.8	3.1 ± 1.6	1394 ±1549	16.2 ± 14.6	9.0 ± 4.1
	3		46	1.5 ± 1.3	2.6 ± 1.4	1172 ± 1524	6.3 ± 9.6	10.2 ± 4.1
	Site mean			2.2 ± 2.2	2.9 ± 1.5	1334 ± 1531	12.5 ± 13.9	8.9 ± 4.3
	p-value (type)			< 0.05	ns	ns	ns	ns
	p-value (breed)			ns	ns	ns	ns	ns
Mufindi	1	Local	25	9.9 ± 23.3	3.4 ± 1.5	980 ± 1423	2.2 ± 5.3	6.7 ± 2.1
	2		34	3.6 ± 4.0	3.2 ± 1.6	759 ± 569	2.4 ± 6.1	6.6 ± 2.4
	3		66	3.9 ± 4.3	3.4 ± 1.7	952 ± 945	1.3 ± 2.9	7.4 ± 3.0
	1	Improved	2	4.8 ± 2.2	4.6 ± 1.8	616 ± 342	10.4 ± 4.5	7.8 ± 1.8
	2		14	16.7 ± 17.1	4.3 ± 2.5	4694 ± 4013	9.7 ± 9.0	17.0 ± 1.7
	3		3	11.8 ± 12.2	3.0 ± 1.3	1678 ± 1030	9.5 ± 8.6	8.5 ± 2.0
	Site mean			6.2 ± 13.2	3.4 ± 1.6	1001 ±1215	3.2 ± 6.3	7.2 ± 2.8

		p-value (type)		ns	ns	ns	< 0.001	< 0.001
		p-value (breed)		ns	ns	ns	< 0.001	< 0.001
Mvomero	1	Local	25	2.7 ± 2.0	3.0 ± 1.3	1169 ± 1071	11.0 ± 8.7	3.7 ± 3.3
	2		43	12.0 ± 40.5	4.3 ± 3.4	1943 ± 1911	6.1 ± 8.2	7.7 ± 3.5
	3		43	5.8 ± 10.7	3.5 ± 1.7	1050 ± 790	2.6 ± 7.1	2.7 ± 3.2
	1	Improved	8	1.6 ± 1.1	2.2 ± 1.2	555 ± 109	6.4 ± 4.4	6.5 ± 1.4
	2		7	5.1 ± 5.1	2.4 ± 1.3	1860 ± 1269	3.1 ± 5.2	8.3 ± 5.3
	3		8	7.0 ± 9.7	3.6 ± 1.5	2084 ±1235	9.6 ± 6.3	11.0 ± 3.7
		Site mean		7.0 ± 23.9	3.5 ± 2.4	1434 ±1391	6.0 ± 8.0	5.5 ± 4.2
		p-value (type)		< 0.05	< 0.05	ns	< 0.005	< 0.005
		p-value (breed)		ns	< 0.05	ns	ns	ns
Njombe	1	Local	19	4.4 ± 3.8	3.3 ± 1.7	1271 ± 1622	1.5 ± 5.5	7.0 ± 0.0
	2		11	5.7 ± 7.9	2.6 ± 1	855 ± 747	0.0 ± 0.0	7.0 ± 1.7
	3		14	6.8 ± 7.6	3.3 ± 1.8	962 ± 676	0.6 ± 1.7	5.3 ± 2.6
	1	Improved	55	4.6 ± 6	2.6 ± 1.2	1148 ± 1284	7.3 ± 7	7.4 ± 2.5
	2		104	5.6 ± 8.1	2.9 ± 1.4	1761 ±1365	7.1 ± 7.6	7.5 ± 2.6
	3		98	6.3 ± 9.1	3 ± 1.3	1642 ±1521	6.8 ± 6.2	7.2 ± 3.0
		Site mean		5.6 ± 7.8	2.9 ± 1.4	1507 ± 1400	6.1 ± 6.9	7.2 ± 2.6
		p-value (type)		ns	ns	ns	< 0.001	< 0.001
		p-value (breed)		ns	ns	ns	< 0.001	< 0.001
Rungwe	1	Local	3	1.2 ± 1.2	2.3 ± 0.6	412 ± 109	3.0 ± 2.6	5.7 ± 2.3
	2		24	1.8 ± 1.6	3.0 ± 2.3	513 ± 431	0.1 ± 0.6	5.4 ± 2.4
	3		34	1.8 ± 1.2	2.9 ± 1.4	457 ± 360	1.1 ± 3.2	7.0 ± 2.3
	1	Improved	8	1.9 ± 1.8	3.5 ± 0.9	456 ± 278	6.4 ± 7.5	7.0 ± 0.0
	2		98	1.8 ± 1.3	2.5 ± 1.2	899 ± 805	6.6 ± 8.1	7.0 ± 2.6
	3		93	1.5 ± 1.3	2.9 ± 1.5	798 ± 903	5.7 ± 6.8	7.4 ± 2.8
		Site mean		1.7 ± 1.3	2.8 ± 1.5	750 ± 772	4.9 ± 7.0	7.0 ± 2.6
		p-value (type)		ns	ns	ns	ns	ns
		p-value (breed)		ns	ns	ns	< 0.001	< 0.001
	p-value (site)			<0.001	<0.001	<0.001	<0.001	<0.001

ns = not statistically significant (p-value > 0.05)

Productivity and greenhouse gas emissions across household types and sites

Households with improved cattle have on average 280% higher milk productivity (Fig. 3.6a), which results in lower emissions intensities per unit of milk (Fig. 3.6b) despite higher emissions per unit of livestock (emissions per livestock unit are provided in SI Figure S1). Estimated GHG emissions intensities (kg CO_2eq kg^{-1} FPCM) are between 29 to 267% higher at the Tanzania sites than the Kenya ones, and are on average 290% higher among stratum 1 households (rearing local cattle) (Fig. 3.6b). GHG emissions per livestock unit are on average 8% higher for improved cattle (*Ls 1 Imp, Ls 2 Imp* and *Ls 3 Imp*), due to their higher intake of nutrient-dense feeds (and therefore higher gross energy intake), and also because of greater CO_2 emissions associated with fossil energy from these feeds (ie. from processing/transporting of feed and fertilizer inputs). These estimates correspond with values reported previously for the respective regions. Emissions intensities in Kenya have been reported to range from 2.0 to 4.0 kg CO_2eq kg^{-1} FPCM for improved cattle and from 7.0 to 8.0 kg CO_2eq kg^{-1} FPCM for local cattle (FAO New Zealand 2017). In Tanzania reported ranges are from 2.2 to 3.5 (improved cattle) and 20 to 30 (local cattle) kg CO_2eq kg^{-1} FPCM (FAO New Zealand 2018). These values are largely consistent with the estimates shown in Figure 3.6b, with the exception of local cattle in Tanzania. The higher emissions intensities herein (Fig. 3.6b) are a result of relatively high milk yields (470 litres yr^{-1}) for these cattle compared to the national average of 200 litres yr^{-1} (on which FAO New Zealand's estimates are based).

Results of statistical tests show significant differences in average GHG emissions intensities across household types (Fig. 3.6b) at all sites except Nandi. Adopting improved cattle reduces emissions intensities per unit of milk on average by 74.3% as shown by statistically significant differences in emissions intensities between stratum 1 and 2 households at all sites except Nandi. These findings show that the typology effectively discerns differences in emissions intensities across households. Further, the differences across improved cattle adopting and non-adopting households demonstrates breed ownership is statistically significant in explaining variation in emissions intensities across households and sites. The anomalous findings for emissions intensities in Nandi, are a result of an 8% lower milk yield combined with a 13% larger share of non-producing animals in that district relative to the Kenyan average, resulting in herd productivity of 24% less than the Kenyan average (Fig. 3.6a).

Dairy input use

Analysis of input use intensity (Fig. 3.7) indicates significant differences across sites. Especially in Murang'a, Njombe, and Rungwe input use is high, presumably because these are the sites with better market access (Table 3.3). Among the categories of expenses on dairy inputs, feeds were generally the largest expense across all sites. In Nandi relatively little is expended on feed, and instead inputs on animal husbandry form the largest category of expenses (mostly preventive health inputs/services). At each of the six sites, farms with improved cattle (stratum 2) spend significantly more on inputs per livestock head, on average 8.9 times greater than for those with local cattle.

Low emissions dairy practices

The feeding practice and feed scarcity indicators are shown in Table 3.8. Across all sites, stratum 2 households fed on average 11.1 times more improved forages and 13.0 times more concentrates and supplements than stratum 1 households. These differences between strata are statistically significant for 4 sites: Nandi, Njombe, Rungwe, and Mufindi. Moreover, at each of the 6 sites, stratum 2 households have higher rates of adoption of feed conservation. Differences in means tests (Table 3.8) indicate that differences in adoption of feed conservation are significant at 3 sites for household types, and 1 site for breed ownership. For those months of feed scarcity, the typology was effective in discerning households at 3 sites, Murang’a, Njombe, and Rungwe. Breed ownership is highly effective in identifying differences in feed scarcity, which are statistically significant at all sites except Nandi.

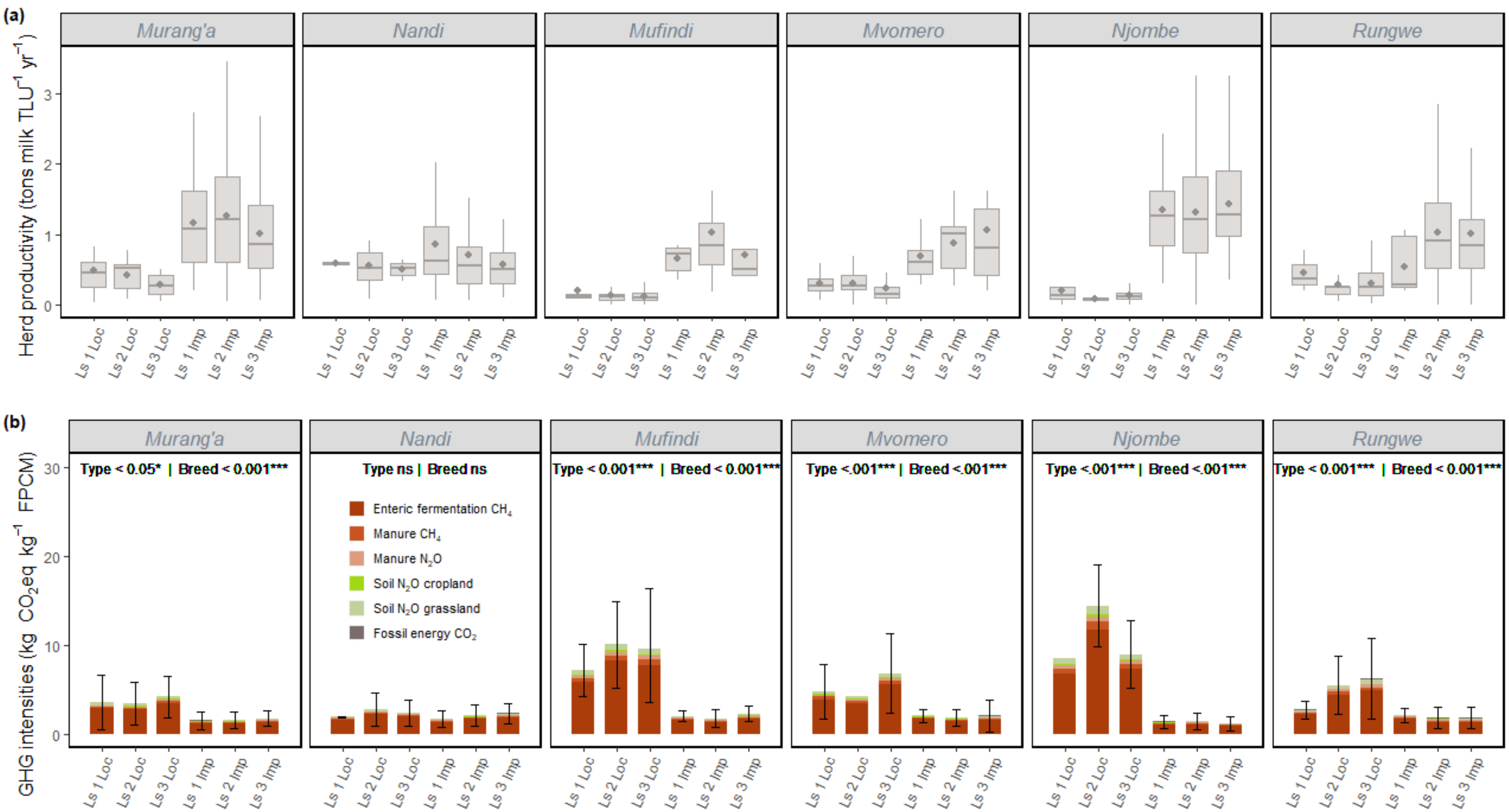

Figure 3.6: Herd productivity (a) and greenhouse gas emissions intensities (b) across sites and household types. In (a) solid points indicate average for a given household type and site. Error bars in (b) denote standard deviation. Text on panels in (b) show results of difference in means tests for household types (Type) and breed type (local or improved) (Breed).

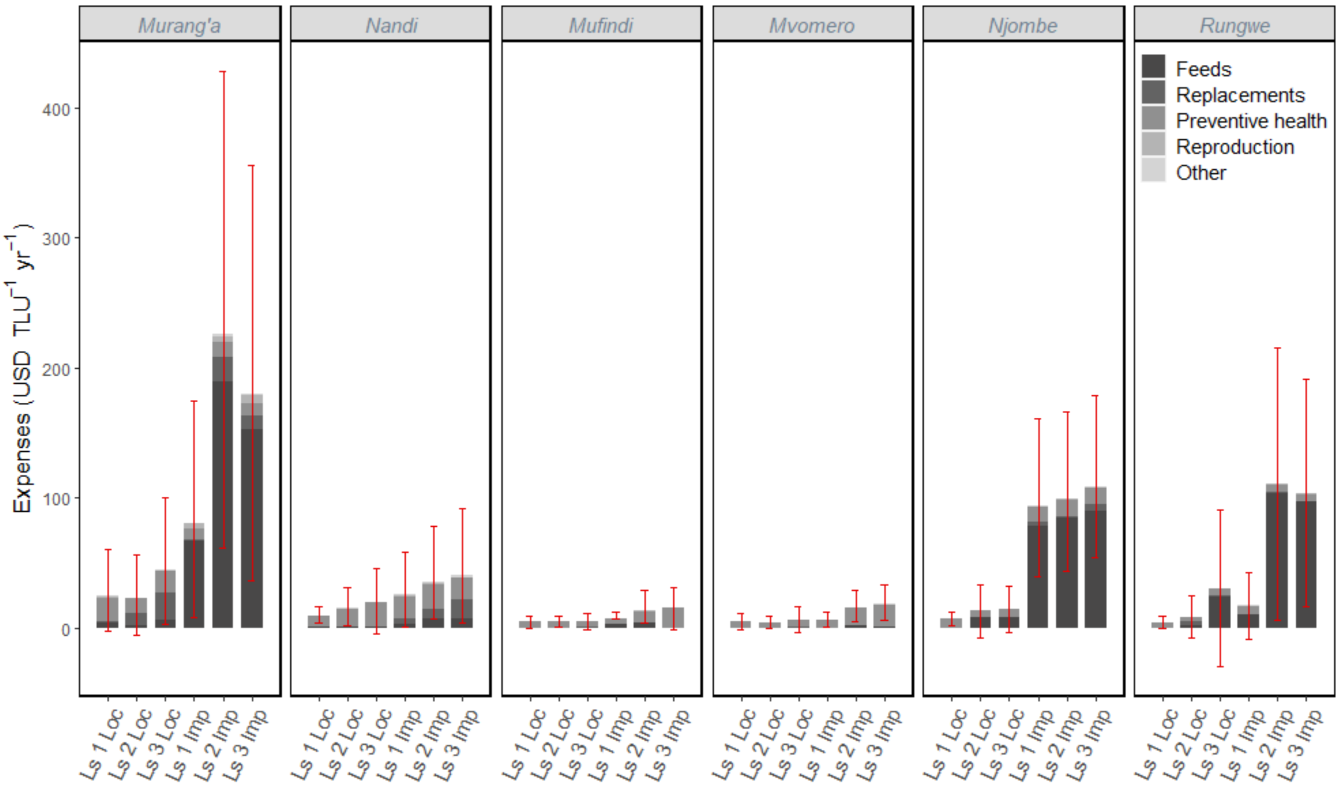

Figure 3.7: Dairy activity expenses across sites and households. Error bars denote standard deviation.

Table 3.9 summarizes levels of adoption of AI, preventive health practices, and manure management systems. AI is, as expected, more commonly adopted by households with improved cows. Adoption of preventive health measures is more nuanced. In some sites, stratum 2 households have higher rates of adoption, such as for vaccines and deworming treatments in Nandi. In others, stratum 1 households have the highest rates of adoption, such as for anti-tick treatments in Rungwe. Between 19-100% households across sites collect manure. However, in all sites but Nandi and Mvomero manure storage systems are rare (<23% of households). Stratum 2 households have on average a 117% higher adoption rate of manure storage systems, compared with strata 1 households. The frequency with which manure is applied to the fields varies significantly across sites, and is especially high in Murang’a, Njombe and Rungwe. No clear relationships are observed between household types and the frequency of manure application. As with the endowment indicators, adoption of the low emission dairy practices is highly variable across sites, with site effect statistically significant for all practices with the exception of manure management. Overall, the typology in some cases discerned adoption of the 10 low emissions dairy practices for which differences in means tests are conducted, for which 36 out of the 60 site x adoption pairs are significant at the 95% confidence level (p-value < 0.05) for a total significance percentage of 60%. The relationship between breed ownership and adoption is significant for 30 of the 60 site x adoption pairs, for a total significance percentage of 50%.

Table 3.8: Indicators of diet quality and feed scarcity across sites, households and differences in means (ANOVA and chi-squared tests) (type = household types, breed = adoption of improved breeds, site = survey site). TLU: Tropical Livestock Unit.

Site	Livelihood strategy, breed		Concentrates & by-products (kg dry matter TLU yr^{-1})	Improved forages (kg dry matter TLU yr^{-1})	Feed conservation (% household practicing)	Feed scarcity (month per yr^{-1})
Murang'a	*1*	Local	0	314.5 ± 649.9	0	1.2 ± 1.6
	2		0	565.7 ± 1563.9	0	2.5 ± 1.7
	3		0	210.7 ± 506.3	0	2.0 ± 1.4
	1	Improved	203.0 ± 278.7	1266.3 ± 2146.1	4.1 ± 20	0.2 ± 0.8
	2		355.7 ± 407.9	912.5 ± 1555.7	15.8 ± 36.7	0.0 ± 0.2
	3		321.1 ± 410.2	720.2 ± 1181.9	5.4± 22.6	0.1 ± 0.3
	Site		275.8 ± 380.3	835.8 ± 1509.1	8.0 ± 27.1	0.3 ± 0.9
	p-value (type)		Ns	< 0.05	< 0.05	< 0.001
	p-value (breed)		Ns	< 0.05	ns	< 0.001
Nandi	*1*	Local	9.8 ± 33.9	201.9 ± 493.1	0	2.0 ± 1.1
	2		0	0	0	1.5 ± 1.0
	3		0	0	0	1.2 ± 1.5
	1	Improved	20.2 ± 99.1	513.9 ± 1090	9.2 ± 29.2	1.1 ± 1.2
	2		23.3 ± 83.2	481.9 ± 846.8	10.5 ± 30.8	1.9 ± 1.4
	3		52.5 ± 159.2	327.0 ± 849.5	22.2 ± 42.0	2.0 ± 1.5
	Site		26.9 ± 105.4	425.8 ± 901.4	11.6 ± 32.1	1.7 ± 1.4
	p-value (type)		Ns	ns	ns	ns
	p-value (breed)		< 0.05	< 0.005	ns	ns
Mufindi	*1*	Local	0	0	0	1.1 ± 1.3
	2		0.0 ± 0.1	0	3.2 ± 17.8	0.7 ± 1.1
	3		5.0 ± 22.0	0	0	0.3 ± 0.8
	1	Improved	137.2 ± 208.3	245.2 ± 323.3	20.0 ± 44.7	0.6 ± 1.3
	2		713.8 ± 1236.3	670.1 ± 1038.5	0	0
	3		207.3 ± 257.3	657.7 ± 1507	0	0
	Site		38.8 ± 208.7	78.1 ± 481.8	2.2 ± 14.8	0.7 ± 1.1

	p-value (type)		< 0.001	< 0.001	ns	ns
	p-value (breed)		< 0.05	< 0.001	ns	< 0.005
Mvomero	*1*	Local	8.4 ± 41.0	0	0	1.2 ± 1.7
	2		0	0	2.4 ± 15.4	0.7 ± 1.0
	3		0.8 ± 5.0	0	0.0 ± 0.0	0.9 ± 1.1
	1	Improved	0	62.2 ± 133	12.5 ± 35.4	0
	2		26.6 ± 70.3	1414.9 ± 3641.5	28.6 ± 48.8	0.4 ± 1.1
	3		154.1 ± 323.3	13.6 ± 25.5	12.5 ± 35.4	0.0 ± 0.0
	Site		12.6 ± 86.7	80.2 ± 845.3	3.8 ± 19.2	0.7 ± 1.2
	p-value (type)		< 0.001	< 0.001	< 0.005	ns
	p-value (breed)		ns	< 0.001	ns	< 0.001
Njombe	*1*	Local	34.3 ± 69.2	0.0 ± 0.0	8.3 ± 28.9	1.2 ± 1.6
	2		30.8 ± 87.6	0	0	1.5 ± 1.3
	3		37.6 ± 58.5	0	0	2.7 ± 1.1
	1	Improved	354.9 ± 413.5	706.2 ± 867.5	25.5 ± 44.1	0.0 ± 0.1
	2		367.4 ± 395.8	843.5 ± 926	34.1 ± 47.7	0.1 ± 0.5
	3		426.9 ± 397.7	755.1 ± 1251.5	33.3 ± 47.4	0.0 ± 0.4
	Site		335.3 ± 390.9	666.3 ± 1004.8	27.7 ± 44.8	0.3 ± 0.9
	p-value (type)		< 0.001	ns	< 0.05	< 0.001
	p-value (breed)		< 0.001	ns	< 0.001	< 0.001
Rungwe	*1*	Local	40.4 ± 70.0	28.4 ± 49.1	0	0.7 ± 1.2
	2		16.0 ± 59.2	92.8 ± 362	0	0.2 ± 0.4
	3		188.6 ± 424.9	155.9 ± 398	0	0.4 ± 0.8
	1	Improved	72.6 ± 110.7	298.9 ± 442	0	0
	2		611.2 ± 2221.8	502.1 ± 550.5	1.0 ± 10.1	0.1 ± 0.3
	3		447.5 ± 601.7	467.3 ± 406.7	1.1 ± 10.4	0.0 ± 0.2
	Site		419.3 ± 1429.2	394.9 ± 483.1	0.8 ± 8.8	0.1 ± 0.4
	p-value (type)		< 0.001	< 0.001	ns	< 0.001
	p-value (breed)		< 0.005	< 0.001	ns	< 0.05
p-value (site)			< 0.001	< 0.001	< 0.001	< 0.001

ns = not statistically significant (p-value > 0.05)

Table 3.9: Adoption of select preventive health and manure management practices/technologies across households and sites, and results of differences in means (ANOVA and chi-squared tests) across household types (type), sites (site), and adoption of improved cattle breeds (breed). All variables represent % of households adopting.

Site	**Livelihood strategy, breed**		**Artificial insemination**	**Preventive health**			**Manure management**		
				Anti-ticks	Deworming	Vaccines	Manure managed	Storage system	Frequent field application[1]
Murang'a	1	Local	11.1 ± 33.3	77.8 ± 44.1	22.2 ± 44.1	66.7 ± 50.0	100.0	22.2 ± 44.1	44.4 ± 52.7
	2		0	75 ± 45.2	33.3 ± 49.2	66.7 ± 49.2	91.7 ± 28.9	16.7 ± 38.9	8.3 ± 28.9
	3		0	100.0	25.0 ± 45.2	83.3 ± 38.9	100.0	0	33.3 ± 49.2
	1	Improved	73.5 ± 44.6	28.6 ± 45.6	55.1 ± 50.3	93.9 ± 24.2	98.0 ± 14.3	14.3 ± 35.4	49.0 ± 50.5
	2		72.6 ± 44.8	40.0 ± 49.2	47.4 ± 50.2	92.6 ± 26.3	97.9 ± 14.4	12.6 ± 33.4	61.1 ± 49
	3		74.1 ± 44.0	31.2 ± 46.6	44.6 ± 49.9	91.1 ± 28.6	97.3 ± 16.2	8.0 ± 27.3	56.2 ± 49.8
	Site mean		65.4 ± 47.7	39.8 ± 49	45.3 ± 49.9	90.0 ± 30.1	97.6 ± 15.4	11.1 ± 31.4	53.3 ± 50.0
	p-value (type)		< 0.001	< 0.001	ns	< 0.05	ns	ns	< 0.05
	p-value (breed)		< 0.001	< 0.001	< 0.05	< 0.005	ns	ns	< 0.005
Nandi	1	Local	0	97.1 ± 17.1	67.6 ± 47.5	70.6 ± 46.2	88.2 ± 32.7	23.5 ± 43.1	8.8 ± 28.8
	2		0	91.9 ± 27.5	85.5 ± 35.5	50.0 ± 50.4	77.4 ± 42.2	11.3 ± 31.9	0
	3		0	94.7 ± 22.9	68.4 ± 47.8	36.8 ± 49.6	84.2 ± 37.5	36.8 ± 49.6	0
	1	Improved	0	100.0	20.0 ± 44.7	80.0 ± 44.7	100.0	40.0 ± 54.8	0
	2		33.3 ± 57.7	66.7 ± 57.7	33.3 ± 57.7	100.0	100.0	66.7 ± 57.7	0
	3		0	90.9 ± 30.2	27.3 ± 46.7	90.9 ± 30.2	90.9 ± 30.2	54.5 ± 52.2	0
	Site mean		0.7 ± 8.6	93.3 ± 25.1	70.1 ± 45.9	59.0 ± 49.4	83.6 ± 37.2	23.9 ± 42.8	2.2 ± 14.8
	p-value (type)		< 0.001	ns	< 0.05	< 0.05	ns	< 0.05	ns
	p-value (breed)		ns	ns	< 0.001	< 0.05	ns	< 0.005	ns
Mufindi	1	Local	0	91.7 ± 28.2	20.8 ± 41.5	75.0 ± 44.2	37.5 ± 49.5	0	0
	2		0	85.7 ± 35.4	11.9 ± 32.8	66.7 ± 47.7	35.7 ± 48.5	0	2.4 ± 15.4
	3		0	85.7 ± 35.4	16.7 ± 37.7	47.6 ± 50.5	19.0 ± 39.7	0	0
	1	Improved	0	62.5 ± 51.8	50 ± 53.5	87.5 ± 35.4	62.5 ± 51.8	12.5 ± 35.4	0
	2		0	100.0	57.1 ± 53.5	100.0	57.1 ± 53.5	0	0
	3		0	100.0	75 ± 46.3	87.5 ± 35.4	87.5 ± 35.4	12.5 ± 35.4	12.5 ± 35.4
	Site mean		0	87 ± 33.7	23.7 ± 42.7	66.4 ± 47.4	36.6 ± 48.4	1.5 ± 12.3	1.5 ± 12.3

	p-value (type)		< 0.001	ns	< 0.05	< 0.05	< 0.005	< 0.05	ns
	p-value (breed)		< 0.001	ns	< 0.001	< 0.05	< 0.001	< 0.05	ns
Mvomero	1	Local	0.0 ± 0.0	100 ± 0.0	50 ± 52.2	66.7 ± 49.2	91.7 ± 28.9	8.3 ± 28.9	0.0 ± 0.0
	2		0.0 ± 0.0	81.2 ± 40.3	75.0 ± 44.7	62.5 ± 50.0	93.8 ± 25.0	12.5 ± 34.2	6.2 ± 25
	3		0.0 ± 0.0	100 ± 0.0	88.9 ± 33.3	77.8 ± 44.1	88.9 ± 33.3	33.3 ± 50.0	0.0 ± 0.0
	1	Improved	0.0 ± 0.0	97.9 ± 14.6	51.1 ± 50.5	97.9 ± 14.6	97.9 ± 14.6	57.4 ± 50.0	2.1 ± 14.6
	2		10.2 ± 30.5	97.7 ± 15.0	51.1 ± 50.3	94.3 ± 23.3	98.9 ± 10.7	55.7 ± 50.0	3.4 ± 18.3
	3		3.7 ± 19	92.6 ± 26.4	49.4 ± 50.3	96.3 ± 19	100.0 ± 0.0	59.3 ± 49.4	2.5 ± 15.6
	Site		4.7 ± 21.3	95.3 ± 21.3	53.4 ± 50	91.7 ± 27.6	98.0 ± 13.9	51.4 ± 50.1	2.8 ± 16.4
	p-value (type)		ns	< 0.05	< 0.05	< 0.001	ns	< 0.01	ns
	p-value (breed)		ns	ns	< 0.05	< 0.001	ns	< 0.01	ns
Njombe	1	Local	0.0 ± 0.0	33.3 ± 57.7	66.7 ± 57.7	33.3 ± 57.7	66.7 ± 57.7	0.0 ± 0.0	33.3 ± 57.7
	2		0.0 ± 0.0	70.8 ± 46.4	29.2 ± 46.4	45.8 ± 50.9	95.8 ± 20.4	8.3 ± 28.2	29.2 ± 46.4
	3		0.0 ± 0.0	79.4 ± 41.0	38.2 ± 49.3	47.1 ± 50.7	91.2 ± 28.8	11.8 ± 32.7	35.3 ± 48.5
	1	Improved	0.0 ± 0.0	87.5 ± 35.4	50 ± 53.5	37.5 ± 51.8	100.0 ± 0.0	0.0 ± 0.0	37.5 ± 51.8
	2		2.0 ± 14.2	60.2 ± 49.2	50 ± 50.3	74.5 ± 43.8	100.0 ± 0.0	21.4 ± 41.2	51.0 ± 50.2
	3		6.5 ± 24.7	69.9 ± 46.1	31.2 ± 46.6	71 ± 45.6	98.9 ± 10.4	11.8 ± 32.5	47.3 ± 50.2
	Site		3.1 ± 17.3	67.7 ± 46.9	40 ± 49.1	65.4 ± 47.7	97.7 ± 15	14.6 ± 35.4	45.0 ± 49.8
	p-value (type)		ns	ns	ns	< 0.005	< 0.001	ns	ns
	p-value (breed)		< 0.001	< 0.001	< 0.001	< 0.001	ns	< 0.001	< 0.001
Rungwe	1	Local	11.1 ± 33.3	77.8 ± 44.1	22.2 ± 44.1	66.7 ± 50.0	100.0 ± 0.0	22.2 ± 44.1	44.4 ± 52.7
	2		0.0 ± 0.0	75.0 ± 45.2	33.3 ± 49.2	66.7 ± 49.2	91.7 ± 28.9	16.7 ± 38.9	8.3 ± 28.9
	3		0.0 ± 0.0	100.0 ± 0.0	25.0 ± 45.2	83.3 ± 38.9	100.0 ± 0.0	0.0 ± 0.0	33.3 ± 49.2
	1	Improved	73.5 ± 44.6	28.6 ± 45.6	55.1 ± 50.3	93.9 ± 24.2	98.0 ± 14.3	14.3 ± 35.4	49 ± 50.5
	2		72.6 ± 44.8	40.0 ± 49.2	47.4 ± 50.2	92.6 ± 26.3	97.9 ± 14.4	12.6 ± 33.4	61.1 ± 49.0
	3		74.1 ± 44.0	31.2 ± 46.6	44.6 ± 49.9	91.1 ± 28.6	97.3 ± 16.2	8.0 ± 27.3	56.2 ± 49.8
	Site		65.4 ± 47.7	39.8 ± 49.0	45.3 ± 49.9	90.0 ± 30.1	97.6 ± 15.4	11.1 ± 31.4	53.3 ± 50.0
	p-value (type)		< 0.001	< 0.001	ns	< 0.05	ns	ns	< 0.05
	p-value (breed)		< 0.001	< 0.001	< 0.001	< 0.001	ns	ns	< 0.001
p-value (site)			< 0.001	< 0.001	< 0.001	< 0.001	ns	< 0.001	< 0.001

ns = not statistically significant (p value >0.05

3.4 Discussion

3.4.1 Diversity in livelihood strategies

Based on breed ownership plus four functional variables depicting income sources, livestock diversification, and cropping orientation, households are grouped into 6 different types. Each type pertains to one of three livelihood strategies, differing in the degree of specialization in dairy, and between farm and off farm-based income (Table 3.6). Stratification of households by cattle breed has the indirect effect of delimiting households based on endowment. Stratum 1 households have on average 82% more land (2.4 ha) and 16% more household labour (0.32 man-days) (Table 3.7). Stratum 2 households have on average 45% more income and their household heads have on average over 2 more years of formal education. Thus, while stratum 1 are better endowed in physical resources (land, labour) stratum 2 are better endowed in financial and human capital resources. Stratum 2 households are also more market oriented overall (Fig. 3.5a and b) and are more integrated into the cash economy, receiving a larger share (18%) of income from market transactions (Fig. 3.5c). Kihoro *et al.* (2021) developed a similar typology of dairy households in Tanzania accounting for structural traits including assets, livestock ownership (herd size), market access, and functional traits including diversification. While Kihoro *et al.*'s typology includes herd characteristics as a clustering variable, this extends only to the number of livestock, and therefore the typology groups together households owning improved and local cattle. The advantage therefore of the typology presented here, which stratifies households by breed of cattle owned, is that each type displays relative homogeneity in herd productivity and consequently on dairy emissions intensities (Fig. 3.6a,b).

Household types will presumably differ in tendencies to adopt new practices or technologies. Studies done in Ethiopia (Didanna *et al.* 2018, Dehinenet *et al.* 2014) found that households with a larger income from milk sales were more likely to adopt improved cattle breeds and feeding, and to manage manure more intensively. In this study and at most sites, in addition to having more income from dairy, *Dairy specialists* also have higher market orientation in dairy (Fig. 3.5a) and have been selling milk for longer (Table 3.7). These household types can be expected to be more receptive to and benefit from policy initiatives that enhance access to extension services, improve access to inputs, and enhance the marketability of their milk. For *Diversified farmers*, adopting new practices that enhance resource use efficiency may raise incomes, and because dairy contributes a high portion of household income, these households are likely to benefit more from adoption. *Off farm reliant* are the least dependent on agriculture, and therefore are the least likely to benefit from and presumably to adopt new practices or technologies. While these households generally have moderate to good financial positions relative to others (Table 3.7), a larger percentage of household labour is devoted to off farm employment, about one third relative to one quarter for farm dependent households (*Dairy specialists* and *Diversified farmers*) (full results not shown). Becoming more specialized in dairy may therefore be relatively less effective in increasing income compared to off farm employment.

3.4.2 Associations between breeds, input use, and GHG emissions intensity

Stratifying households by breed is based on the expectation that variation in emissions intensities would be strongly influenced by cattle breed. This is validated by the statistically significant association between breed ownership and emissions intensities (Fig. 3.6b). As a result of different productivity levels across local and improved cattle rearing households, emissions intensities are on average 290% greater among stratum 1 compared to strata 2 households. Among stratum 1, GHG emissions intensities range from 2.0 to 4.2 kg CO_2eq kg^{-1} FPCM in Kenya and from 2.7 to 14.4 kg CO_2eq kg^{-1} FPCM in Tanzania. Among strata 2 emissions intensities range from 1.4 to 2.3 kg CO_2eq kg^{-1} FPCM in Kenya and 1.2 to 2.3 kg CO_2eq kg^{-1} FPCM in Tanzania. Difference in means tests are significant at all sites except Nandi, for which unusually high productivity of local cattle is reported, as well as relatively low productivity among improved cattle (Fig. 3.6a). This results in a smaller gradient in emissions intensities between strata for that site (Fig. 3.6b). Breed ownership is also highly correlated with diet qualities, manure management, and input use. Quantity of forages fed is statistically significantly higher for stratum 2 households for 5 sites. Feeding more concentrates and by-products is statistically significantly higher at 4 sites. Differences in manure management practices are statistically significant for 2 to 3 sites for the three separate indicators (Table 3.9). Households rearing improved cattle spend nearly USD 9 on dairy-related inputs for every USD 1 of inputs spent by households rearing local cattle.

To further investigate the range of emissions intensities, histograms are plotted depicting the dispersion in estimated values for each stratum (Fig. 3.8). Visual analysis of the range of overlap in emissions intensities between strata suggests that management practices are less effective in influencing emissions intensities than adopting higher yielding cross-breeds of *Bos taurus*. Mean emissions intensities among stratum 1 households is 7.1 kg CO_2eq kg^{-1} FPCM, for which the interquartile range was 5.6 kg CO_2eq kg^{-1} FPCM. Mean emissions intensities among stratum 1 households is 1.8 kg CO_2eq kg^{-1} FPCM, for which the interquartile range is 1.2 kg CO_2eq kg^{-1} FPCM. Even among the least emitting stratum 1 households, emissions intensities do not compare well with the average of stratum 2. These findings demonstrate that even with optimal dairy management practices, stratum 1 households do not attain the same level of emissions intensities as stratum 2 households. The predominant theme in current low emissions development dialogues in the dairy sector is on productivity gains to realise emissions reductions (e.g. Henderson *et al.* 2015, Mottet *et al*. 2015, Notenbaert *et al.* 2020). Consequently, these results suggest that greater uptake of improved breeds in particular has substantial potential for reducing greenhouse gas emissions intensities; more so than strategies which aim to enhance productivity among the indigenous cattle herd. However, owing to the greater reliance of improved cattle on good management and external inputs, their adoption will be highly dependent on a conducive enabling environment (Duncan *et al*. 2013).

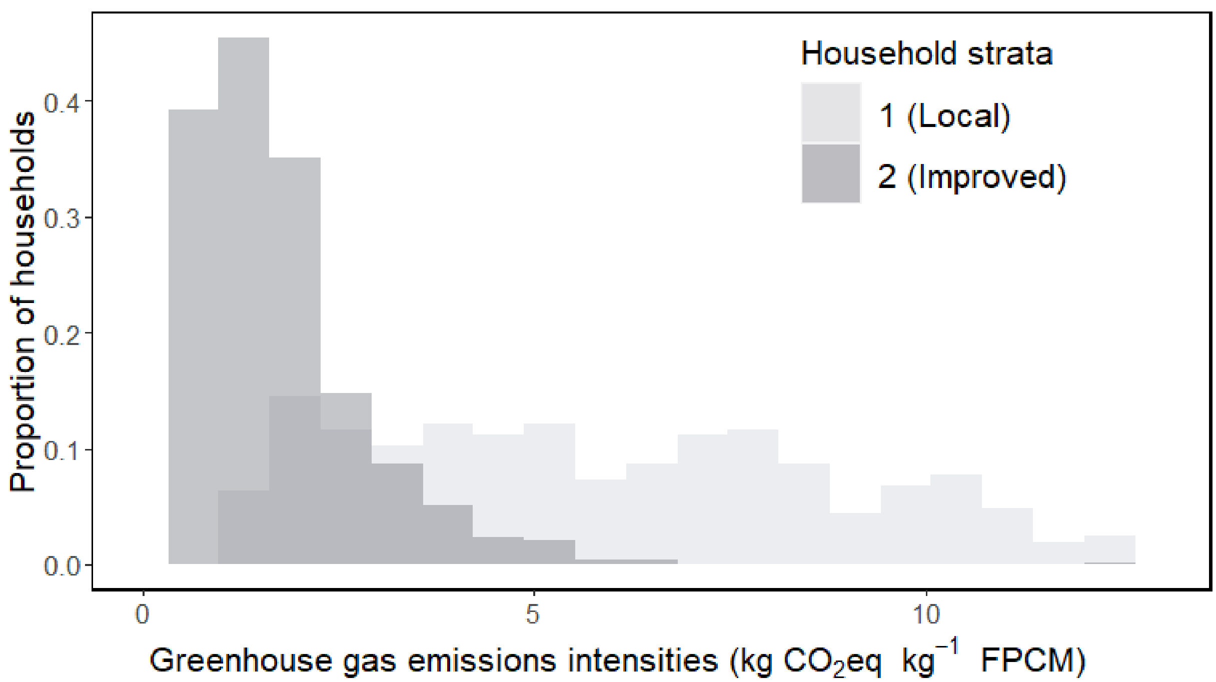

Figure 3.8: Histograms of greenhouse gas emissions intensities among households rearing local (stratum 1) and improved cattle (stratum 2).

3.4.3 Policy frameworks to support low emissions dairy

Kenya's dairy NAMA is designed to facilitate adoption of low emissions practices through various channels including better access to extension, financing to promote on-farm investments through banks and SACCOS (savings and credit cooperative organizations), and greater availability of improved forages through the commercial fodder production industry (GOK 2017). Tanzania has not yet taken concrete steps towards enacting dairy mitigation targets. However, existing development initiatives under the livestock master plan share similar objectives and implementation strategies with Kenya's NAMA, including improved access to extension and development of commercial forage markets (Michael *et al.* 2018). Should Tanzania implement mitigation initiatives in future, there is a reasonable chance the model will share elements similar to that of Kenya's. To provide quantitative estimates for the design of policy frameworks, this section contrasts endowment, practices, and orientation variables for the two household types described above. Because of the substantial potential for emissions reductions from improved breed adoption, and the acknowledged knowledge gap on factors influencing their adoption (Shikuku *et al.* 2016), this discussion includes a specific focus on improved breed adoption in Tanzania. This is done by comparing indicators for *Ls 1 Loc* with strata 2 households in Tanzania (those that have adopted improved cattle). For *Ls 1 Imp* households (who already own improved cattle), the discussion focusses on feeding and other husbandry practices, and relates to households in both Kenya and Tanzania.

Ls 1 Loc households in Tanzania are on average 30% poorer than strata 2 households, with an average annual income of 874 *versus* 1,245 USD for stratum 2 (Table 3.7). *Ls 1 Loc* households have on average 6% less cropland, but 12% more household labour. They also have slightly higher land allocated to cash crops, relative to other strata 1 households (73% of farmed land *versus* 69%). This latter finding suggests households specializing in dairy have relatively more cash crop orientation, potentially as a result of synergies between dairy and cash cropping. Less than 4% of these households participate in extension, compared to 29% among strata 2 households. However relative to other strata 1 households, nearly four times as many participate in extension, owing to the low percentage of *Ls 2* and *Ls 3 Loc* participating in extension (on average only 1%). *Ls 1 Loc* has the same history of selling milk as strata 2 households, both between 6 to 7 years on average.

Among *Ls 1 Imp,* those in Kenya have among the highest rates of adoption of improved forages, feeding on average 840 kg TLU yr^{-1}, 17% more than other strata 2 households in Kenya (Table 3.8). Moreover, for all strata 2 households almost all (>99%) this forage is obtained from farm production. However, *Ls 1 Imp* households feed 60% less in concentrates relative to other strata 2 households. This suggests that *Ls 1 Imp* households have longer term investments in land resources relative to other households rearing improved cattle. Other household types may prefer to buy concentrates for supplementation as a means to increase milk yields, rather than investing in production of forage. These households on average have been selling milk for over 16 years, slightly higher than the mean of other strata 2 households of 14.8 years. However, participation in extension is very low, with only 3.4% of households participating.

In Tanzania, *Ls 1 Imp* for three sites feed less improved forages than other strata 2 households and in all four sites feed less concentrates (Table 3.8). On average, these households feed only 554 kg DM TLU^{-1} yr^{-1} in improved forages, relative to an average of 636 kg DM TLU^{-1} yr^{-1} among other stratum 2 households. Studies in Kenya have shown that increasing forage supplementation to up to 3.6 kg per cow per day through on farm production can increase dairy income by up to 24% (Makau *et al*. 2019). The currently low uptake of good forage feeding practices among households that are highly oriented in dairy suggests these households could increase income through better forage feeding. For all stratum 2 households 100% of forages are obtained from farm production, which suggests that commercial trade in forages is not present in these districts. Tanzanian *Ls 1 Imp* households have more land on average but 6% less household labour. Moreover, these households have an average of 56% of land dedicated to food crops versus 52% for other stratum 2 households. This suggests that households may be unwilling to divert land from food production to grow forages, and that labour is a key constraint. *Ls 1 Imp* also have on average 26% less household income than other stratum 2 households, but have nearly double the rate of participation in extension, at 41% opposed to 26% for other strata 2 households.

In summary, in Tanzania *Ls 1 Loc* households rank closely with strata 2 households in land, labour resources, and dairy experience. However, their incomes are on average nearly one third less than strata 2 households. Based on the four categories of constraints evaluated, capital endowment is the biggest difference between households that have and have not adopted improved cattle. For *Ls 1 Imp* households in Kenya, uptake of concentrate feeding is low relative to other strata 2 households. Other strata 2 households in Kenya feed considerably more, yet have similar endowments of capital, implying that this is presumably not a constraint related to cash availability. Because these households have on average a significant history of selling milk (> 16 years), this low level of concentrate feeding could be addressed by improving extension messages about efficient concentrate feeding practices. For *Ls 1 Imp* households in Tanzania improved forage uptake is low and this represents an area with potential for reducing emissions intensities. Interventions that spare household labour could be promising for these households, such as greater availability of forages through markets, and access to high yielding forage varieties. Better concentrate supplementation regimes through market acquired concentrates also represent a strategy for increasing milk yields. Supplementing cows with 2 kg concentrate per day during lactation was estimated by Rufino *et al.* (2009) to increase lifetime milk production by nearly 40%. As more than 40% of these households participate in extension, focused training on best concentrate supplementation practices could enhance uptake of good supplement regimes among these households.

3.4.4 Limitations and suggestions for future research

The typology developed by this study is based primarily on functional (livelihood) characteristics, as ascertained by variables depicting primary sources of income and market orientation (% of milk sold). The characterization of diversity in livelihoods however could be improved by also including qualitative variables based on desires, attitudes, and perceptions reported by survey respondents. Including these could have strengthened the depiction of varability in livelihoods being pursured by households within the dataset. A more thorough typology could thus benefit by including subjective in addition to objective characterization of livelihoods. This study does not account for market access characteristics in factor reduction or clustering analysis. Households in a given district can be expected to have broadly homogeneous market characteristics, owing to the geographic proximity of all households sampled at each site. However, within each sample there will be minor variations in market access, as a result of distance to major villages, cities, roads, or highways. Future studies could thus improve in this respect by accounting for household level indicators of market access. Another topic not fully explored in this study is on geographic variability relevant in categorising household types and targeting protocols. This study included regions which differed substantially in market access, NGO presence, and to a lesser degree agroecological characteristics. Farm diversity could be better represented by first aggregating households in regions with similar characteristics. Thus, while the typology developed here may not explicitly distinguish geographic variability, the advantage is that it characterises variation in dairy producing households across mid to high agroecological potential throughout the region. Finally, while GHG emissions accounted for in this study take into account variability in feed baskets (proportions of different feeds in the diet), a limitation of the methodology is the inability to account for variability in total dry matter intake. One method of improving on this limitation would be to use feed intake equations or a livestock model (for which presumably the same or similar equations are used) to estimate dry matter intake based on feed quality parameters and livestock characteristics.

3.5 Conclusion

This study proposes a household typology to prioritise interventions to reduce GHG emissions intensities from dairy production in Kenya and Tanzania. Stratifying households by breed of cattle has generated a typology which clusters households based on levels of GHG emissions intensities from dairy production. This study shows that households rearing local cattle emit nearly 4 times as much CO_2eq emissions per unit of milk on average than do households rearing improved cattle. The limited variation in emissions intensities within each stratum suggests that potential reductions in emissions intensities from improved management among local cattle breeds are limited. By contrast, significant reductions are possible through promoting greater uptake of improved cattle. Adoption of improved breeds however is likely to involve hard tradeoffs in intra-household resource allocation (land, labour, capital). Realizing climate mitigation targets consistent with welfare gains for rural livelihoods will therefore hinge on the ability to target improved beed adoption interventions to households that would benefit from them. Based on the three distinct livelihood orientations observed in this study, dairy specialists are likely to benefit the most and have the highest propensity for adopting efficiency improving (and therefore emissions reducing) practices, including improved breeds (for households that have not yet adopted, *Ls 1 Loc*). For these households, those that rear local cattle (*Ls 1 Loc*) therefore represent good candidates for targeting interventions for improved cattle breeds. Those that rear improved cattle (*Ls 1 Imp*) represent good candidates for targeting interventions for feeding, animal husbandry, and manure management. Because dairy-specialist households have a higher rate of participation in extension, enhancing uptake of emissions reducing practices through higher quality extension is a sensible strategy for upscaling low emissions dairy practices.

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Supplementary information 3

SI 3.1 Household indicators

Survey respondents reported value of on-farm production, sales, etc., in local units, such as debes (8 kg of maize), kisados (5 kg of maize), or gorogoros (2 kg of maize). These were converted to SI units based on the respective conversion ratios (Tittonnell *et al.* 2003). The monetary values were converted from local currencies (Kenyan and Tanzanian shillings) to USD based on the 2018 exchange rates of 102.2 Kes USD^{-1} and 2,258 Tsh USD^{-1}.

Income and cash expenditure on cropping and dairy inputs

Income from the sale of crops was estimated as follows:

$$\text{Crop income}_i = \sum_C QCS_c * PP_c - \sum_z CE_z \qquad \textit{(Eq. 3.1)}$$

Where crop income is the annual income (USD yr^{-1}) from cropping activities for household I, QCS_c is quantity of crop product c sold (kg hh^{-1} yr^{-1}), PP_c is the producer price of crop c (USD kg^{-1}) and CE is the crop expenses for crop expense category z. The types of inputs (z) included were inorganic fertilizer, seeds, herbicide, pesticides, hired labour for cropping activities, expenses on farm machinery, and rented cattle. For households who sold positive amounts of milk in the past year, net income from dairy production was estimated as follows:

$$\textit{Dairy income}_i = \sum_C QMS * P_m - \sum_x VDE_x \qquad \textit{(Eq. 3.2)}$$

Where Dairy income is the annual net income from the sale of milk (USD yr^{-1}) for household i, QMS is the quantity of milk reported sold in the past year (litres), P_m is the reported price received per litre of milk (USD), and VDE are variable cash dairy expenses reported over the past year (USD hh^{-1}). The latter included cash expenses on purchased feeds, expenses on replacement cattle, inputs and services for animal health, expenses related to reproduction (artificial insemination, delivery of calves), and any other miscellaneous dairy expenses reported by the respondent. Two additional sources of income were included: income from other livestock (poultry, sheep, goats) and from other farm activities (such as from plantation forests in Mufindi district). Because the survey did not consider expenses on these livelihood activities, they were reported as gross revenue. Finally, off farm income was estimated based on the reported income from non-farm sources for all members of the family as:

$$\textit{Off-farm income} = \sum_v Off\ farm\ income_v \qquad \textit{(Eq. 3.3)}$$

Where off-farm income is income from off-farm activity *v*. These activities included all types of off-farm employment, as well as remittances, dividends, pensions paid to household members, and other forms of off-farm cash income (e.g. capital gains from the sale of assets). The total household cash income was approximated as the sum of the above categories:

$$\text{Cash income}_i = \text{Crop income}_i + \text{Dairy income}_i + \text{Other farm revenue}_i + \text{Other livestock revenue}_i + \text{Off-farm income}_i \quad \textit{(Eq.3.0.4)}$$

Where cash income is the annual cash income from all sources (on and off-farm) (USD yr^{-1}), *Other farm revenue$_i$* and *Other livestock revenue$_i$* are the revenue streams for household *i* as described above. Cash income was combined with the value of farm produce consumed to estimate the total (cash + non-cash) income of the household:

$$\text{Total income}_i = \text{Cash income}_i + \text{Value of consumption}_i \quad \textit{(Eq. 3.5)}$$

Where Total income (USD yr^{-1}) is the total income for household i, and Value of consumption is the value of all on farm produce consumed by household i (USD yr^{-1}). The latter included from food, cash and fodder crops, dairy and other livestock products (USD hh^{-1} yr^{-1}). Total expenses on the crop and dairy enterprise were calculated as the sum of variable expenses reported above. These were calculated as:

$$\text{Crop enterprise expenses}_i = \sum_z CE_z \quad \textit{(Eq. 3.6)}$$

Where Crop enterprise expenses are the total annual expenses on the crop enterprise (USD yr^{-1}) and CE are the crop expenses as reported above. The dairy enterprise expenses were defined as:

$$\text{Dairy enterprise expenses}_i = \sum_x VDE_x \quad \textit{(Eq. 3.7)}$$

Where VDE are the variable dairy enterprise expenses (USD yr^{-1}) for household i and VDE_x are the variable dairy expenses reported over the past year for inputs x as described above. Expenses on the dairy enterprise were then reported in relation to the total TLU owned per household.

Finally, the livelihood orientation of the household (cash income *versus* food self-sufficiency) was approximated using two indicators (equations 1 and 2 below) to approximate the degree of commercial orientation for dairy, and second for all other agricultural commodities (Douxchamps *et al.* 2016).

$$\text{Market orientation dairy}_i = 100 \, x \, \frac{Value\ of\ milk\ sold\ (USD\ yr^{-1})}{Value\ of\ milk\ produced\ (USD\ yr^{-1})} \quad \textit{(Eq. 3.8)}$$

$$\text{Market orientation all other goods}_i = 100 \times \frac{\sum_c (QCs_c * PP_c) + \sum_l (QLs_l * PP_l)}{\sum_c (QCp_c * PP_c) + \sum_l (QLp_l * PP_l)} \quad \textit{(Eq. 3.9)}$$

In equation 3.9, c and l represent crop and livestock products (excluding dairy) produced and/or consumed by household i, QCP, QLS, QLP represent the quantity (kg) of crop products produced, livestock products sold, and livestock products produced, respectively, for household i. PP_l are the producer prices of the respective livestock products (USD kg^{-1}).

SI 3.2 Dairy greenhouse gas emission quantification

Direct emissions of methane and nitrous oxide at herd-level

Quality for feeds included in the survey were obtained from FAO databases and other literature sources (Table S3.1). The estimation of feed intake across dry and rainy seasons were estimated by relating farmer reported feed intake at the time of the survey with feed availability ranking scores (ARS), adopted from the method used by Lanyasunya *et al*. (2006). For the purposes of this study, ARS are defined as the relative intake of a given feed in either the dry or rainy season relative to the annual average. These were calculated for the four feed categories of residues, improved (sown) forages, native grass, and concentrates/by-products (Table S3.1). The ARS were calculated from survey based feed assessments for the respective regions (Wassena *et al.* 2013, Mwendia *et al.* 2019, Muyekho *et al.* 2014, Lanyasunya *et al.* 2006).

For households reporting grazing cattle at least 1 hour per day, feed intake from grazing was estimated by subtracting survey respondent reported feed on offer from dry matter requirements of the herd. Dry matter intake was assumed to be 2.5 kg per 100 kg bodyweight per day and was set to be reduced by up to 20% in months where farmers reported feed scarcity. Grazed feed intake was modelled as a weighted average of the two predominant grazing land types for each site during rainy and dry seasons, which were in all cases native grasslands and croplands (e.g. consuming stover after crop harvest) respectively.

From these diets, methane from enteric fermentation and nitrous oxide emissions from manure management were calculated using IPCC (2006) equation 10.1 using a methane conversion emission factor (Y_m) calculated using a predictive model based on dry matter intake, digestibility, and neutral detergent fibre, from Jaurena *et al.* (2016). The emission factors specified for manure CH_4 were based on a weighted average for each household representing the percentage of manure excreted on pasture versus the fraction managed. The fraction excreted on pasture was based on the reported time grazing per day. Manure from storage was modelled as solid storage systems which is the predominant management system in the region (Rufino *et al.* 2014). Manure methane was calculated based on volatile solids excreted from cattle, from IPCC (2006) equation 10.23. The value used for the methane producing capacity (B_0) was the IPCC default value for the African continent of 0.13 m^3 CH_4 kg VS^{-1} (IPCC 2006). Manure nitrous oxide was calculated as the sum of direct, volatilized, and leached N from manure that is converted to N_2O (IPCC Equations 10.25 - 10.29). Manure N per animal was estimated based on the IPCC default factor for dairy cattle of 0.8 kg N retained kg N intake^{-1}. Default IPCC emission factors for Africa were used for all manure emission factors (IPCC 2006).

Carbon dioxide and nitrous oxide from land use, inputs, and feed processing

Croplands and grassland areas devoted to feeding dairy cattle were determined by dividing the total annual amounts fed to the herd for each household, and dividing by the respective yield of the feed. Yields were obtained from FAO (FAO, 2021c) and from literature sources providing yields of common dairy forages in East Africa (Lukuyu *et al.* 2012, Tessema *et al.* 1984) (Table S3.2). For dairy concentrate feeds which are commonly imported from outside the region, embodied feed coefficients were used from literature. This include for rice bran and dairy meal, for which emission factors of 1.36 kg CO_2eq kg^{-1} were used (Phong *et al*. 2011). The N_2O emitted from feed production was then calculated as the total annual fluxes from all land categories used for feed production after correcting for the ratio of total biomass consumed as feed. For improved forage, the fraction consumed was set at 1, and for stover and concentrate the fractions ranged from 0.20 to 0.66 depending on harvesting and processing ratios (Table SM1). The nitrous oxide fluxes per hectare were derived from field experimental trials taking values of 0.45, 0.40, and 0.80 kg N_2O ha^{-1} yr^{-1} for croplands, native grasslands, and sown forages respectively (Pelster *et al.* 2017, Rosenstock *et al.* 2016). Embodied emission factors for concentrate feeds and N fertilizer were used to estimate energy CO_2. These took values of 0.0786 kg CO_2eq kg^{-1} compound feed, which is calculated assuming 186 MJ of electricity and 188 MJ of gas per 1,000 kg of feed (FAO 2016) and a travel distance of 200 km, which is representative of processed feeds produced in the region (Mbwambo *et al.* 2016). For N fertilizer, an emission factor of 5.66 kg CO_2eq kg^{-1} N was used (Kool *et al.* 2012). The total value for Fossil energy CO_2 emissions were thus based on the sum of emissions from feed processing and transport and manufacturing of fertilizer.

Table S3.1: Feed availability ranking scores for four feed categories in each district.

District	Rainy				Dry			
	Concentrates & by-products	Sown forages	Native grass	Residues	Concentrates & by-products	Sown forages	Native grass	Residues
[a]*Murang'a*	1.02	1.13	1.07	0.76	0.98	0.88	0.93	1.32
[b]*Nandi*	1.43	1.29	1.09	0.46	0.70	0.78	0.92	2.17
[c]*Mufindi*	1.20	1.20	1.20	0.67	0.83	0.83	0.83	1.50
[d]*Mvomero*	1.20	1.17	1.17	0.82	0.83	0.86	0.86	1.21
[b]*Njombe*	1.20	1.20	1.26	0.82	0.83	0.83	0.79	1.21
[b]*Rungwe*	1.20	1.27	1.00	0.95	0.83	0.79	1.00	1.06

[a] Muyekho *et al.* (2014)
[b] Lanyasunya *et al.* (2006)
[c] Mwendia *et al.* (2019)
[d] Wassena *et al.* (2013)

Table S3.2: Yield, greenhouse gas emission, and nutrient parameters used in calculation of milk carbon footprint

Feed	Category	Total biomass yield	N_2O flux	Fraction biomass as feed [h,i]	Dry matter [a,c,j] kg kg^{-1}		Crude protein [a,c,j] kg kg^{-1}		Acid detergent fibre [a,c,j] kg kg^{-1}		Neutral detergent fibre [a,c,j] kg kg^{-1}	
		Mg ha^{-1} yr^{-1}	kg ha^{-1} yr^{-1}		Dry	Fresh	Dry	Fresh	Dry	Fresh	Dry	Fresh
Mixed native grass	Grass	2.1[e]	0.4 [g]	1.00	850	155	46	69	518	345	854	569
Napier grass	Sown forage	12.0[d]	0.785 [f]		893	179	103	97	425	429	711	715
Rhodes grass		11.1[d]			864	249	101	90	412	430	757	750
Lucerne		9.9 [d]			894	199	182	206	334	309	448	393
Sesbania		26.9 [d]			920	173	308	255	156	195	294	255
Calliandra		4.5 [d]			905	349	133	208	271	371	608	556
Brachiaria grass		5.2 [d]			838	412	52	75	451	387	703	683
Desmodium		7.9 [d]			852	242	128	155	399	371	512	514
Guatemala grass		10.0 [d]			908	220	62	88	481	435	771	724
Clover		6.2 [d]			827	140	227	140	371	288	431	282
Star grass		7.4 [d]			850	300	64	86	415	373	707	672
Maize stover	Crop residues	1.05[b]	0.45 [g]	.	928	296	39	68	496	396	750	699
Oat stover		1.4 [b]		0.67	892	263	91	105	381	310	617	542
Sweet potato vine		22.2 [b]			885	130	132	165	322	317	401	427
Banana stems		115.4 [b]			943	69	146	51	400	453	557	577
Sorghum stover		1.4 [b]			900	281	75	82	444	350	687	579
Sugar cane tops		122.0 [b]			309	268	49	67	403	392	677	696
Bean cover		8.5 [b]			887	200	71	93	485	351	697	416
Cotton seed cake	Concen-trate	0.5 [b]	0.45 [g]	0.20	909		473		178		270	
Dairy meal		--		--	873		165		93		347	
Sunflower cake		0.6 [b]		0.20	890		324		320		450	
Maize germ		1.51 [b]		0.10	956		256		122		450	
Soybean cake		0.2 [b]		0.20	879		518		83		137	
Maize meal		1.5 [b]		0.70	902		143		93		347	
Linseed cake		1.5 [b]		0.20	906		341		153		254	
Maize bran		1.5 [b]	.45 [g]	0.10	887		119		145		442	

Wheat bran	Crop by-products	1.2 [b]		.1	870	173	134	452
Rice bran		--	--	--	900	142	32	124

[a] FAO (2021a)
[b] FAO (2021b)
[c] ILRI (2021)
[d] Lukuyu *et al.* (2012)
[e] Tessema *et al*. (1984)
[f] Rosenstock *et al.* (2016)
[g] Pelster *et al*. (2017)
[h] Wilson and Lewis (2015)
[i] Mushi (2016)
[j] Abate and Abate (1991)

Table S3.3: Weights (kg liveweight) used to calculate tropical livestock units of herd

Cohort	Local[a]	Improved[b,c]
Cows	350	450
Heifers	250	300
Bulls	370	450
Juvenile Males	250	250
Male calves	100	110
Female calves	100	110

[a] Kashoma *et al.* (2011)
[b] Kivaria *et al.* (2006)
[c] Msanga and Bee (2006)

SI 3.3 Herd emissions results

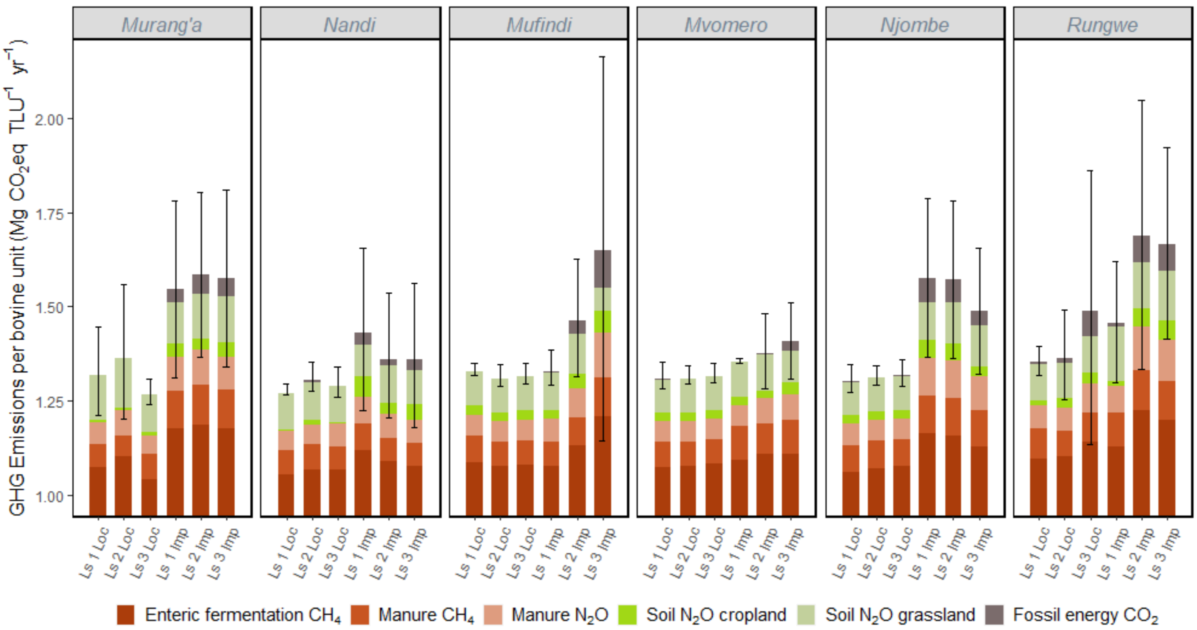

Figure S3.1: Greenhouse gas emissions per livestock unit across sites and household types. y-axis is clipped at 1.0 to display only variable ranges. Error bars denote standard deviation

4 Feeding efficiency gains can increase the greenhouse gas mitigation potential of the Tanzanian dairy sector

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Abstract

The study uses an attributional life cycle assessment (LCA) and simulation modelling to assess the effect of improved feeding practices and increased yields of feed crops on milk productivity and GHG emissions from the dairy sector of Tanzania's southern highlands region. The LCA accounts for both non-CO_2 emissions from dairy production and the CO_2 emissions resulting from the demand for croplands and grasslands using a land footprint indicator. Baseline GHG emissions intensities range between 19.8 - 27.8 and 5.8 - 5.9 kg CO_2eq kg^{-1} fat and protein corrected milk for the Traditional (local cattle) and Modern (improved cattle) sectors. Land use change contributes 45.8 - 65.8% of the total carbon footprint of dairy. Better feeding increases milk yields by up to 60.1% and reduced emissions intensities by up to 52.4 and 38.0% for the Traditional and Modern sectors, respectively. Avoided land use change is the predominant cause of reductions in GHG emissions under all the scenarios. Reducing yield gaps of concentrate feeds lowers emission further by 11.4 – 34.9% despite increasing N_2O and CO_2 emissions from soils management and input use. This study demonstrates that feeding intensification has potential to increase LUC emissions from dairy production, but that fertilizer-dependent yield gains can offset this increase in emissions, through avoided emissions from land use change.

4.1 Introduction

Tanzania is a low-income country of East Africa characterised by relatively low agricultural productivity and a national greenhouse gas (GHG) emissions profile dominated by the land use sector. Land use change (LUC) is the largest contributor to national emissions, representing 66.0% of its estimated 319 Mt of annual CO_2eq emissions, with agricultural emissions (excluding LUC) accounting for 18.8% of national emissions (WRI 2020). About 55% of Tanzania's land area is occupied by woodlands and forests, and these areas are under increasing pressure from anthropogenic activities, especially agriculture (MNRT 2015). The expansion of land areas for crops and grazing are the two largest causes of deforestation in the country (Doggart *et al.* 2020). The country has committed to reduce emissions by 10-20% relative to the business as usual scenario by 2030 under the Paris Agreement (URT 2017a), although to date, the agricultural sector is not included in Tanzania's nationally determined contribution (NDC). The implementation of climate change mitigation initiatives in the land and agriculture sectors is hampered by conflicts with economic development objectives (Nachmany *et al*. 2018) and by the lack of foresight analyses linking the impact of proposed GHG mitigation strategies to changes in emissions and productivity (URT 2017a) .

In the coming years, growth in demand for milk and dairy products caused by rising urban consumption is expected to lead to a national milk supply gap of 5,600 Mg yr^{-1} by 2030 (Michael *et al*. 2018). The Tanzanian Livestock Master Plan (hereafter LMP) is a development program that, amongst others, aims to close this milk supply gap in order to alleviate poverty and raise rural incomes (Michael *et al*. 2018). There is potential for concurrently including Tanzania's dairy sector in the NDC and the development initiatives in the LMP; this, because the LMP prioritizes productivity growth as a means to closing the projected supply gap. Such measures, *via* their impact on feed conversion efficiency, could result in reductions in GHG emissions intensities (e.g. Herrero *et al.* 2013), potentially producing win-win outcomes should these two initiatives be combined. To increase the likelihood of success of these mitigation policy initiatives, a framework is required for quantifying the GHG emissions reductions possible in reference to a baseline (Clapp and Prag 2012), for which no such analysis has been done.

From a practice point of view, better livestock diets are widely viewed as essential to improving productivity and reducing GHG emissions from dairy (Gerber *et al.* 2011). Tanzania's dairy sector is constrained by lack of adequate feed resources, associated with a widespread degradation of grasslands, land shortages in some regions, poor uptake of better forage production and conservation practices, and a poorly developed animal feed processing industry (Michael *et al*. 2018, Maleko *et al.* 2018). Such factors lead to significant seasonal variations in milk production and offtake (Swai and Karimuribo *et al*. 2011). Dry season feed deficits and low genetic potential of much of the herd lead to depressed milk productivity growth, and to a high national average emissions intensity of 19.9 kg CO_2eq per kg FPCM (fat and protein corrected milk) (FAO New Zealand 2019) . Kenya and Ethiopia emit 3.8 and 24.5 kg CO_2eq kg^{-1} FPCM respectively (FAO New Zealand 2017a,b), indicating that there is room for improvement. Feeding management can influence productivity and GHG emissions in multiple ways. Adding more nutrient-dense feeds to diets can improve milk yields and reduce methane (CH_4) emissions intensity (Richards *et al*. 2017). However, higher total energy content of diets can also increase methane production per animal (Knapp et al. 2014). Other risks include increasing CO_2 emissions from expanding cropland areas (Sousanna *et al.* 2010) and N_2O emissions from intensification of feed crop production (Huddel *et al.* 2020). Changes in feeding practices can also lead to land sparing by substituting low yielding grass and forages with higher yielding feed crops, for which regional and global studies have suggested can reduce grassland requirements (Havlik *et al.* 2012). and reduce deforestation (Burney, Davis, and Lobell 2010). As an estimated 96% of cattle in Tanzania are reared in extensive grazing systems (Mbwambo *et al.* 2016), a reasonable hypothesis is that land sparing is a leading strategy for reducing dairy GHG emissions.

This study assesses the effect of improved feed management in Tanzania's dairy sector on GHG emissions in relation to the output growth targets of the LMP. The analysis seeks to evidence the merits of linking the LMP to climate change mitigation initiatives, such as a dairy sector Nationally Appropriate Mitigation Action (NAMA). A life cycle assessment (LCA) is used to quantify GHG emissions and aimed to build off of previous authors using similar quantification methods, including Mottet *et al.* (2015), Brandt *et al.* (2018, 2020), and more recently Notenbaert *et al.* (2020). While all these studies account for the role of improved productivity in reducing direct dairy sector emissions, to date no study has evaluated specifically the role of land sparing and the potential for avoided land use change emissions to contribute to reductions in the dairy carbon footprint. For this purpose, a land footprint indicator is employed, which has been used previously for assessing GHG emissions and productivity indicators of ruminant livestock systems in sub-Saharan Africa (Gerssen-Gondelaach *et al*. 2017, Bosire *et al*. 2019). This indicator helps assess the implications of crop and grassland expansion on LUC emissions and is consistent with the IPCC (2006) Guidelines for National Greenhouse Gas Inventories (IPCC 2006). The objective is to quantify the impact of improved feeding management on milk output and sectoral emissions by 2030. The study focusses on high productive systems in the southern highlands regions of Njombe, Mbeya, and Iringa and the Morogoro region. These regions are well suited agroclimatically for dairy production, and are increasingly attracting private and public sector investments in order to secure milk production for growing urban centres such as Mbeya and Dar es Salaam (SAGCOT 2019).

4.2 Methods

4.2.1 Modelling approach and data sources

The analytical framework involves coupling the *Liv*estock *Sim*ulation model (*LivSim*) (Rufino *et al.* 2009), an algorithm to calculate the land footprint of the dairy sector, and a greenhouse gas quantification protocol based on principles of life cycle assessment (Fig. 4.1). *LivSim* is a dynamic model that simulates the lifetime productivity of dairy cows based on feeding and genetic potential (Rufino *et al.* 2009). *LivSim* is used to simulate individual cohorts of dairy animals (cows, bulls, juvenile males, heifers, calves) across their lifetime, and the milk production and GHG emission estimates are aggregated to the production system level. These form the basis for defining a baseline of milk production, emissions, and land use, and for assessing the impact of feeding efficiency gains. The model is coded in the Python programming language (PSW 2021) as a shell program that runs *LivSim* (also coded in Python) with additional code to define the land footprint and conduct the life cycle assessment.

The land footprint indicator includes all land directly used for providing feed biomass: cultivated and grazing land, and land use ‘upstream’ from the farm for production of concentrate feeds. This framework allows an assessment of the impact of changes in diets, or in productivity gains through higher crop yields, to the changes in land use and milk productivity. The dairy land footprint, expressed as hectares per tropical livestock unit (250 kg liveweight), is as forth defined as all crop and grassland directly used for feeding dairy cattle:

$$Dairy\ land\ footprint_{b,s}(ha\ TLU^{-1}) = \sum_{c=1}^{C}\sum_{f=1}^{F}\frac{Feed\ on\ offer_{\ s,b,c,f}}{Yield_{\ f}\ \times\ Use\ efficiency_{f}} \quad \textit{(Eq. 4.1)}$$

Where *b* represents the cattle breeds, *s* represents the livestock production systems, *C* represents the cattle cohorts, *F* represents the feeds included in the model, *Feed on offer* is the annual feed provision per TLU for a given breed, cohort and for a specific feed (Mg TLU^{-1} yr^{-1}), *Yield* the annual yield of the given feed (Mg ha^{-1} yr^{-1}), and *Use efficiency* the fraction of biomass that is either harvested or grazed. Feed on offer includes all feed available from grazing, harvested on-farm, or purchased from the market.

The model is parameterized with data from a survey of 1,199 smallholder dairy farms conducted in southern Tanzania from November 2017 to August 2018. Surveying activities, performed as part of the IFAD-funded Greening Livestock project, were informed by a stratified random sampling protocol, capturing diversity in dairy farming households (by cattle breed, and socioeconomic factors) among mid to high potential systems across four sampled districts (Fig. 4.2). Baseline indicators characterizing existing feeding practices were developed, which in turn represent diets within the livestock simulations. For the remainder of this paper this survey dataset will be referred to as GLS (2019).

4.2.2 Livestock systems and milk production in south and coastal Tanzania

This study focusses on mixed (M) crop-livestock production, rainfed (R), tropical (T) humid (H) systems (hereafter MRT, MRH), following the Robinson *et al.* (2011) classification. MRT and MRH systems comprise a total of 43,400 km^2 (18,500 km^2 MRT; 24,900 km^2 MRH) across the four regions. In these regions, rainfall is unimodal; the rainy season stretches from November to April, followed by a six-month dry period (Mbulolo *et al.* 2012). Feed sources within these systems depend, to varying degrees, on biomass consumed from grazing, crop residues, cultivated forages, and concentrates acquired off farm. Seasonal variation in feed quantity and quality leads to different grazing and feeding practices across seasons. During the dry season residues from crops form a larger percentage of diets due to the lower availability of natural and planted forages. Concentrates are available from the market year-round but they are generally used sparingly to improve productivity of cows and to maintain nutrient availability during periods of feed scarcity (Wassena *et al.* 2013). Protein-dense concentrates, especially sunflower cake, are used to improve milk yields of cows, while maize bran is commonly used as a supplement to maintain energy availability throughout the year (Mbwambo *et al*. 2016). Both of these feeds are produced and processed locally (FAO 2020, Mbwambo *et al*. 2016). The baseline diets in the present study, including the seasonal biomass intake from cut-and-carry feeding systems, market purchases, and grazing, are specified using GLS (2019) data (described in SI 4.1).

The land footprint is disaggregated based on the dominant sources of feed biomass, and the corresponding land uses (Table 4.1). This allows the impact of changes in croplands and grasslands to land use change emissions to be linked, as per the IPCC (2006) Guidelines. The main feed categories used are: primary crop products (sunflower cake and maize bran), secondary crop products (maize stover), and grass. Grasslands are further divided into native (unmanaged) and sown (managed). The nutritional value and biomass yields of native grasslands are based on the literature on predominant native grass species in the region. Two types of grasses are distinguished based on their yields and nutrient contents: low quality, species of grasses are referred to as ‘Pasture’, which are either harvested or grazed, while ‘Napier grass’ (*Pennisetum purpureum*), which is the most common improved forage produced in the region (GLS 2019), is considered a high quality, high yielding forage used primarily in cut-and-carry systems.

The fraction of feed available from the total biomass yield, which takes into account the use efficiency, harvesting and manufacturing ratios (e.g. the ratio of bran or cake obtained from the grain or seed portion of the crop) are shown in Table 4.1. The biomass available from crop residues was calculated using a harvest index of 0.35 (Fischer and Palmer 1984). For concentrates the ratio of processed feed products (bran from maize or cake from sunflower) are obtained from literature (Mushi 2016, Wilson and Lewis 2015). The use efficiency ranges from 0.50 to 0.95, and are set to 0.50 for grass and pasture, consistent with values that have been used in previous assessments such as Kavana *et al.* (2005). These values reflect the high stocking rates among highland grazing systems in Tanzania (FAO 2006), which result in 0.39-0.61 forage use efficiency (Smart *et al.* 2010). The use efficiency for Napier grass is set at 0.75 consistent with the typical value of reported harvesting ratios from field experimental trials in sub-Saharan Africa (Manyawu *et al*. 2013). The use efficiencies for maize and sunflower were set at 0.95 which are consistent with the nationally reported harvesting efficiency of FAO Stat (FAO 2020). The feed biomass yields per feed type, land use classifications, baseline soil N_2O fluxes (see SI for how these were estimated) and C densities of these land use types are shown in Table 4.1.

Dairy cattle populations and milk production

The dairy sector includes all milking cows, replacement females (heifers and female calves), and reproductive cohorts (bulls, juvenile males, and male calves) which are required for maintaining the stock of cows. Between 90-98% of the cows milked in the study areas are indigenous (*Bos indicus*) cattle, while the other 2-10% are crossbred (*Bos indicus* x *Bos taurus*) or purebred (*Bos taurus*) (Mruttu et al. 2016, NBS 2016). Studies indicate that milk production by improved dairy cattle breeds ranges from 1,350-2,200 litres lactation^{-1} (Ojango *et al*. 2016, Mruttu *et al.* 2016) and calving intervals range from 400-520 days (Ojango *et al*. 2016, Mruttu *et al.* 2016). For indigenous cattle, milk yields are typically 500-600 litres lactation^{-1}, and calving intervals range from 450-600 days (Ojango *et al*. 2016, Chenyambuga *et al.* 2009). Due to the difference in productivity between local indigenous and improved cattle, this study disaggregates the dairy sector (and the dairy land footprint) by breed, resulting in two sectors: the Traditional (local cattle) and Modern (improved cattle) sectors.

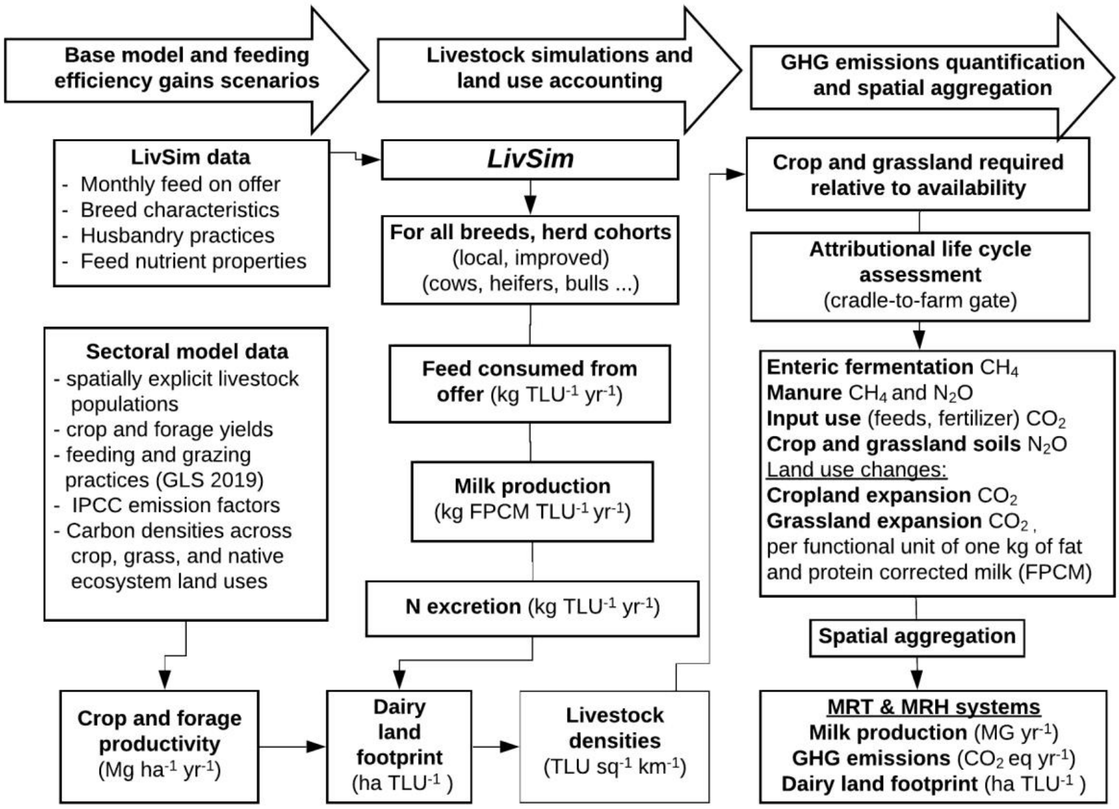

Figure 4.1: Analytical framework. A dynamic livestock simulation model (*LivSim*) is linked to an attributional life cycle assessment (LCA) and a spatial aggregation procedure. The model is written in the Python programming language.

4.2.3 Quantification of greenhouse gas emissions

The dairy sector's GHG emissions are calculated using an attributional life cycle assessment (FAO LEAP 2019). The LCA boundary is defined as 'cradle to farm gate'. Thus all major GHG emissions sources from resource extraction through to the farm gate are included. Post-farm gate emissions such as for transporting and processing raw milk are not considered. Emissions sources are expressed in relation to a functional unit of one kilogram of fat and protein corrected milk (FPCM) which is calculated as milk production standardized to 4% fat and 3.3% protein (IDF 2010). The inventory of GHG emissions sources (Fig. 4.1) includes enteric fermentation (CH_4), manure (CH_4 and N_2O), organic and inorganic N inputs into crop and grassland soils (N_2O), energy use from manufacturing and transport of feed

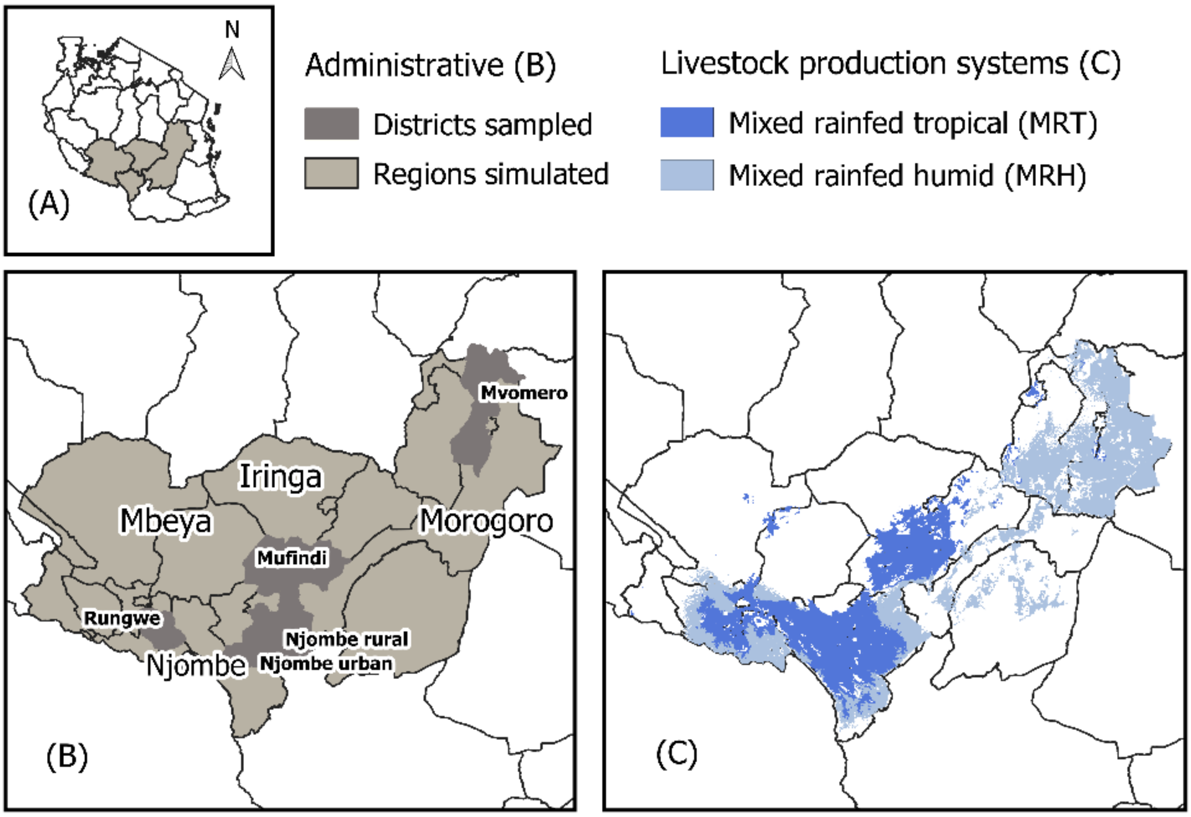

Figure 4.2: Geographic focus of study. (A) shows the region within which the study focusses. (B) Shows the administrative regions (Mbeya, Njombe, Iringa, Morogoro) for which the model simulations are run and the districts (Rungwe, Njombe urban and rural, Mufindi, and Mvomero) the survey sampled from. (C) Shows the livestock production systems within which the simulations are conducted.

and fertilizer inputs (CO_2), and land use change emissions (CO_2) from changes in crop and grasslands driven by the direct changes resulting from increased demand from dairy cattle. A mass allocation factor is used to allocate the total GHG emissions from the dairy herd to production of milk and meat, and this value ranged from 0.85 to 0.95. Meat production is calculated using culling rates for each sex (7.7 and 14.0% for female and male cattle, respectively) and a dressing percentage of 52% (Mruttu *et al*. 2016). Methane and nitrous oxide are converted to CO_2 equivalents using global warming potentials of 28 kg CO_2eq kg^{-1} of CH_4 and 265 kg CO_2eq kg^{-1} of N_2O (IPCC 2013). The GHG emissions from enteric fermentation, manure, and soils are calculated in line with IPCC (2006) guidelines taking emission factors derived from literature or estimated using equations from literature (SI 2). In cases where local emission factor data are not available, default IPCC (Tier 1) values are used. CO_2 emissions from energy used during the manufacturing of fertilizer inputs, feed processing, and the transportation of feed and fertilizer to the farm were included by linking fertilizer and concentrate feed use to CO_2 emissions using embodied emission factors obtained from literature (SI 2). Sources of GHG emissions omitted include those from cattle respiration, farm machinery, electricity, inputs other than feeds and fertilizers, and the construction of farm structures, as these are generally considered minor especially in a low-income context (IDF 2010). The results of the baseline values of N_2O fluxes as modelled from IPCC equations (SI 2) from crop and grassland soils are shown in Table 1.

Carbon dioxide emissions from land use change

Land use changes attributed to changes in feed demand were categorized into one of two transitions: 1) *Cropland expansion*: grasslands being converted to croplands, and 2) *Grassland expansion:* other native ecosystems being converted to grasslands. Observational data conducted in south Tanzania indicates that grazing and cropland expansion jointly affect wetlands, shrublands, and forests (Msofe *et al*. 2020, Doggart *et al*. 2020). Native ecosystems are therefore based on these three land use categories. Indirect land use change from feed cropland replacing grasslands is accounted for *via* what Schmidt *et al.* (2015) refers to as the 'competition effect'. That is, as croplands displace grasslands, a proportional increase in grassland occupation must take place to satisfy forage requirements. Thus, because *grassland expansion* can result in native ecosystems being displaced, *cropland expansion* (via the displacement of grasslands) can also (indirectly) lead to the displacement of native ecosystems.

The CO_2 emissions for these land use changes are estimated using the stock change method (Verchot *et al*. 2016, IPCC 2006). Under this framework, the flux of C (Mg C ha^{1} yr^{-1}) resulting from the conversion of land is related to the difference in C densities between the current and the previous land use. The C densities for a given land use category are equal to the sum of the five following pools: soils, below and above ground biomass, coarse woody debris, and litter (IPCC 2006). Following the practice of LUC accounting in dairy LCA, the CO_2 emissions after land use change are amortized over a twenty-year period (IDF 2015, BSI 2011). The transition coefficient for *cropland expansion* was based on the differences between grassland and cropland C stocks reported in Table 4.1. This resulted in a difference of 11.0 ± 2.0 Mg C ha^{-1} between crop and grasslands.

Estimating CO_2 emissions from conversion of native ecosystems to grasslands

The extent of grassland expansion is calculated based on the relative availability and utilization of grassland for both LPS based on the density of dairy cattle and availability of grassland per grid cell (see SI for details), following an approach similar to that of Havlik *et al*. (2014). Thus, native ecosystems are converted to grasslands when the demand for grasslands exceeds availability. To calculate the transition coefficient, native ecosystem C stocks are estimated using spatially-explicit land cover data at a 100x100m pixel resolution (Bruzonne *et al.* 2020). The C stock density of native ecosystems is estimated as a weighted mean of the shrub, forest, and wetland categories. The C densities of these land categories (for the non-soil C pools) are based on national carbon stock inventory data (Mauya et al. 2019) and for soils, based on a topsoil dataset compiled from 1,400 locations across Tanzania (Kempen *et al.* 2018) (Table 4.1). The weights are based on the proportion of shrub, forest, and wetland in a given grid cell (Bruzonne *et al.* 2020). This data is up-scaled to the same spatial resolution as the LPS data and then aggregated to derive a C stock difference between grasslands and native ecosystems representative of both MRT and MRH systems in the study region. The resulting values are 31.5 ± 6.3 and 30.9 ± 6.2 Mg C ha^{-1} for MRT and MRH systems, respectively. These values are in agreement with the estimates provided by Carter *et al*. (2018). LUC emissions from grassland and cropland expansion at LPS level are calculated based on the total amount of land undergoing the given transition in any one year, and the amount of CO_2 emitted, after amortization, per unit of land for that LUC transition.

Table 4.1: Biomass productivity, nitrous oxide fluxes, and carbon density parameters for feed and land use categories in model.

Land Use	Feed	Annual yield	Available feed biomass	Use efficiency	Nitrous oxide flux	Carbon density		
		Mg DM ha^{-1}	Mg DM ha^{-1} yr^{-1}	Fraction	kg N_2O ha^{-1} yr^{-1}	Mg C ha^{-1}		
						Soils[b]	Other pools[e]	Total
Croplands	Maize	1.46 [d]	0.44 (bran) 2.18 (stover)	0.95	0.73 (stover) 1.03 (bran)	38.0	3.5	41.5
	Sunflower	1.03 [d]	0.36 (cake)	0.95	0.90			
Grasslands	Napier grass	13.04 [a]	13.04	0.75	0.51	48.0	4.5	52.5
	Pastures	10.00[c]	5.0	0.50	0.08			
	Grasslands	3.00[c]	1.50	0.50	0.13			
Wetlands						42.0	4.4	46.4
Shrubland						41.0	16.6	57.6
Forest						69.0	37.8	106.8

Sources: [a] Malecko *et al.* (2018), [b] Kempen *et al.* (2018), [c] URT (2017b), [d] FAO Statistics (2020), [e] Mauya *et al.* (2019)

4.2.4 Scenarios

Three scenarios are explored involving improved feeding practices with and without feed crop yield improvements suitable to the agroecological conditions of southern and eastern Tanzania and for each dairy population (indigenous and improved). Similar scenarios were tested previously for Kenya by Brandt *et al*. (2018, 2020). This study modifies the scenarios to the policy context and priorities and to the best practice recommendations for the dairy sector in Tanzania (Table 4.2).

Under the strategy '*Conservation'* (*Cn*), urea-molasses treated maize stover was fed to cows in place of untreated maize stover. A urea-molasses treatment is proposed to enhance the nutritional quality of stovers (Malecko *et al.* 2018). Therefore, in the dry season when availability and nutrient quality of forages is reduced, feeding treated maize stover can increase protein intake. The '*Forage*' strategy (*Fo*) evaluated the role of higher rations of Napier feeding, in place of grass and pasture. For the '*Concentrate'* strategy (*Co*), supplemental concentrates were provided to cattle according to supplementing regimes aimed at optimizing milk yields for local and improved cattle (Bwire and Wiktorson 2003, Rufino *et al*. 2009). Concentrate mixtures are based on the strategies of Bwire and Wiktorrson (2003) who evaluated the effects of supplementing 67% maize bran and 33% sunflower cake rations on the performance of crossbred cattle in Tanzania. The concentrate and forage strategies are evaluated at a higher intensity level for improved cows given their higher feed conversion efficiency (Chagunda *et al.* 2009) and hence greater returns from improved feeding (Table 4.2). All three of these strategies are evaluated additively by first implementing the conservation strategy, then assessing the additional effect of *Fo* and *Co*. This is because scenario analysis reveals that feeding greater concentrates is not effective in improving milk yield unless seasonal feed deficits are first reduced (e.g. by using feed conservation and greater forage quality). For the results of additional scenarios, and the seasonal variation in nutrient availabilities for the cow simulations, see SI Section 6.

The Tanzanian Grazing-Land and Animal Feed Resources Act (URT 2010) seeks to catalyse the development of Tanzania's commercial feed processing industry. Scenarios therefore consider yield gains in maize and sunflower for concentrate production, which are the two most common sources of concentrate feeds in the region (Mbwambo et al. 2016). Current yields of these crops (Table 4.1) are significantly below their potential, with water limited yield potential having been reported up to as high as 6.0 (maize) and 3.0 (sunflower) Mg ha^{-1} yr^{-1} (Van Bussel *et al*. 2015, GAEZ 2020). Data from field experiments in Western Kenya (Hickman *et al.* 2015) are used to estimate the effect of higher N fertilizer application on yields and N_2O emissions of maize and sunflower used in concentrate production. The yield gains are set as 50% of the yield gap based on the values reported above and in Table 1. The requirement for N fertilizer used to achieve these yields are based on a yield response of 14 kg ha^{-1} kg N^{-1}, with an emission factor of 0.015 kg N_2O kg N^{-1} (Hickman *et al.* 2015). The crop yield scenarios are implemented in addition to the above feeding strategies, and denoted with a '*+Cyg'* ('*Crop yield gains'*). The results of the yield gap and N_2O calculations used for these simulations are shown in SI 4.

Table 4.2: Definitions of scenarios examined and their target populations of cattle.

Sector	Cattle population	Feeding strategy	Scenario abbreviation	Description
Traditional	Indigenous	Conservation	*L – Cn*	All maize stover fed to cows is treated with urea-molasses.
		Conservation plus forage quality	*L – CnFo*	*L – Cn* with Napier grass increased to 25% of feed on offer, replacing grass and pasture.
		Conservation plus forage quality with supplementation	*L - CnFoCo*	*L - CnFo* with 2 kg d^{-1} of concentrates fed during early lactation, and 0.5 kg d^{-1} during other periods. Concentrate intake is comprised of 67% maize bran and 33% sunflower cake.
Modern	Improved	Conservation	*I – Cn*	All maize stover fed to cows is treated with urea-molasses.
		Conservation plus forage quality	*I – CnFo*	*I – Cn* with Napier grass increased to 50% of feed on offer, replacing grass and pasture.
		Conservation plus forage quality with supplementation	*I - CnFoCo*	*I - CnFo* with supplement feeding involving 5.0 kg d^{-1} of concentrates during early lactation, and 1.5 kg d^{-1} during other periods. Concentrate intake is comprised of 67% maize bran and 33% sunflower cake.

Baseline production growth and greenhouse emissions

A baseline provides a reference level against which a mitigation goal can be established (Clapp and Prag, 2012). The production practices used in the baseline represent those in the absence of specific mitigation interventions (Hood and Soo 2017). The dairy herd population for 2020 is established using spatially-explicit data on livestock population densities (Gilbert *et al.* 2018) and annual growth rates in herd size. Feeding practices were obtained from GLS (2019) (SI 1). Model parameters for the *Baseline* are thus set by extrapolating historical values over the 10-year timeframe of the assessment. Throughout the 10-year simulation period, the herd size is assumed to grow by 5.5% and 4.5% annually for local and improved cattle, respectively (NBS 2013). No changes are assumed for feeding or other herd management practices that would otherwise affect productivity or herd compositions. The yields of feed crops are assumed to grow consistently with historical averages of 3.4% and 4.1% annually for maize and sunflower, respectively (FAO 2020). The scenarios are run modifying the availability of feeds, with and without yield improvements. For these scenarios, the populations and herd structures remain constant. The scenarios described above for both Traditional and Modern systems are thus run to compare to the *Baseline* scenario. This results in a total of 14 runs (2 baselines + 2 sectors x 3 feeding scenarios x 2 crop yield variants) for each LPS.

4.2.5 Uncertainty assessment

Uncertainty in GHG emissions is quantified in line with the IPCC (2006) Guidelines. In the baseline, the sources of uncertainty are dairy cattle numbers per LPS, feed on offer per head, biomass yields, and emission factors (including coefficients on LUC transitions). For subsequent simulations the dairy herd and feed intakes are specified in relation to the baseline, and therefore for all other scenarios the only sources of uncertainty are in emission factors and biomass yields. Monte Carlo (MC) simulations are run for the baseline and each subsequent scenario to estimate the GHG emissions error range at a confidence interval of 95%. The standard error in emission factors are specified based on IPCC (2006) Guidelines. The uncertainty in the emission factor for enteric fermentation (Y_m), which is calculated using Tier 3 guidelines, is set at 10%, consistent with previous studies estimating Y_m using Tier 3 guidelines (Bannink *et al.* 2011). The coefficients for LUC are calculated from country specific inventory studies and thus are either Tier 2 or 3 emission factors (Kempen *et al.* 2018, Mauya *et al.* 2019). Moreover, because these coefficients are highly dependent on the C density data reported by Mauya *et al*. (2019) who report relatively low uncertainty (0.9% for forest and 1.8% for non-forest land), the standard errors for such were set at 20%. Because this study includes simulations for greater N-fertilizer application, which may result in highly variable and uncertain changes in N_2O emissions, the standard error of this emission factor (EF_1 soil N inputs) is set at more than double the required upper range for Tier 1 emission factors, taking a value of ± 66%. All other emission factors ranging from Tier 1 to 3 are set based on IPCC guidelines, thus ranging from 7 to 30% (SI 5).

4.3 Results

4.3.1 Evaluation of the baseline

Direct emissions intensity (excluding LUC emissions) for the baseline are 9.3 ±1.7 (95% confidence interval) and 7.8 ±1.4 kg CO_2eq kg^{-1} FPCM (MRT and MRH, respectively) for the Traditional sector. For the Modern sector, these emissions are 2.8±0.62 and 3.2±0.72 kg CO_2eq kg^{-1} FPCM (MRT and MRH, respectively) (Fig. 4.3A and B). Emissions from LUC, expressed as emissions intensities, are 18.5 ± 4.1 and 12.0±2.6 kg CO_2eq kg^{-1} FPCM (MRT and MRH, respectively) for the Traditional sector and 3.0 ± 0.81 and 2.6±0.57 kg CO_2eq kg^{-1} FPCM for the Modern sector. The CO_2 emissions from LUC (*cropland* and *grassland expansion*) throughout the simulation period (2020-2030) contribute between 45.8-65.8% of the total GHG emissions from milk production. Of the total LUC emissions, 7.7-29.2% (2.6 and 2.4 for MRT and MRH Traditional, and 0.98 and 0.81 kg CO_2eq kg^{-1} FPCM for MRT and MRH modern sector, respectively) are from *cropland expansion*. The remaining 70.8–92.3% (18.5 and 12.0 for MRT and MRH Traditional, and 2.0 and 1.60 kg CO_2eq kg^{-1} FPCM for MRT and MRH Modern sector, respectively) are from *grassland expansion*. The difference in LUC emissions between MRT and MRH is attributable to (a) a higher percentage of *grassland expansion* in MRT resulting in the conversion of native ecosystems, and (b) a larger land footprint for the dairy sector in MRT, owing to the larger herd overhead (i.e. the larger proportion of unproductive male and female cohorts in the herd, see herd composition by system in SI Table S1).

Since this study is the first quantitative assessment of GHG emissions that includes CO_2 emissions from LUC from the Tanzanian dairy sector, these emissions estimates cannot be compared directly with other literature. However, using the Global Livestock Environmental Assessment Model (GLEAM), FAO New Zealand (2009) estimated direct emissions in Tanzania's dairy sector, which included emissions from enteric fermentation, manure, N_2O emissions from managed soils, as well as CO_2 from feed and fertilizer production/transport. FAO New Zealand estimated emissions intensities from these sources within the range of 20-28 and 2-3 kg CO_2eq kg^{-1} FPCM for the Traditional and Modern sectors respectively (including from both MRT and MRH systems). This latter study, which is a nationally representative study of Tanzania, estimated lower milk yields for local cattle (200 litres per lactation). In the present study focussing specifically on mid to high productivity (i.e. excluding pastoral) systems in the southern highlands and Morogoro, yields are estimated at significantly higher levels (582 and 538 litres per lactation for the MRT and MRH baselines, respectively). Hence, the direct emissions intensities are estimated to be 53.5 - 61.0% lower than those estimated by FAO New Zealand. The emissions intensities for the Modern sector of the present study are comparable to those of FAO New Zealand and those of neighbouring countries with a high proportion of crossbred dairy cattle (e.g. Kenya). In Kenya, emissions intensities have been estimated to be 2.2 - 3.0 kg CO_2eq kg^{-1} FPCM (Wilkes *et al*. 2020).

4.3.2 Impact of feeding intensification on direct non-CO_2 GHG emissions

Direct emissions intensities are reduced by up to 28.2 ± 5.1 and 29.2 ± 5.3% for local cattle in MRT and MRH, respectively (Fig. 4.3A). For improved cattle, the scenarios lead to declines in direct emissions intensities of up to 28.0 ± 6.2 and 26.7 ± 5.9% (MRT and MRH) (Figure 3B). The scenarios resulting in the largest declines in emissions intensities are the forage quality plus concentrates scenarios (*L-CnFoCo* and *I-CnFoCo*), and for the simulations without yield gains in feed crops. Since the diets for scenarios with and without yield gains are identical, the slightly higher value for direct emissions intensities for the yield gains scenarios is a result of the increase in soil N_2O emissions from croplands by 16-40%, and in energy use CO_2 by between 220-242%.

All the scenarios assessed for all systems lead to greater intake of metabolizable energy and protein, which leads to 18-52% and 6-63% gains in milk yields for cows in the Traditional and Modern sectors, respectively (Table 4.3). All the scenarios result in greater annual gross energy intake per cow, and while these represent modest declines in Y_m, up to a maximum of 7.5%, the impact on CH_4 emissions from enteric fermentation are negligible. Changes in enteric CH_4 range between -3.8% to + 8.7%. Manure CH_4, also because of higher gross energy intake, increases by up to 15.4%. Manure N_2O increases by up to 40.5%, because of the higher protein concentration of the diets and consequently higher N excretion in manure. The only scenarios that did not lead to higher manure CH_4 is *Conservation* (*Cn*). In summary, the scenarios therefore result in modest increases in absolute GHG emissions from enteric fermentation, manure and soils, by between 0.0 – 14.1 % (Traditional) and 0.0 – 33.1 % (Modern) (Fig. 4.3C and D). However, through their impacts on milk yields, these scenarios have significant impacts in reducing emissions intensities, up to 29.2% (Traditional) and 28.0% (Modern). The scenarios thus improved emissions efficiency (emissions per unit FPCM), but they did not actually reduce direct non-CO_2 emissions in absolute terms (i.e. per TLU).

Table 4.3: Effects of feeding scenarios on milk yield for the Traditional sector (local cattle) and Modern sector (improved cattle).

Scenarios	Feeding practices	Mixed rainfed tropical			Mixed rainfed humid		
		Milk yield			Milk yield		
		Lactation	Annual	Change	Lactation	Annual	Change
		(kg FPCM cow^{-1} $lactation^{-1}$)	(kg FPCM cow^{-1} yr^{-1})	(%)	(kg FPCM cow^{-1} $lactation^{-1}$)	(kg FPCM cow^{-1} yr^{-1})	(%)
Traditional Sector (local cattle)							
Base	Baseline	582	358		538	331	
L-Cn	Feed conservation	689	424	+18.4	611	377	+13.9
L-CnFo	Feed conservation, forage quality	823	507	+41.6	758	466	+23.6
L-CnFoCo	Feed conservation, forage quality, concentrates	858	528	+47.4	813	501	+51.4
Modern Sector (improved cattle)							
Base	Baseline	1413	932		1326	875	
I-Cn	Feed conservation	1458	991	+6.3	1387	915	+8.3
I-CnFo	Feed conservation, forage quality	1833	1264	+35.6	1580	1059	+25.3
I-CnFoCo	Feed conservation, forage quality, concentrates	2163	1492	+60.1	1965	1355	+54.9

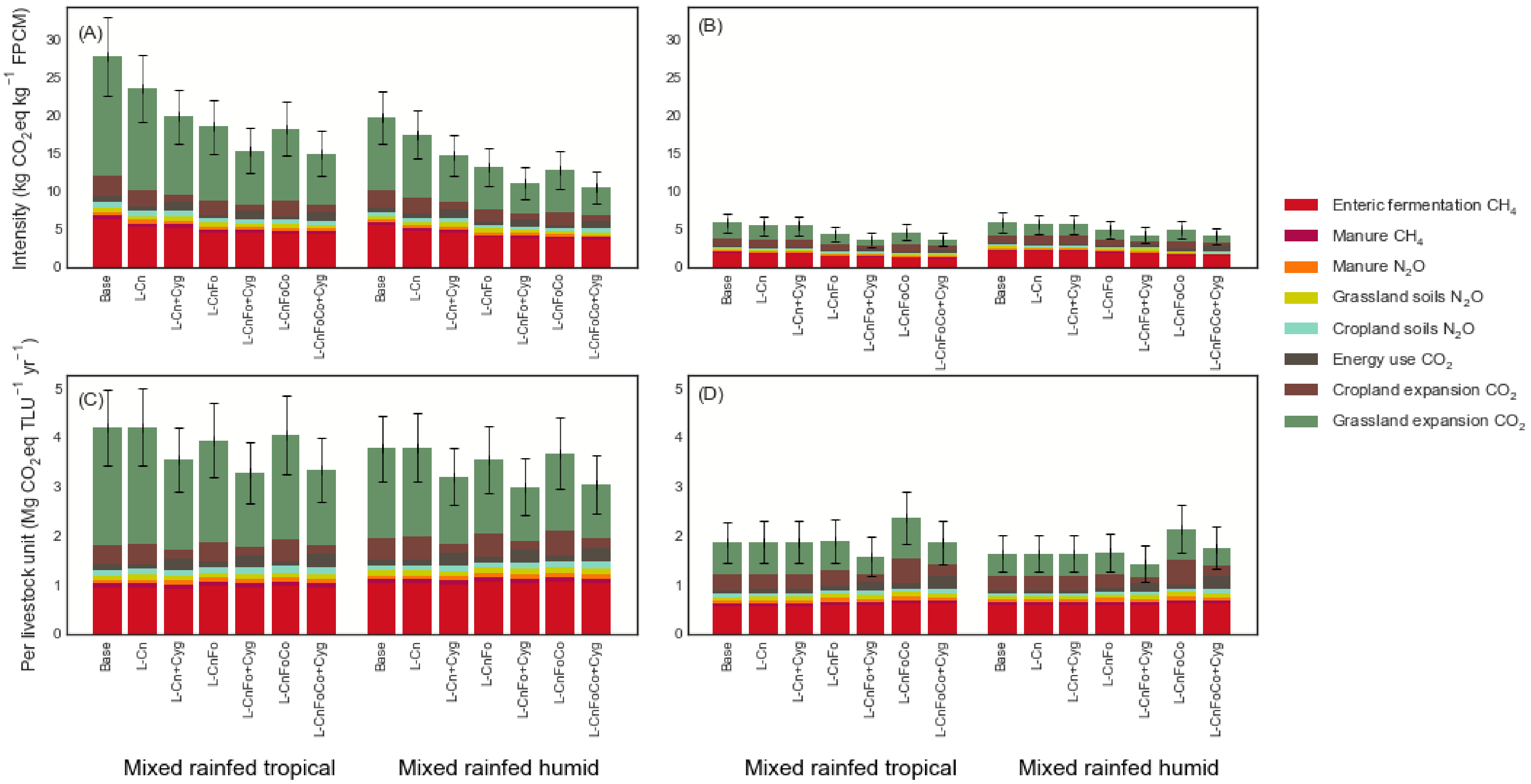

Figure 4.3: Greenhouse gas emissions for Traditional (A and C) and Modern (B and D) dairy sectors.

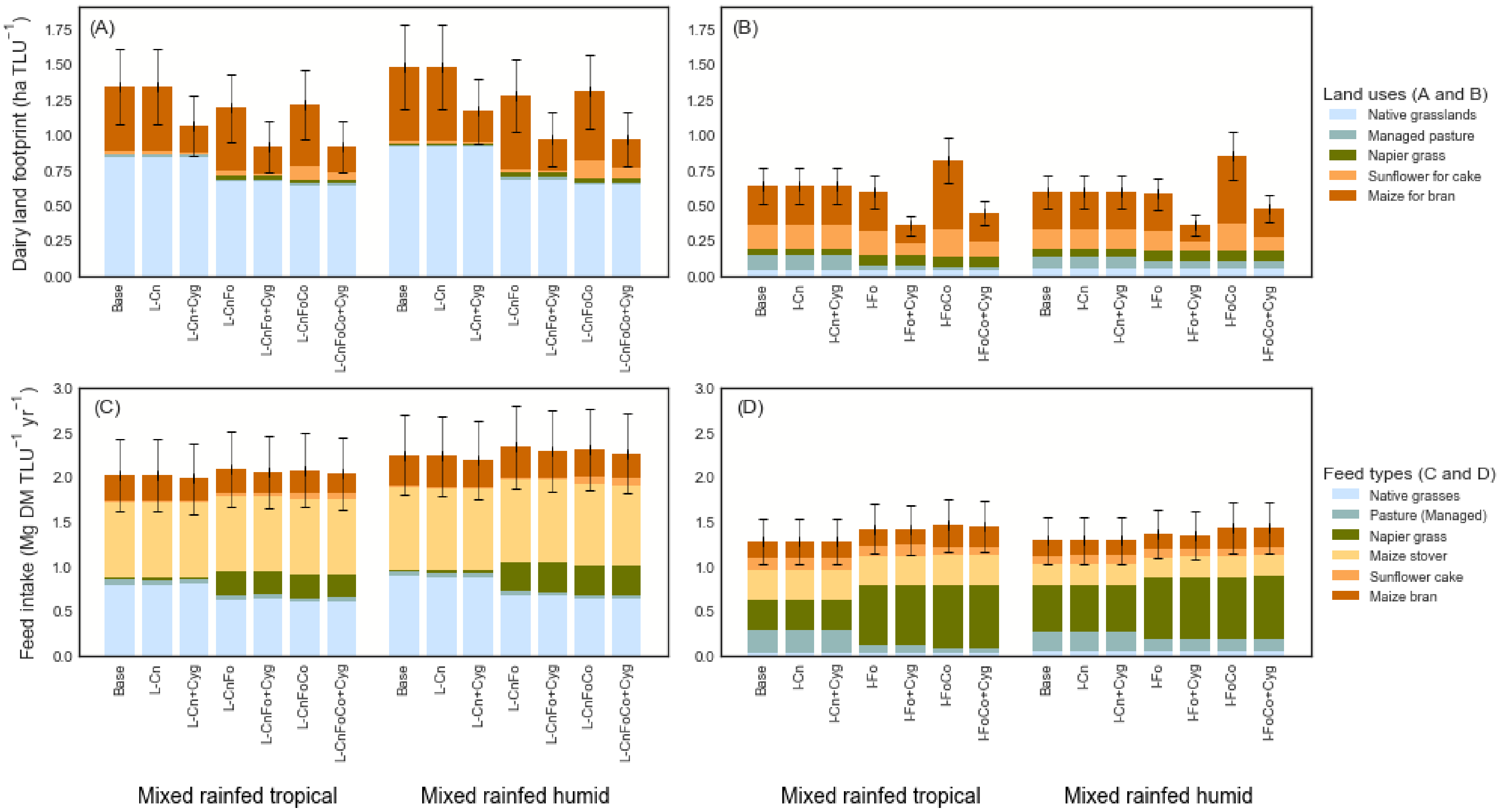

Figure 4.4: Dairy land footprint and feed intakes for Traditional (A and C) and Modern (B and D) dairy sector.

4.3.3 Land use effects of changes in feed mixes (not including crop yield gains)

The scenarios result in 4.6 - 45.0% greater cropland area and 17.6-28.9% less grassland area under use as part of the dairy land footprint (Fig. 4.4A and B). The scenarios *L-Cn* and *I-Cn* are exceptions as they did not result in LUC because this strategy only involves the treatment of available maize stover fed to cows. For the Traditional sector, dedicating greater area to feed crops under *L-CnFoCo* resultes in between 410.0 – 557.0% greater land under sunflower and 3.0-7.0% less land under maize (for concentrate production). For the Modern sector (*I-CnFoCo*), between 15.0-37.0% greater maize and 75.2-82.2% greater sunflower areas result from the increase in concentrate feeding. These scenarios consequently result in between 2.0-11.5% (Traditional) and 52.0-66.5% (Modern) greater CO_2 emissions from *cropland expansion* relative to baseline. Concurrently, the land areas required for grasslands decline by between 21.0-25.7% (Traditional) and 29.0 – 29.4% (Modern).

The net effect of these changes is a reduction in the dairy land footprint by 7.4–9.5% and 6.1–8.2% for the *L-CnFo* and *L-CnFoCo* scenarios, respectively, for the Traditional sector. For the Modern sector, *I-CnFo* and *I-CnFoCo* led to 30.1-32.5% less and 20.9–31.8% greater land footprints, respectively. The increase in cropland area dedicated to concentrate feed crops under *I-CnFoCo* outweigh the decline in grassland area and hence the total land footprint increases (Figure 4B, Panel D, *I-CnFoCo*). These changes result in reductions of between 8.0 - 31.1% (Traditional) and 10.9–16.0% (Modern) in emissions associated with *grassland expansion*. Under *I-CnFoCo*, while the land footprint increases, only between 29.8–49.5% of this additional area expansion results in the conversion of native ecosystems. Therefore, for all scenarios, total LUC CO_2 emissions decline, by 7.2–15.5% for the Traditional sector and 1.2-4.1% for the Modern sector.

Effects of crop yield gains on the land footprint and GHG emissions

The fertilizer-induced yield gains in maize (for bran) and sunflower (for cake) lead to an increase in soil N_2O emissions by a factor of 5.5 for maize and 3.2 for sunflower (full results in SI section 4). These increases occurred concurrent with a 2.25 and 1.0 Mg ha^{-1} yr^{-1} increase in the yields of these crops. Hence, absolute N_2O emissions per hectare for these two crops, as well as yield-scaled N_2O emissions, increase. These yield gains however lead to less area of these two crops needed to satisfy the feed demands for the dairy herd. Relative to the scenarios without yield gains, the total area dedicated to maize (for bran) and sunflower (for cake) decline by 57.6 and 47.4%, respectively (Fig. 4.4A and B), as a result of these yield gains. Moreover, most of the scenarios (with the exception of the feed conservation scenarios) involve the substitution of feeds with relatively low soil N_2O emissions (native grasslands) for feeds which have relatively high N_2O fluxes (Napier grass and concentrate feed crops) (Table 4.1) (Fig. 4.4C and 4D). Therefore, the fertilizer-dependent yield gains have the net effect of increasing total N_2O emissions relative to the scenarios with the same diets with baseline yields for concentrate feeds. Moreover, while the dietary impact of these changes was higher milk productivity (Table 4.3), the growth in milk production is not sufficient to lead to an actual decline in the soil N_2O emissions intensity. Relative to the baseline crop yield growth variant, N_2O emissions intensities therefore rise by a maximum of 34.0%. The additional reliance on concentrate feeds also leads to greater CO_2 emissions from energy use upstream from the farm, increasing by between 220–232% (Traditional sector) and 227.0–246% (Modern sector). This also leads to higher CO_2 emissions from energy use per unit of milk. However, despite the growth in N_2O and CO_2 emissions from crop yield gains, these have the effect of reducing LUC emissions, both from *cropland expansion* (e.g. because less crop area is required to meet the crop feed demands) and from *grassland expansion.* The latter occurs because the yield gains in feed crops imply less grasslands need to be converted to cropland to satisfy the crop feed demands, and hence less expansion of grasslands is needed to replace the grassland converted to croplands. In summary, the fertilizer-dependent yield gains have the effect of increasing N_2O emissions from soils and energy use CO_2, both in absolute terms and per kg FPCM. However, the decline in land converted to cropland due to improved yields results in less *cropland* and *grassland expansion*, and thereby lower LUC emissions. The reduction in LUC emissions outweighs the increase in emissions from soils and energy use, and therefore in net terms, the crop yield gains reduce GHG emissions attributable to milk production by between 11.4-14.4% (Traditional) and 29.5-34.9% (Modern).

4.4 Discussion

4.4.1 Land sparing and GHG mitigation in the dairy sector

To the knowledge of the author, this study presents the first comprehensive assessment of GHG emissions from Tanzania's dairy sector that includes the impact of indirect emissions from expanding crop and grassland areas. Initiatives to include the dairy sector in Tanzania's NDC or, for example, to develop a dairy NAMA will require foresight analyses, which provide empirical evidence quantifying the impact of proposed mitigation strategies on GHG emissions and on milk productivity. This study therefore offers the first assessment of such dimensions, which can be used in subsequent analyses that consider additional mitigation strategies (e.g. animal genetic gains) - also in conjunction with cost-benefit analyses. It thereby supports ongoing public and private efforts to formulate evidence-based mitigation strategies available.

The framework used in this study, based on principles of attributional life cycle assessment, is instrumental in showing how LUC emissions are comparatively significant in relation to direct non-CO_2 emissions. These account for 45.8 - 65.8% of total GHG emissions from the dairy sector. Because all the scenarios result in increases in direct non-CO_2 emissions by between 0.6 - 33.1%, this analysis demonstrates that reducing emissions from LUC will be an important component of future mitigation strategies from the dairy sector. Importantly, this study highlights that reducing the dairy land footprint through improved feeding practices combined with crop yield gains has particular mitigation potential by curbing emissions from cropland and/or grassland expansion.

Based on the feeding strategies and crop yield gains simulated, this study estimates that land occupation of the dairy sector (Traditional and Modern) across the study region occupying 4.34 Million hectares (Mha) (see Figure 4.2) could be reduced by up to 0.788 Mha. This represents a total decline in land occupation of the dairy sector of 30.75% relative to the baseline simulations. The model estimates are that these efficiency improvements could reduce encroachment into native ecosystems from a baseline value of 0.645 Mha to 0.403 Mha, for a total decline 0.242 Mha or 37.5% throughout the 2020-2030 time period. In total, these changes are estimated to translate into a reduction in total LUC emissions of up to 1.85 MT CO_2eq yr^{-1} by 2030, for a maximum reduction of up to 41.5% relative to the baseline. These results could be used to, for example, guide the development of a dairy NAMA or NDC whereby the synergies resulting from improved feeding practices and crop yield gains on dairy sector productivity and land use could be anticipated. The milk yield impacts of the above scenarios could be used to calculate economic benefits resulting from these mitigation initiatives across the four studied regions. These estimates could help stakeholders who must balance multiple criteria in designing climate change mitigation policies (Lin *et al. 2014*), including implementation costs, targeting of populations based on criteria such as breed of cattle owned or household poverty rates, and accounting for the potential co-benefits, risks or spill overs from implementation.

To the knowledge of the author, this is the first study relying on a bottom-up (e.g. LCA) model applied at sub-national scale that has explicitly evaluated the GHG mitigation potential from reduced land occupation in the dairy sector for any country in sub-Saharan Africa (SSA). Previously, Brandt *et al.* (2020) evaluated similar feed and crop yield scenarios in Kenya using a framework that included CO_2 emissions from cropland expansion as well as forest grazing. A key difference of the present analysis is that both *cropland* and *grassland* *expansion* are quantified using longitudinal simulations and the feeding and crop yield scenarios are evaluated in relation to this baseline. For this reason, this study finds that avoided emissions from *grassland expansion* are the predominant driver of emissions reductions. These emission reductions are more significant than the estimated reduction in CO_2 emissions from forest grazing by Brandt *et al*. (2020), which were found to decline by a relatively modest 0.06 kg CO_2eq kg^{-1} milk under the optimal feeding and maize yield scenarios.

Similar as the present study, top down, regional studies using the Global Biosphere Model (GLOBIOM) (Havlik *et al*. 2014) have routinely found that land sparing is a key mitigation strategy in the beef and dairy sectors. Gerssen-Gondelaach *et al.* (2017) calculated that LUC-related emissions across Latin America, South-East Asia, and Sub-Saharan Africa (SSA) occupy between 20 to over 50% of total GHG emissions from beef and dairy production systems. Also using GLOBIOM, Cohn *et al.* (2014) estimate that intensification within Brazil's pasture based beef production systems would reduce pasture area by 16-21 Mha, sparing 15-17 Mha of deforestation, for a 75-80% reduction in deforestation emissions. These authors conclude that LUC mitigation is the most important GHG mitigation strategy for cattle production in these regions, including SSA.

While land sparing brought about by efficiency gains is an important technical component of the mitigation potential, the extent of avoided LUC emissions could be influenced by the presence of and magnitude of a demand or supply rebound (Lambin and Meyfroidt 2011). Valin *et al.* (2013) projects that the demand elasticity for livestock products strongly influences the extent of emissions savings from avoided LUC throughout the SSA region to the year 2050. In the most severe cases (i.e. highly elastic demand) emissions savings from improved efficiency within ruminant production systems are nearly completely negated. In Tanzania, increasing domestic milk production is an important component of the national poverty alleviation strategy (Michael *et al.* 2018). Policy conditions favouring supply growth combined with increasing demand from a growing and increasingly affluent and urbanized population, or from favourable changes to trading conditions, could result in significant growth in production in coming years. This thus poses the risk that efficiency gains result in deforestation similar as the well documented cases in South America (Nepstad *et al.* 2017). We caution therefore that more work is needed to evaluate the potential for these outcomes. To consider this, studies conducting consequential LCA are warranted given that this methodology is better suited to evaluate the indirect environmental effects of 'system expansion', which extend to indirect land use change, import substitution and substitution between beef and milk production (Weidema and Schmidt 2010). Further, it is proposed that, similar to others (Creutzig *et al.* 2016) climate change mitigation research should consider measures to limit consumption growth in addition to technical supply side mitigation.

4.4.2 Prioritizing mitigation activities in the Tanzanian dairy sector

Since LUC emissions comprise a large portion of the C footprint, it logically follows that changes that lead to a reduced land footprint, such as by replacing low yielding native grasslands (<= 3 Mg ha^{-1} yr^{-1}) with Napier grass (>= 10 Mg ha^{-1} yr^{-1}) or through yield gains in feed crops, could result in avoided emissions from LUC. However, this study does not find strong evidence that feed intensification in itself contributes to land sparing. This is a result of the effect of increases in crop-based feeds (maize bran or sunflower cake) on land use (scenario *I-CnFoCo*), which lead to a larger land footprint. The dietary changes under this scenario bring the level of concentrate intake to levels comparable with intensive smallholder dairy farms. For example, Wilkes *et al.* (2020) report that dairy farms in Kenya typically use 1-2 kg cow^{-1} d^{-1} of concentrates. Thus, based on these results, we caution that adoption of improved feeding practices, insofar as these lead to greater demand for feed crops, have potential to exacerbate LUC emissions. However, the present analysis also shows that yield gains in feed crops can offset these additional LUC emissions. Crop yield gains have net negative effect on the overall carbon footprint because additional N_2O and CO_2 emissions from yield gains are low relative to avoided emissions from LUC. Although the present study only assumes a 50% yield gap reduction, it still estimates emissions savings that are 105% larger than those estimated by Brandt *et al*. (2020) (this study simulated crop yield gains of up to 80% of the water limited yield potential for maize). The higher estimated net GHG reductions of the yield gains herein are attributable to the inverse relationship with area of grassland under used for feeding, which in turn translates into reduced conversion of native ecosystems. It is therefore reasonable to expect that initiatives under the Tanzanian Grazing-land and Animal Feed Resources Act (URT 2010) to improve crop yields in the concentrate feed industry could offer significant mitigation co-benefits.

This study illustrates that the Traditional and Modern dairy sectors have vastly different land and carbon footprints. The emissions intensities in the Traditional sector are up to 4.5 times larger than in the Modern sector due to constrained milk productivity, reliance on unproductive grasslands, and the comparatively large herd overhead (larger proportion of unproductive cattle). This results in a significantly higher land footprint or 1.25 – 1.50 ha TLU^{-1} *versus* 0.60 – 0.70 ha TLU^{-1} for the Modern sector. The feeding strategies evaluated for local cows suggest that reducing seasonal feed deficits are essential in improving emissions efficiency of the Traditional dairy sector. Feeding high quality forages or concentrates will not result in improved productivity unless seasonal feed deficits are better managed because poor body condition caused by periodic feed deficits can have lasting effects on milk productivity and reproduction (Makau *et al.* 2019, Rufino *et al*. 2009). Of the scenarios evaluated above and the additional scenarios presented in SI 6, feeding additional concentrates during lactation is not found to be particularly effective if a feed conservation strategy is not first implemented. However, on aggregate, improving the diets of local cattle may not be more cost effective than improving diets of improved cattle as a result of relatively low feed conversion efficiency among *B. indicus* cattle breeds (Chagunda *et al.* 2009). Therefore, in order to realise the potential efficiency gains from improved feeding and feed crop productivity, GHG mitigation initiatives should also simultaneously improve uptake of improved cattle, which currently comprise less than 5% of Tanzania's dairy herd. Based on the results herein it is logical to expect improved breeds combined with yield gains in the feed crop sector will lead to productive synergies leading to a higher land footprint, high milk productivity, and lower emissions intensities. These will be key factors allowing Tanzania's dairy sector to participate in climate change mitigation initiatives while contributing to the national milk production target.

Feeding management in Tanzania's livestock master plan and GHG emission targets

The milk yield gains in our scenarios are as high as 51.4% and 60.1% for local and improved cows, respectively. These milk productivity gains were associated with up to 52.4% and 38.0% declines in emission intensities in the Traditional and Modern sectors, respectively. Using the baseline estimates of milk production from the above simulations, the estimated supply gap projected by the LMP of a factor of 71.0% of the national milk demand by 2030 could be reduced by up to 32.1%. Alternatively, if the milk supply gap were to be wholly eliminated, these changes in feeding practices would allow for a 33.3% reduction in the size of the dairy herd relative to a scenario involving baseline feeding practices. Such changes in feeding practice combined with the yield gap reductions simulated in this study would allow milk production targets to be met with up to 52.4 and 38.0% reductions in emissions intensities for the Traditional and Modern sectors, respectively.

4.4.3 Limitations and suggestions for future research

Data limitations and modelling uncertainty

Emission factors (EFs) in this study are based on the best available estimates from the literature and values ranged from Tier 1 to Tier 3 (IPCC 2006). An advantage of the approach taken here is that the EFs that have the largest impact on the dairy sector's GHG footprint (i.e. enteric fermentation and LUC) are calculated with Tier 2 and 3 factors. Central to the development of more accurate GHG accounting frameworks for crop and livestock production will be the availability of country specific EFs, such as those pertaining to emissions from manure management, and crop and grasslands. The same applies to datasets on livestock population densities, as well as data on feed ratios/intakes of livestock. The present study benefits from the most recent gridded livestock of the world dataset (Gilbert *et al.* 2018), which to the knowledge of the authors is the most accurate source of spatially explicit data on livestock population densities currently available. The diets specified herein are based on household survey data (GLS 2019) which is prone to erroneous farmer recall. Moreover, it is known that livestock diets vary highly across geographies and farm types. This introduces uncertainties in diet baselining. All these sources of uncertainty were nevertheless quantified in the present study through Monte Carlo simulations.

The LUC transition framework in this study is based on the assumption that cropland expansion converts grasslands, which may not always be the case. While this study does not consider management changes within a given land use category, the scenarios assessed were designed to reduce the requirement for grazing (e.g. by reducing the total grassland requirements), and therefore in principle should result in less demand for grazed biomass, and hence degradation of grasslands or native ecosystems. In this respect, the use of a dynamic livestock model is instrumental, because the change in roughage intake with changing dietary regimens is explicitly accounted for. The further development of methodologies for accounting for the impact of grazing practices on land degradation and LUC, and for validating these methodologies on the ground, will assist studies such as this with the development of region- or country-specific GHG emission estimates.

Suggestions for future work

The modelling framework has been made publicly available (see data availability) and thus other researchers working at the intersection of dairy production and climate change mitigation are free and encouraged to extend this analysis further. Extending the framework in this study using a consequential LCA would be warranted given the greater rigour and policy insights provided by this methodology over the attributional approach used here. Examining other mitigation strategies is also warranted, especially genetic gains, animal husbandry (health and reproductive practices) and land management (e.g. grazing practices) which have been not been included here. While mitigation strategies such as these have been evaluated by other authors (Mottet *et al.* 2015, Notenbaert *et al.* 2020) the land sparing impact of these strategies was not included and thus the GHG mitigation was potentially under-estimated. Thus future work to evaluate LUC emissions reductions from these same mitigation strategies would advance knowledge as to synergies between these practices and technologies, helping inform climate policy in the region.

4.5 Conclusion

This study assesses the GHG emission and national milk deficit reduction potential of improved feeding practices and feed crop yield gains in Tanzania's south/eastern regions. Changes in feeding practices involving feed conservation, the addition of high-quality forages to diets, and concentrate feeding, combined with crop yield improvements, have potential to reduce the dairy sector's land footprint that reduce GHG emissions intensities by up to 52.4% in the Traditional and 38.0% in the Modern sectors. These changes in practices can increase milk productivity by up to 60.1% and 51.4% for local and improved cows, respectively. While the feeding strategies evaluated in this study may potentially result in greater LUC emissions, a key finding is that fertilizer-induced yield gains in primary concentrate feed crops lead to net reductions in the C footprint of the dairy sector. These results therefore demonstrate the impacts of the potential feeding options and/or crop sector initiatives, which can be used alongside dairy genetic gains in order to meet the milk production and national GHG mitigation targets.

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Supplementary information 4

SI 4.1 Livestock simulations

LivSim is a dynamic model that simulates the performance of individual cattle in time according to their genetic potential and feeding (Rufino *et al*. 2009). Its development and applications have focused on assessing the impact of productivity improvement among dairy production systems in the tropics, which are characterised as having highly variable quality and availability of feed across seasons. The model has been validated and applied in studies ranging from farm scale to sector level, spanning both East and West Africa (De Ridder *et al*. 2015, Brandt *et al*. 2018). Inputs to the model include breed characteristics, feeding, and other animal husbandry practices which influence productivity and nutrient requirements (grazing practices, reproduction management).

In the present framework, the outputs of the model pertaining to feed intake from feed on offer, average annual milk yield over the production life of the cow, and urinary and faecal N excretion are used as the basis of the LCA and productivity evaluation (Figure S4.1). Based on the feed intake and N excretion, CH_4 and N_2O emissions from enteric fermentation and manure are estimated, thus providing the direct emissions from milk production used in the LCA (SI Section 2). The diet compositions as estimated from GLS (2019), taking into account the biomass yields of individual feed categories (Table 4.1), are used to derive the land footprint for the dairy sector, using equation 1 in methods. This land footprint is the basis for specifying feed on offer every month of the year, based on the feeding practices as specified below. The amount of land dedicated to crop and grasslands is then used for calculating land use change emissions as described in section 4.2.3.

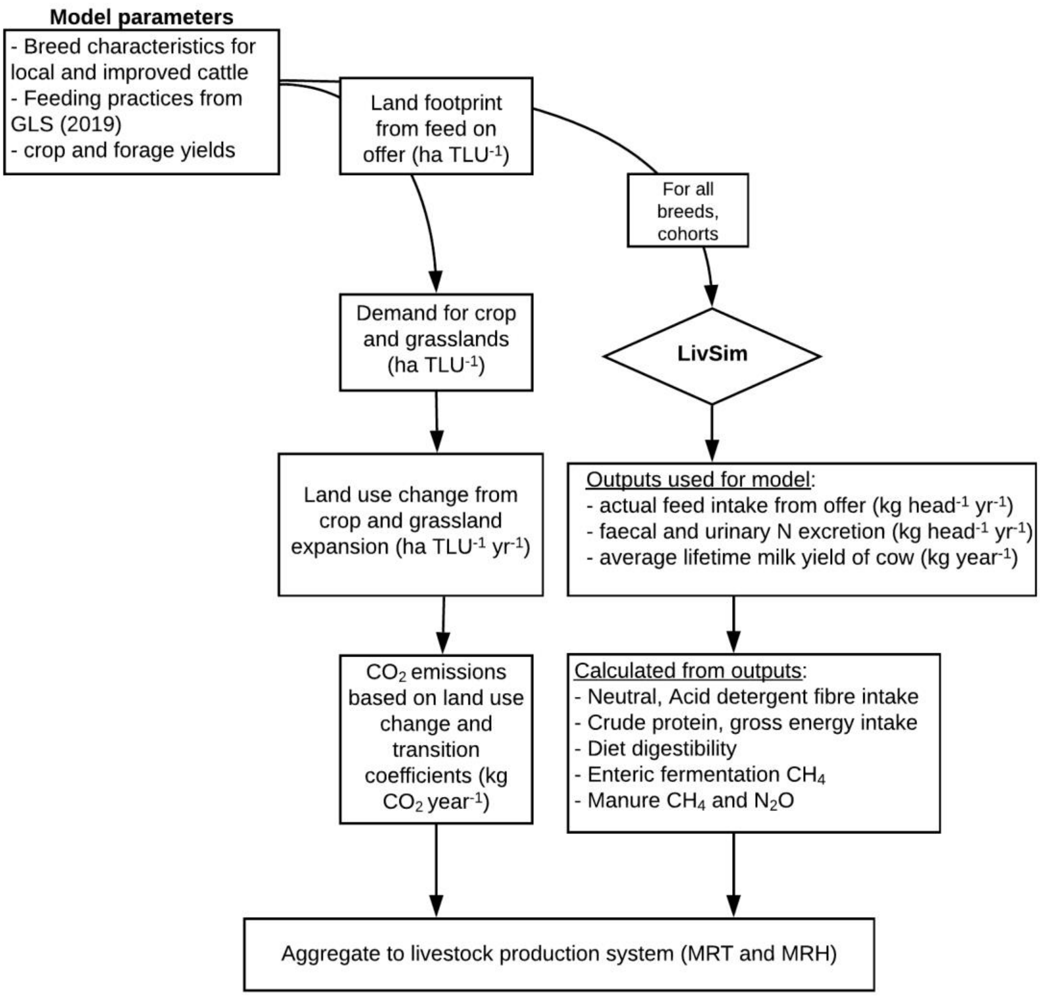

Figure S4.1: Schematic flowchart of the modelling framework, integrating *LivSim* with an accounting of the dairy land footprint, life cycle assessment of GHG emissions, and spatial aggregation to production system level (MRT and MRH)

Parameters obtained from a variety of sources in the literature are used to specify breed parameters representing local and improved cattle in Tanzania (Table S4.1). The activity allowances are set reflecting the amount of grazing time. All animals (both local and improved) are typically kept in corrals at night and grazed during the day. GLS (2019) indicates that improved cattle are typically grazed for less than 2 hours per day. Local cattle are typically grazed for 6 hours or more per day. The feed intake, milk production and excretion results are determined as an annual average calculated over a pre-defined age range for each cohort and breed. These ranges are (for each respective cohort): male and female calves, 0 months to 1 year; juvenile males, 1 to 3 years; heifers, 1 year until first calving; cows, from the beginning of the first calving onwards; and bulls, 3+ years.

The results of the breed and cohort simulations are aggregated to production systems based on the respective cattle populations for each system (MRT and MRH). The populations of cattle by breed and cohort are specified based on a spatially-explicit dataset of cattle population densities (e.g. head of cattle per sq. km.) (Gilbert *et al*. 2018). The ratio of 'dairy cattle', which includes the local and improved breeds described in the text, to the total population (per sq. km) reported by Gilbert *et al*. (2018) are equal to the total value minus the fraction of beef cattle and oxen, as determined from district census data (NBS 2016). The fraction of total dairy cattle categorized as local or improved is also based on district level census data (NBS 2016). The herd compositions for a given breed (i.e. the proportion of total animals in a given cohort: cows, heifers, calves, etc.) are derived from the survey (GLS 2019), as an average value for each LPS (Table S4.2, percentage of cattle for each LPS). This data is then mapped to spatially explicit datasets at 10x10 km resolution of MRT and MRH production systems and then up-scaled to estimate total cattle populations by breed and cohort at the production system level (Table S4.3). The spatial analysis and upscaling is performed in QGIS (QGIS Development Team, 2020)

Table S4.1: Breed parameters used in *LivSim*

Parameter	Local	Improved	Source
Maximum body weight female (kg head^{-1})	450	600	Mruttu *et al*. (2016) Kashoma *et al* (2011)
Maximum body weight male (kg head^{-1})	500	600	Mruttu *et al*. (2016) Kashoma *et al*. (2011)
Maximum milk yield (kg lactation^{-1} cow^{-1})	970	4450	Ojango *et al.* (2016) Galukande *et al*. (1962)
Daily milk yield at maximum (litres)	8	15	Gillah *et al.* (2014) Njau *et al.* (2013)
Lactation length (days)	210	300	Mruttu *et al.* (2016) Mwanbene *et al.* (2014)
Milk fat content (g kg^{-1})	55	41	Rege *et al*. (2001)
Milk crude protein content (g kg^{-1})	41	35	Rege *et al*. (2001)
Calf birth weight (kg)	30	32	Beffa (2005)
Minimum age at first gestation (months)	30	20	Meaker (1980) Mwanbene *et al.* (2014)
Pregnancy length (months)	9	9	Mruttu (2016) Mwanbene *et al.* (2014)
Dry period (months)	11	2	Mruttu (2016) Chenyambuga and Mseleko (2009)
Postpartum length (months)	12	3	Mruttu (2016) Chenyambuga and Mseleko (2009)
Maximum lifetime (years)	13	13	Rufino *et al.* (2009)

Table S4.2: Herd populations by production system

Breed/cohort	MRT	MRH
Local (heads)	603,808	458,307
Cows (%)	38.78	55.46
Heifers (%)	13.61	21.48

Female calves (%)	21.77	6.14
Bulls (%)	11.03	9.81
Juvenile males (%)	2.96	4.59
Male calves (%)	11.86	2.52
Improved (heads)	19,926	15,124
Cows (%)	49.41	45.38
Heifers (%)	11.79	15.99
Female calves (%)	20.01	18.99
Bulls (%)	6.34	7.80
Juvenile males (%)	2.01	3.38
Male calves (%)	10.23	8.46

Specifying feed on offer for LivSim

The method of specifying feed on offer per month for each livestock category involves two steps. First, the household survey is used with supplementary datasets of feeding in the southern highlands region of Tanzania to estimate the annualized feed intake of the feed categories (Table 4.1 in text) per year for each animal in the herd. This annualized value takes into account the deviation in feed intakes across dry and rainy seasons. Then the availability of these feeds for every animal across months (feed on offer for *LivSim*) are specified taking into account the major factors influencing seasonality of each feed category, as described below.

The survey questionnaire disaggregates feed categories into concentrates, by-products, crop residues, improved forages and low quality forages. The intake levels that are derived for each category are used as the basis for the baseline feeding practices in the model. 'Sunflower cake' is the feed representing the level of concentrates fed. 'Maize bran' is used as the feed representative of crop by-products. Maize stover represents crop residues, Napier represents improved forages, and 'Pasture' represents the variety of cultivated low quality forages. For grass consumed from grazing, the species are specified as a mixture of the dominant grass species in Tanzania, *Themeda spp.* and *Hyparrhenia spp.* (Mbwambo *et al.* 2016).

Deriving feed intake from the dairy household survey

GLS (2019) evaluates, based on the recollection of the survey respondent, the feed on offer from individual categories of feeds, obtained from on-farm and off-farm (market purchases) sources. In semi-intensive and extensive systems where cattle consume biomass while grazing, the biomass consumed from grazing is estimated and included as 'grazed feed intake', in addition to feed on offer from farm harvest and market purchases. This intake level is assumed to be at least as great as 2.5% of bodyweight. To estimate feed intake during the alternate season, parameters are derived from Wassena *et al*. (2013) to account for the differences in intake of feed categories between dry and rainy seasons. From these values, the total annual feed intake for the herd is then estimated based on the average intake over the dry and rainy seasons as follows:

$$\text{Annual feed intake}_i = 365 \text{ x } \frac{Daily\ dry\ season\ feed\ intake_i + Daily\ rainy\ season\ feed\ intake_i}{2} \quad \textit{(Eq. 4.2)}$$

Where Annual feed intake is the annual feed intake for a given feed category f (kg TLU^{-1} yr^{-1}), daily dry season feed intake (kg TLU^{-1} d^{-1}) is the daily intake level during the rainy season, and daily dry season feed intake (kg d^{-1}) is the daily feed intake during the dry season. The intake levels estimated from this equation are then aggregated across LPS based on the GPS coordinates of the households, to derive average annual feed intakes representative of MRT and MRH systems for the 6 feeds included in the model. The resulting values, which are the annualized feed on offer for the MRT and MRH systems in the model simulations, are shown in Table S5; the ranges includes the ranges between MRT and MRH systems.

Seasonal variation in feed supply

From the annual feed intake as described above, the monthly feed availability is then determined taking into account practices influencing seasonal availability of feed (Table S4.3). This framework takes into account the seasonality of feed production based on the monthly biomass availability from each feed category, accounting for grazing practices, harvest dates, and rationing practices. The seasonal variation in yield of forages are obtained from Silveira Pedreira *et al*. (2005). Crop stovers are available during the dry season, through either grazing on crop land or from harvested and rationed crops on farm (Mbwambo *et al.* 2016, GLS 2019). Concentrate feeds acquired off farm are the only feeds not affected by seasonality (i.e. they are available year-round). However, their feeding to cows is specified in *LivSim* in relation to the production stage of the animal (lactating, dry, gestating) as described in the scenarios section of the text. The quality parameters for each of the feed types for dry and rainy seasons are specified based on literature and FAO databases (Table S4.4).

Table S4.3: Conditions affecting seasonal availability of feeds

Feed type	Seasonality conditions
Grass	Can be harvested or grazed year-round.
Pasture	
Napier	Can be harvested or grazed year-round.
Maize stover	Available during dry season, by either grazing cattle on croplands (after harvest) or harvesting and providing to cattle *via* cut-and-carry.
Sunflower cake, maize bran	Available year round (purchased from the market). Can be feed to cows according to production cycle: early lactation (first 150 days), late lactation, gestation.

Table S4.4: Nutrient properties of feed types by season

	Dry matter ($g\ kg^{-1}$)		Dry matter digestibility (%)		Metabolisable energy ($MJ\ kg\ DM^{-1}$)		Crude protein ($g\ kg^{-1}$)		Acid detergent fibre ($g\ kg^{-1}$)		Neutral detergent fibre ($g\ kg^{-1}$)	
	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
Native grasslands [1,2]	850	155	41.5	55.3	5.8	7.7	59	78	477	450	767	738
Managed Pastures[1,3]	850	155	45.0	65.0	6.5	8.6	63	94	477	423	800	725
Napier grass[1]	893	179	53.7	61.4	6.2	8.2	97	103	419	425	711	715
Maize stover[1]	928	296	46.8	56.7	6.9	8.4	39	68	396	496	699	750
Maize stover urea molasses treated[1,4]	928	--	46.8	--	6.9	--	100	--	501	--	800	--
Maize bran[1]	887		72.4		11.0		119		145		442	
Sunf. cake[1]	890		61.1		9.1		324		320		450	

Sources :
[1] FAO (2020)
[2] Rubanza *et al.* (2006)
[3] Lukuyu *et al.* (2012)
[4] Abera *et al.* (2018)

Table S4.5: Range of values provided to *LivSim* as feed on offer across production systems (MRT and MRH) for baseline simulations.

Cohort	% of Dry matter						Annual feed on offer (kg DM head^{-1})
	Native grasses	Managed Pasture	Maize stover	Napier grass	Maize Bran	Sunflower cake	
	Local						
Cows	47-50	0-3	31-36	1-2	12-14	0-2	2811±562
Heifers	48-54	5-6	31-36	0-1	8-10	0	2555±511
Female calves	48-54	5-6	31-36	0-1	8-10	0	2190±438
Bulls	48-54	5-6	31-36	0-1	8-10	0	8500±1700
Juvenile males	48-54	5-6	31-36	0-1	8-10	0	8000±1600
Male calves	48-54	5-6	31-36	0-1	8-10	0	2190±438
	Improved						
Cows	6-7	19-21	12-17	32-35	10-12	8-13	3614±723
Heifers	16-17	24-25	12-17	32-35	10-11	0	3541±708
Female calves	16-17	24-25	12-17	32-35	10-11	0	2519±504
Bulls	16-17	24-25	12-17	32-35	10-11	0	3650±730
Juvenile males	16-17	24-25	12-17	32-35	10-11	0	3577±715
Male calves	16-17	24-25	12-17	32-35	10-11	0	2519±504

Notes: Standard errors reported for dry matter intake represent range of error used in uncertainty analysis

SI 4.2 Calculation of direct greenhouse gas emissions sources

Based on the feed intake from feed on offer as calculated from *LivSim*, emissions from enteric fermentation, manure, and managed soils are calculated according to the updated IPCC (2019) methodology (IPCC 2019), however for consistency this paper will still refer to IPCC (2006). The managed soils included in this assessment extend to the land categories included as part of the dairy land footprint as described in Table 4.1 of the text. All values are first calculated as an annual per livestock unit, expressed as CO_2 equivalents, and then aggregated to calculate GHG emissions for each production system, taking into account the number of cattle in each production system (as described above). Within the study region, the predominant manure management system is solid storage (Rufino *et al*. 2014) however there is significant variation in the percentage of manure that is managed versus excreted on pasture. In the present study manure emissions from CH_4 includes manure that is managed and excreted on pasture. Manure N_2O includes only managed manure, and N_2O emissions from manure applied or excreted on soils is included as N_2O emissions from crop and grassland soils, according to IPCC (2006) chapter on N_2O emissions from managed soils.

Methane from enteric fermentation is estimated as a percentage of gross energy intake per animal using the following equation from Jaurena *et al*. (2016):

$$Y_m = 3.5 + 0.243 \times DMI + 0.0059 \times ADF + 0.057 \times DMD \quad \textit{(Eq. 4.3)}$$

Where Y_m is the methane conversion factor (% of gross energy converted to CH_4), DMI is dry matter intake (kg head^{-1} day^{-1}), ADF is intake of acid detergent fibre (g kg^{-1} DM), and DMD is dry matter digestibility (g kg^{-1} DM). Manure CH_4 is estimated based on volatile solids, methane producing capacity (B_o), and the methane conversion factor (MCF) using IPCC (2006) equations 10.23 and 10.24. The methane producing capacity takes a value of 0.13 m^3 CH_4 kg VS^{-1}, which is the IPCC default value for the African continent (IPCC 2006). The MCF is calculated as a weighted average for each livestock production system and breed of cattle based on the default MCF values for solid storage and pasture (Table S4.5).

Manure N_2O is calculated as the sum of direct N_2O from nitrification and denitrification of manure nitrogen, and indirect N_2O from volatilization and leaching of N in storage. Nitrogen excretion quantified by *LivSim* is used to calculate direct and indirect N_2O emissions based on equations 10.25, 10.26 and 10.27 from IPCC (2006). Again, IPCC (2006) default emission factors for solid storage systems and excretion on pasture are used.

The fraction of manure N available for soil application is based on the fraction stored minus the amount lost from directly and indirectly through volatilization and leaching. This along with the manure N excreted on grasslands is then used as an N input into soils, which is then used in accordance with the IPCC (2006) framework for soil N_2O emissions, which includes N_2O emissions from manure, inorganic fertilizer and residue N (equations 11.1, 11.9, 11.10, and 11.11). For manure excreted on grasslands, a Tier 2 emission factor is used (taking a value of 0.00105) based on field experimental studies in the region (Pelster *et al*. 2016). Application rates of N fertilizer take values of 20 kg N ha^{-1} yr^{-1} for maize and sunflower, and 10 kg N ha^{-1} yr^{-1} for food crops, representing typically observed application rates for the southern highlands region of Tanzania (Hutton *et al*. 2017, IFDC 2012). It is assumed no fertilizer is applied on forage crops or grasslands. N from crop residues and forage/pasture renewal are calculated for each feed with values taken from table 11.2. For food crops the fraction removed was set at 0.5. Mass based allocation factors on N_2O emissions from cropland dedicated to stover and concentrate production in order to distinguish between the fraction consumed as feed and co-products. These allocation factors are based on the ratio of feed biomass to total biomass yield (Table 4.1 in main text). The resulting (baseline) N_2O emissions for the three cropland types and two forages (before allocation) are shown in Table 4.1 of the text. All the emission factors used in the study and their sources are shown in Table S4.5.

Emissions associated with the production of inputs produced upstream from the farm are included in the model as 'Energy use CO_2'. These sources extend to the emissions associated with processing and transporting concentrate feeds, and for manufacturing fertilizer. The predominant concentrate feeds used in the southern highlands, maize bran and sunflower cake, are grown and processed domestically (Mbwambo *et al*. 2016, FAO 2020). The emissions associated with transportation are based on an average travel distance from the point of feed processing to the farm of 200 km. The coefficients from fossil energy use are based on Kool *et al.* (2012). The energy requirements for feed processing take values of 186 MJ of electricity and 188 MJ of gas per 1,000 kg of feed DM. For this production energy requirement and an average travel distance of 200 km, an embodied feed emission factor of 0.0786 kg CO_2 eq kg compound $feed^{-1}$ is derived. CO_2 emissions from manufacturing and transport of fertilizers are based on the fertilizer use values listed per feed category as listed above, and using an embodied emission factor of 5.66 kg CO_2 kg N^{-1} (FAO 2016). The total value for 'Energy use CO_2' emissions are thus based on the sum of emissions from feed processing and transport and manufacturing of fertilizer.

Table S4.6: Emission factors used in attributional life cycle assessment of dairy sector

Emission factor	Value	Source
Y_m	Estimated as in Jaurena *et al.* (2016)	Jaurena *et al.* (2016)
[a] MCF	0.015 (pasture) 0.04 (solid storage)	IPCC (2006)
[a] EF_3 storage (direct manure N_2O)	0.005	IPCC (2006)
[a] EF_3 pasture (direct manure N_2O)	0.00105	Pelster *et al*. (2017)
[a] EF_4 (indirect manure N_2O)	0.01	IPCC (2006)
[a] EF_5 (indirect manure N_2O)	0.0075	IPCC (2006)
[a] Fraction N volatilized -- pasture	0.2	IPCC (2006)
[a] Fraction N leached – pasture	0.3	IPCC (2006)
[a] Fraction N volatilized – solid storage	0.3	IPCC (2006)
[a] Fraction N leached – solid storage	0.4	IPCC (2006)
EF_1 (soil N inputs)	0.0105 (inorganic N), 0.01 (organic N)	Hickman *et al*. (2015), IPCC (2006)
EF_5 (leaching and runoff)	0.0075	IPCC (2006)
Fraction gas volatilized (organic N)	0.1	IPCC (2006)
Fraction gas volatilized (synthetic N)	0.2	IPCC (2006)
Fraction lost manure management	0.4	[IPCC (2006)

[a] Specified in the model for each production system as a weighted average based on the fraction of manure excreted on pasture vs. managed, as estimated from GLS (2019)

SI 4.3 Spatial estimation of grasslands availability and utilization

The conversion of woody native ecosystems occurs in the model when the requirement for grasslands exceeds the availability of feed per spatial unit (100 km^2). The availability of grasslands and percentage utilized for grazing and cut and carry feeding are estimated based on the land cover data (Bruzonne *et al*. 2020), the cattle population densities (Gilbert *et al.* 2018), and the parameters specified to reflect productivity and efficiency of grazing/harvesting of grassland species included in the model. The feed categories described in the body of the paper, which are included in this framework, are all feed categories that are not included under the crop category for the Bruzonne *et al*. land cover data. This includes Napier grass, managed pasture, and native grasslands. The extent of grassland utilization is calculated with the following equation:

$$\text{Grassland utilization} = \frac{Cattle\ density \times Grass\ consumption\ \times Use\ efficiency}{Grassland\ yield} \quad \textit{(Eq.4.4)}$$

Where grassland utilization (km^2) is the extent of grasslands per spatial unit being utilized for ruminants, cattle density (head km^{-2}) is based on (Gilbert *et al.* 2018), grass consumption (Mg DM $head^{-1}$ yr^{-1}) is the grass consumption per animal as specified above, utilization efficiency is the fraction of grass available that is harvested or consumed by grazing cattle (Table 1 of text), and grassland yield is the yield of grassland (Mg DM ha^{-1} yr^{-1}) (Table 4.1 of main text).

In the final year of the model simulation period (2030) the grassland available for use by the dairy sector is equal to grassland area in the base year (2020) minus the expected expansion from non-dairy sector sources. These sources include cropland as an aggregate, and the grassland occupied for grazing by beef cattle. *Cropland expansion* is calculated based on the crop land area in the base year (Bruzonne *et al.*) and the annual growth rate as calculated from FAO (FAO 2020). The growth rate in land needed for beef cattle grass consumption is calculated based on the beef cattle population and the land requirement for their grass consumption, which is calculated from (Herrero *et al*. 2013).

SI 4.4 Modelling yield gains and nitrous oxide emissions from N-fertilizer

The results of the calculations used to simulate yield gains and N_2O emissions are reported here. These simulations only extend to maize and sunflower used for producing concentrate feeds (maize for producing bran and sunflower for producing cake), reasoning that commercial oriented producers would have adequate technical and managerial capacities to efficiently increase fertilizer use, while the majority of financial and labour constrained smallholder (dairy) producers have low technical capacity to adequately apply fertilizers (Tittonnel *et al*. 2005). Moreover, developing the commercial feed production and processing industries for maize and sunflower are part of the broader component for developing Tanzania's dairy industry (Michael *et al*. 2018).

The yields of maize and sunflower are revised from their regional average values of 1.46 (maize) and 1.03 (sunflower) Mg ha^{-1} yr^{-1} (FAO 2020) upwards by 50% of the yield gap, thus taking values of 3.71 and 2.03 Mg ha^{-1} yr^{-1}. The N-fertilizer application rates in the *baseline* yield scenario take values of 20 kg N ha^{-1} yr^{-1} and in the 50% yield gap scenario these are increased to 161.0 and 69.5 kg N ha^{-1} yr^{-1}. Under *Base* yield the N_2O fluxes for maize and sunflower (calculated based on IPCC methodology in SM 2) are estimated at 1.03 (maize) and 0.9 (sunflower) kg N_2O ha^{-1} yr^{-1}. In *50% yield gap* these values increase to 5.68 (maize) and 2.9 (sunflower) kg N_2O ha^{-1} yr^{-1}. Under *Base* the yield scaled N_2O emissions thus take values of (maize) 1.03 kg N_2O ha^{-1} yr^{-1} / 3.71 Mg ha^{-1} yr^{-1} = 0.28 kg N_2O Mg^{-1} and (sunflower) 0.9 kg N_2O ha^{-1} yr^{-1} / 1.03 Mg ha^{-1} yr^{-1} = 0.87 kg N_2O Mg^{-1}. In the *50% yield gap* scenario the yield scaled N_2O emissions take values of (maize) 5.67 kg N_2O ha^{-1} yr^{-1} / 3.71 Mg ha^{-1} yr^{-1} = 1.53 kg N_2O Mg^{-1} and (sunflower) 2.9 kg N_2O ha^{-1} yr^{-1} / 2.03 Mg ha^{-1} yr^{-1} = 1.43 kg N_2O Mg^{-1}. Thus, while greater N application rates up to 161.0 and 69.5 kg N ha^{-1} yr^{-1} for maize and sunflower, respectively, increase yields (and hence reduce the dairy land footprint), total N_2O emissions per hectare and per unit yield increase.

Si 4.5 Sources of uncertainty

Table S4.7: Sources of uncertainty

Variable used in model	Relative standard error
Grassland yields	+/- 20
Maize yield	+/- 20
Sunflower yield	+/- 20
Cattle populations	+/-20
Feed intake per tropical livestock unit	+/-25
Y_m	+/- 10
Bo	+/- 30
MCF	+/- 20
EF_1 (soil N inputs)	+/- 66
EF_3 storage (direct manure N_2O)	+/- 30
EF_3 pasture (direct manure N_2O)	+/- 7
EF_4 (indirect manure N_2O)	+/- 30
EF_5 (indirect manure N_2O)	+/- 30
Fraction N volatilized -- pasture	+/- 7
Fraction N leached -- pasture	+/- 7
Fraction N volatilized -- storage	+/- 7
Fraction N leached -- storage	+/- 7
EF_4 (atmospheric deposition)	+/- 30
EF_5 (leaching and runoff)	+/- 30

Fraction gas volatilized (organic N)	+/- 30
Fraction gas volatilized (synthetic N)	+/- 30
Fraction lost manure management	+/- 30
C stock density croplands	+/- 20
C stock density grasslands	+/- 20
C stock density native ecosystems	+/- 20
Embodied feed and fertilizer footprints	+/- 30

SI 4.6 Dry season milk yield and nutrient scarcity by feed scenario

Table S4.8: Yield and dry season nutrient deficits for cows across feeding scenarios

Scenario	Mixed rainfed tropical			Mixed rainfed humid		
	Local cows					
	Milk yield (kg hd^{-1} yr^{-1})	Metabolisable energy deficit (MJ d^{-1})	Metabolisable protein deficit (g d^{-1})	Milk yield (kg hd^{-1} yr^{-1})	Metabolisable energy deficit (MJ d^{-1})	Metabolisable protein deficit (g d^{-1})
Base	358	14	19	331	15	6
L-Cn	424	13	0	377	16	3
L-Fo	472	12	25	425	13	21
L-CnFo	507	11	0	466	9	2
L-Co	(infeasible; results in mortality due to undernutrition in non-lactating periods)					
L-FoCo	437	12	10	47	7	0
L-CnFoCo	528	13	0	501	12	2
	Improved cows					
Base	932	14	19	875	15	6
I-Cn	991	13	0	915	16	3
I-Fo	1207	9	7	1035	9	4
I-CnFo	1264	12	0	1059	9	2
I-Co	1049	7	0	12	32	0
I-FoCo	1458	6	3	1335	12	3
I-CnFoCo	1492	13	0	1355	12	2

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5 Livestock mitigation and national development targets: a feasibility study for Tanzania’s dairy sector

Abstract

Improving productivity of African livestock offers potential to exploit synergies between climate mitigation and improved food security. However, few countries have adopted firm mitigation targets for this sector. Here we assess whether mitigation can be integrated into the development programme outlined for Tanzania’s dairy – the ‘dairy roadmap’ – which aims to reduce import dependence and contribute to rural poverty alleviation through a larger, more efficient domestic dairy sector. Focusing on four districts with high productivity potential, we quantify the anticipated benefits from improving dairy genetics and feeding, key aspects of the roadmap, and their contributions to the national milk production target, mitigation of GHG emissions and income effects among rural dairy households. The analysis presented here demonstrates that the dairy production target can be met with absolute reductions in GHG emissions up to 14%, consistent with the 10 to 20% target of the Nationally Determined Contribution (NDC). Scenarios simulating partial production targets (70%) lead to reductions in emissions up to 30%. Reaching the same production target with historical trends in animal genetic proportions leads to small emissions reductions (< 5%), indicating that to increase production and to reduce absolute emissions improved dairy breeds must be adopted. All scenarios have positive aggregate welfare impacts, increasing mean dairy household income by between 20 and 26%. This study is the first to provide rigorous evidence to support climate mitigation initiatives congruent with national development objectives for the livestock sector in the sub-Saharan Africa region.

5.1 Introduction

The livestock sector contributes about a quarter of Africa's agricultural GDP (FAO 2021a) while also acting as an important source of income and nutrition for millions of rural households. In the East Africa region in particular, dairy is especially important, contributing between 20 to 50% of domestic agricultural GDP (Makoni *et al.* 2013). However, the dairy sector in the region is characterised by large productivity gaps relative to middle- and high-income countries (Herrero *et al.* 2013) and contributes a relatively large share of national greenhouse gas (GHG) budgets (WRI 2021). Improving productivity of the livestock sector has been identified as a strategy that may both benefit rural livelihoods, *via* income generation and higher food security, and also reduce GHG emissions intensities (emissions per unit product) (Herrero *et al.* 2016). Foresight analyses conducted at region and continental scales have found that potential exists for both improving food security and reducing GHG emissions through adoption of well-known mitigation strategies (Hasegawa *et al.* 2018, Valin *et al*. 2013). However, enactment of climate policy, through quantitative mitigation targets stipulated in NDCs (Nationally Determined Contributions), must occur at the national level. Few analyses at present exist to inform whether and how climate mitigation within the African livestock sector can be designed to match national circumstances. Partly because of this, few countries have adopted firm climate commitment targets.

Tanzania, located in central East Africa, has the second largest ruminant herd in East Africa after Ethiopia (FAO 2021b), and the third largest in Africa. The country has an inefficient dairy processing industry (Katijuonga *et al.* 2014), significant imports of processed dairy products, and is highly dependent on imports relative to its largest East African peers (URT 2016a, FAO 2021c). Through the 2016 'dairy roadmap' (the 'roadmap') (Michael *et al.* 2018), the government seeks to reduce import dependence as part of its national development agenda focusing on poverty alleviation and economic development (URT 2016b). A key roadmap objective is to promote uptake of crossbred (*Bos indicus* x *Bos taurus*) or 'improved' cattle, and better feeding and husbandry practices among rural dairy households. As the roadmap's overarching strategy is to deliver economic growth *via* enhanced productivity, it could result in 'co-benefits' for climate by reducing GHG emissions intensities (Herrero *et al*. 2013, Gerber *et al*. 2011). However, it is unclear that the objective of increasing milk production can be accomplished with reductions in absolute GHG emissions consistent with the 10 to 20% target of the country's NDC (URT 2017a).

Genomic selection is increasingly recognized as an important strategy for improving environmental performance of African livestock (Marshal *et al.* 2019). The crossbreeding of indigenous ('local') cows with high yielding *B. taurus* cattle breeds may result in substantial milk yield gains while preserving adaptive traits such as resistance to disease and heat stress associated with a warming climate (Chagunda *et al.* 2016, De Haas *et al.* 2016). As a result of higher feed conversion efficiency, improved breeds produce between 20% to 65% less methane per kg milk, varying based on animal husbandry and feeding practices (Marshal *et al.* 2019, Chagunda *et al*. 2009). Through the Tanzanian Livestock Sector Analysis (TLSA) (URT 2017a), the government has stipulated target adoption levels for improved breeds they hope to be achieved in high priority districts in south and coastal regions. It is reasonable to expect that achieving such targets, resulting in a transition to a herd with significantly more improved cattle genetics, would be instrumental in enabling the country's milk production target to be met with GHG emission reductions consistent with the NDC. The action plan however can be expected to result in tradeoffs for rural livelihoods associated with the costs of adopting improved breeds and of alternative pathways towards meeting the breed adoption targets. Better understanding these tradeoffs and potential synergies with GHG emissions reductions can help better align national development priorities with climate mitigation for Tanzania's livestock sector.

Scenarios assess alternative outcomes for districts that differ in their breed percentages (% of improved to cattle) and targets for improved breed adoption among dairy households (adoption rate) defined by the TLSA (URT 2017b) (Table 5.1). The scenarios therefore disentangle the role of breed targets in contributing to climate mitigation for a given level of production (*Status quo vs. Inclusive, Inequitable*), and of the rate of improved breed adoption on income among dairy producing households (*Inclusive vs. Inequitable*). Changes to breed ownership, herd sizes and feeding practices may affect dairy households in a number of ways. This includes the amount of milk produced (leading to changes in nutrition or income) of changes in capital expenditure to acquire improved cattle and expend more on inputs, or of costs associated with growing more forages on farm. The roadmap scenarios could thus impact nutrition status of dairy households *via* changes to food self sufficiency, income from marketed farm products, or both. This study therefore adopts an income indicator that captures farm production expressed in monetary values as well as cash sources of income (farm and off farm). This approach, following that of Rufino *et al.* (2013), allows considering the welfare impacts of the roadmap scenarios across dairy households, rearing both local and improved cattle. Scenarios are conducted over the 12-

year period between 2018 and 2030, allowing the base year (2018) to be calibrated with a survey conducted in the same year, and for the scenarios to align with the roadmap initiative and the NDC reference period, which are both for the year 2030 (Michael *et al.* 2018, URT 2017a).

The two objectives of the study are:

(1) to quantify the potential for improved breeds and feeding to contribute to absolute GHG emissions reductions consistent with the production target,

(2) to quantify the direct impacts of the roadmap objectives on incomes for dairy producers throughout the study area.

Table 5.1: Description of five scenarios assessed in this study: Baseline, Status quo, Inequitable, Inclusive, and Middle road. Parameters and assumptions in model simulations are included. Targets are based on the Tanzania Livestock Sector Analysis and dairy roadmap. These include the percentage improved breeds in each district, the percentage of dairy households adopting improved breeds, and total milk production in each district.

<table>
<tr><th rowspan="3">Scenarios</th><th colspan="3">Dairy breeds</th><th rowspan="3">Milk production[a]</th></tr>
<tr><th rowspan="2">% improved per district</th><th colspan="2">Household adoption</th></tr>
<tr><th>% adopting[b,c]</th><th>Mean herd size (head)</th></tr>
<tr><td>*Baseline*</td><td colspan="4">Historically extrapolated</td></tr>
<tr><td>*Status quo*</td><td>Same as *Baseline*</td><td rowspan="2">20% Mufindi
15% Mvomero
20% Njombe
20% Rungwe</td><td rowspan="2">3-6 Mufindi
2-5 Mvomero
3-4 Njombe
3-5 Rungwe</td><td rowspan="3">*Baseline* x 2.10</td></tr>
<tr><td>*Inequitable*</td><td rowspan="3">60% Mufindi
27% Mvomero
60% Njombe
85% Rungwe</td></tr>
<tr><td>*Inclusive*</td><td>60% Mufindi
45% Mvomero
60% Njombe
60% Rungwe</td><td>6 Mufindi
11 Mvomero
4 Njombe
4 Rungwe</td></tr>
<tr><td>*Middle road*</td><td>40% Mufindi
30% Mvomero
40% Njombe
40% Rungwe</td><td>8 Mufindi
11 Mvomero
4 Njombe
5 Rungwe</td><td>*Baseline* x 2.57</td></tr>
</table>

[a] Based on 2030 national target of 2.57 x 'Business as usual' by the dairy roadmap (Michael *et al*. 2018)
[b] Defined in reference to the targets of the TLSA which involve up to 60% and 45% of households in highlands and coastal regions respectively.
[c] By newly adopting households

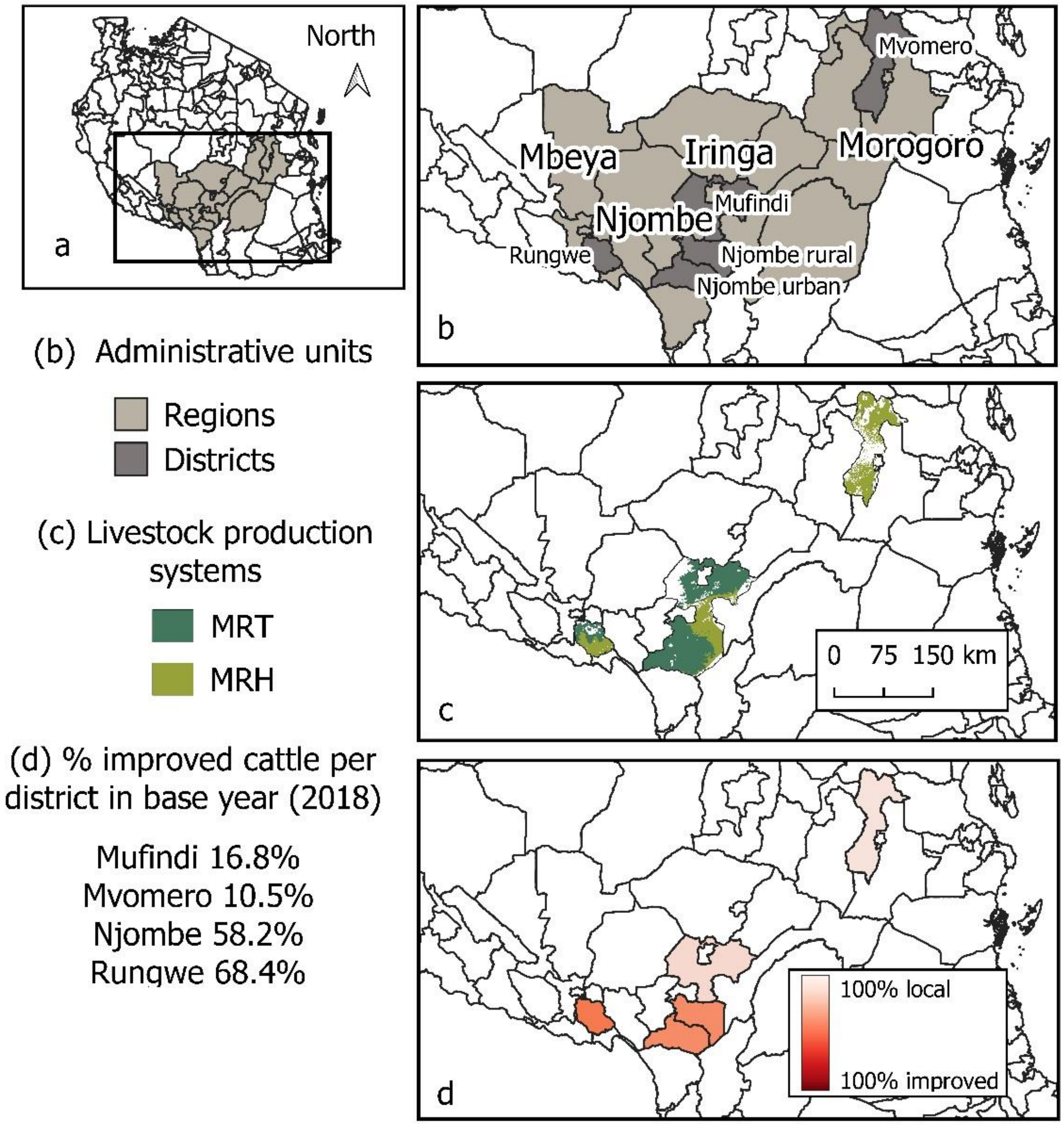

Figure 5.1: Spatial overview of study region. Panels show administrative units (a) livestock production systems simulated (b) and dairy herd breed composition for base year (2018) as % improved cattle. Base year herd genetic compositions are based on the greening livestock survey (GLS 2019). Figure is developed in QGIS (QGIS Development Team 2021).

5.2 Methods

5.2.1 Milk production in South and coastal Tanzania

The study simulates mid to high agroecological potential production systems across four districts in south and coastal Tanzania (Fig. 5.1a,b). These include mixed rainfed tropical (MRT) and humid (MRH) systems, following Robinson *et al.* (2011). The spatial extent of these production systems covers 11,700 km^2 MRT and 8,200 km^2 MRH for a total simulated area of 19,900 km^2. Within the four districts between 20 to 35% of rural households own cattle (URT 2017b). Smallholder farm households are the predominant dairy producers in the study area, which typically own herds of up to 10 heads of cattle. However, especially in the more extensive districts of Mvomero and Mufindi, agropastoral households are also common typically owning herds of up to 30 heads of local cattle. Milk produced is primarily consumed on farm, with only about 10% being sold, primarily in informal supply chains (URT 2016a). Cattle subsist on diets of grazed biomass, cultivated forages, concentrates purchased on the market, and crop residues provided after the crop harvest (Mbwambo *et al.* 2016). As a result of the unimodal rainfall pattern, resulting in a six-month dry season (May to October), feed quality and quantity is highly seasonal. To reduce feed deficits in the dry season, farmers commonly feed crop stovers, supplement with concentrates acquired from the market, and in rare instances practice silage or hay making with forages produced during the rainy season (Mbwambo *et al.* 2016).

Dairy farm diversity

To characterise dairy farms, this study uses data from a household survey conducted in the first half of 2018, as part of IFAD's 'Greening livestock' project. The 'Greening livestock' survey (GLS 2019), previously described by Kihoro *et al.* (2021) and chapter 3, is a survey of 1,199 dairy producers, based on stratified random sampling within mid to high potential systems across the four districts. Most households in the dataset own at least one of either local or improved cattle, less than 10% of the sample own both. Households are therefore stratified into two strata to provide inputs for the model: stratum 1, households rearing local cows only, and stratum 2, households rearing one or more improved cows. Only 16% of stratum 2 households own local cows. Therefore, to reduce complexity this study does not account for revenue and expense streams associated with local cattle for stratum 2 households. Using GPS coordinates of the households, data from the two strata provide geo-referenced model inputs for cattle diets, parameters in income accounting, and in the interpolation of the number of dairy households throughout the four districts (further details below).

5.2.1 Modelling methodology

The study adopts an integrated framework linking spatially explicit simulation modelling at production system (Robinson *et al*.) level with an income accounting module of dairy producers based on the household survey (GLS 2019). This method linking landscape level processes with survey data mimics loosely the frameworks described by Reed *et al.* (2020) and employed by Salecker *et al*. (2019). The production system level model is based on livestock simulation modelling using the *Livestock Simulator* (hereafter *LivSim*) (Rufino *et al*. 2009). *LivSim* simulates feeding and milk production for respective cattle populations (local and improved) for eight units representing each district -- production system pair (4 districts x 2 production systems). In each simulation unit the *Baseline* cattle populations are projected through the 12-year period based on historical growth rates. Under the roadmap scenarios cattle populations are calibrated to meet the 2030 milk production and breed targets (see section 5.2.3). Land use change and GHG emissions for each scenario are quantified using the land footprint indicator and life cycle assessment (LCA) adopted from chapter 4 (Hawkins *et al*. 2021).

In a second step the populations of respective cattle breeds are allocated to dairy producing households under alternative scenarios of improved breed adoption. The base year (2018) quantity of dairy households in each district rearing local and improved cattle are interpolated *via* data triangulation (see 5.2.2 model calibration). Under *Baseline* households maintain the same cattle breeds throughout the entire period. The roadmap scenarios involve breed adoption among dairy households up to the adoption targets provided by the TLSA (URT 2017b). Herd sizes at household level re-defined for each scenario are used to calculate dairy income, net of costs associated with adopting improved cattle, better feeding and more intensive use of inputs associated with each scenario (Section 5.2.5). Income sources other than from production of milk are treated exogenous, and total household income is then calculated and divided by the average household size (# of people) to calculate income per capita. The simulation modelling at production system level is conducted in Python (PSW 2021), running *LivSim* (also coded in Python), drawing auxiliary data from excel and conducting the LCA. The outputs of this stage are then used as inputs for the income accounting module which is run in Excel (Microsoft Corporation 2020).

5.2.2 Dairy cow simulations

LivSim is used to simulate individual cattle representing different cohorts over their lifetime for each simulation unit. Six dairy cattle cohorts are simulated: cows, bulls, juvenile males, heifers, male and female calves. Simulation outputs for the six cohorts are then aggregated to the production system level. Milk production and GHG emissions (described further in section 5.2.4) are then aggregated across populations of local and improved cattle and simulation units and reported as a total over all simulation units. Table S5.1 summarizes breed coefficients used in *LivSim*. Literature sources for breed coefficients are based on *B. indicus* (local) and *B.indicus* x *B. taurus* crosses (improved) within southern Tanzania and the East Africa region more broadly (Kashoma *et al*. 2011, Galukande *et al.* 1982, Gillah *et al.* 2014, Njau *et al.* 2013, Mwambene *et al.* 2014, Rege *et al*. 2001, Beffa *et al*. 2005, Meaker *et al.* 1980, Chenyambuga and Mseleko et al. 2009). Nutrient properties of feeds used in the simulations, for both the dry and rainy season, are derived from FAO's 'Feedipedia' database (FAO 2021d) and additional literature sources representative of the region (Lukuyu *et al.* 2012, Rubanza *et al*. 2006). These values are summarized in Table S5.7.

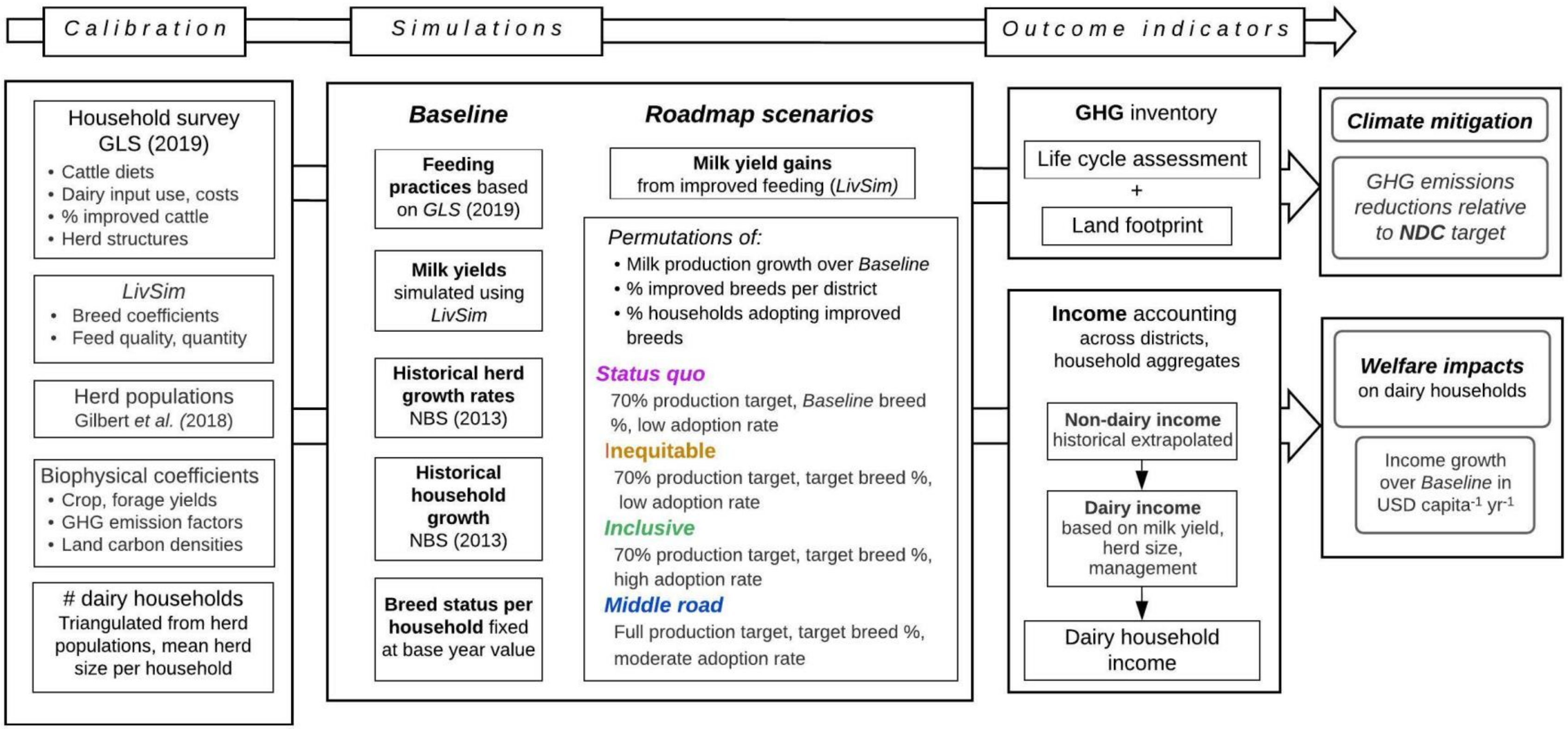

Figure 5.2: Outline of model workflow simulating GHG emissions and income among dairy households across four districts. Calibration involves specifying parameters from the household survey, for local and improved cattle in *LivSim*, herd population and biophysical data for life cycle assessment (LCA), and the estimated quantity of dairy households per district. Simulations represent respectively a *Baseline* ('Business as usual') and four scenarios involving permutations of key roadmap objectives. Impact indicators include dairy GHG emissions quantified using the LCA and land footprint indicator, and household income among dairy households based on the milk yield, herd sizes, and input use associated with each scenario.

Dairy land footprint

The dairy land footprint indicator used in this study is based on chapter 4 (Hawkins *et al.* 2021). The land footprint links sources of feed biomass to land use based on the yields and use efficiencies of individual feed sources (Hawkins *et al.* 2021). As the scenarios involve changes to cattle populations and diets, this results in changes to the demand for cropland and grasslands. This change in land demand then results in land use transition pathways which are used to account for CO_2 emissions as part of the LCA (see section 5.2.4 land use accounting).

The land footprint takes into account each major category of biomass from which cattle derive feed. Maize bran and sunflower cake, the two predominant dairy supplements in south/coastal Tanzania (Mbwambo *et al.* 2016), form the concentrate component of diets. Forage sources include native grasses, managed pasture, and Napier grass (*Pennisetum purpureum*), the latter being the prevalent high-quality forage used by dairy households in the region (GLS 2019). Maize stover is considered as the source of crop residues. These feeds are sourced domestically (Mbwambo *et al*. 2016, FAO 2020a) and thus biomass yields, processing ratios (the fraction of compound feed derived per unit grain or oilseed), and feed use efficiencies are based on local and regionally representative data as reported in Table S5.2. Yields of feed crops throughout the simulation period are extrapolated consistent with historical growth rates; 3.4% for maize and 4.1% for sunflower (FAO 2021e).

Model calibration

Populations of cattle for each simulation unit in the base year are based on the gridcell dataset of Gilbert *et al.* (2018), extrapolated from the census year (2012) to the initial year of the simulation based on district level historical herd growth rates (results are shown in Fig. S5.1a). The ratio of dairy to total cattle is equal to the total number of cattle minus beef cattle and oxen, determined from district census data (NBS 2016). The ratio of each cohort as a fraction of the respective herd (local and improved), are derived from GLS (2019), summarized in Table S5.3. The percentage of improved to total cattle in the base year are specified at district level based on the numbers of livestock in each district from the sampled households, with the results for each district shown in Figure 5.1d. This population and herd structure data are then mapped to spatial datasets of MRT and MRH production systems (shown in Fig. S5.1b) and aggregated, resulting in the base year cattle populations by cohort for each of local and improved herds for every simulation unit.

Household census data in Tanzania does not distinguish between households rearing dairy cattle from other households. To overcome this data gap, the base year quantity of households rearing each cattle breed are triangulated from the cattle population (Gilbert *et al.* 2018) and survey data (GLS 2019). Specifically, the number of households rearing local and improved cattle are estimated based on the respective herd populations (local and improved) and mean herd size per household strata, as follows:

$$Dairy\ households_{d,s} = \frac{Cattle\ population_{d,s}}{Mean\ cattle\ reared\ per\ household_{d,s}} \quad \text{(Eq. 5.1)}$$

Where dairy households$_{d,s,}$ is the number of households rearing dairy cattle (local or improved) for a given district and stratum, cattle population$_{d,s}$ is the population of dairy cattle for a given district and stratum, mean cattle reared per household is the average number of dairy cattle reared per household in a given district and stratum, and *d* and *s* relate to the four districts and two household strata respectively. The cattle populations for stratum 1 and 2 represent respectively local and improved cattle and therefore this equation relates populations of local and improved cattle to household types of stratum 1 and 2 respectively.

5.2.3 Roadmap scenarios

In the *Baseline* simulation populations of cattle are specified to grow at rates consistent with the average annualized growth rates across the four districts calculated from regional census data (NBS 2013) for the 2003 to 2008 period. These values are 3.2% and 4.3% for local and improved cattle, respectively. The growth in the number of households rearing cattle is consistent with the historical growth rates in rural livestock rearing households based on census data, which are calculated as an average of 6.4% for the four districts (NBS 2013). The diets used in the *Baseline* simulations are specified based on survey data for stratum 1 and 2 households respectively. Additional information on how these diets are specified is provided in SI 5.1, and the results are listed in Table S5.4.

Increased Production. Under the roadmap scenarios, herd sizes are re-calibrated based on the higher milk yields associated with improved feeding and breed adoption outcomes consistent with each scenario. The re-calibrated herd sizes for each simulation unit result in a value of milk production of respectively 2.10 and 2.57 times higher than *Baseline*. These values represent respectively 70% and 100% of the national target of 2.57 times 'Business as usual'.

The number of dairy cattle required to meet the production target with milk yields and breed proportions (% improved cattle) specified under each scenario is determined by multiplying the herd size under *Baseline* by a scaling factor, as follows:

$$H_{d,l} = T_{d,l} \times \frac{\sum_s Cows_{b,l} \times Frac\_s\_b_{s,l} \times Yield_{b,s,l}}{\sum_s Cows_{b,l} \times Frac\_s\_r_{s,l} \times Yield_{r,s,l}} \qquad \text{(Eq. 5.2)}$$

Where H is a herd scaling factor, based on the proportional increase in cow population needed to meet the production target with the breed compositions and milk yields of a given scenario, T is the proportional increase in milk production over *Baseline*, Cows is the population in either the *Baseline* or roadmap scenarios, Frac_s are the fractions of local or improved cattle in the *Baseline* ('_b') or roadmap scenarios ('_r') respectively, and $Yield_{b,d,s,l}$ are the milk yields in kg FPCM cow^{-1} yr^{-1} under the base ('b') and roadmap ('r') scenarios for either local or improved cattle in a given simulation unit. The set l in equation (1) represents the two production systems (MRT and MRH).

Table 5.2: Milk yield and cattle population by type (local and improved), district and production system for for five simulated scenarios: *Baseline, Status quo, Inequitable, Inclusive* and *Middle road*. Milk production is simulated with *LivSim*. Production increases are set to 70% of the target for all scenarios expect for middle road. Herd populations and feeding are the same for the *Inequitable* and *Inclusive* scenarios, which differ only in adoption rates across households.

Scenarios	Breed type	*Mufindi*		*Mvomero*		*Njombe*		*Rungwe*	
		MRT	MRH	MRT	MRH	MRT	MRH	MRT	MRH
		Milk yield (kg FPCM cow^{-1} yr^{-1})							
Baseline	Local	306.8	278.2	231.5	306.5	600.7	386.4	446.0	351.0
	Improved	1567.7	1003.6	1113.4	1003.6	1289.7	1000.2	1445.2	1376.6
	Cattle numbers (10^{3} head)								
	Local	1212.7	123.9	42.7	912.9	239.7	28.9	228.0	116.8
	Improved	277.0	28.3	5.7	121.8	378.7	45.7	559.3	286.5
All roadmap scenarios	Milk yield (kg FPCM cow^{-1} yr^{-1})								
	Local	603.1	634.8	611.8	588.5	673.7	683.2	559.0	499.0
	Improved	3375.7	2984.1	3405.8	2943.9	3151.4	2945.9	2823.1	2982.1
	Cattle numbers (10^{3} head)								
Status quo	Local	2803.3	237.9	68.2	1703.1	464.8	44.3	599.4	283.4
	Improved	640.4	54.3	9.1	227.3	734.3	70.0	1470.2	695.2
Inclusive & Inequitable	Local	640.9	56.0	44.2	1129.9	182.6	17.4	664.0	315.5
	Improved	961.3	84.1	16.4	417.9	1035.0	98.7	995.9	473.2
Middle road	Local	784.7	68.6	54.2	1383.4	596.3	56.9	304.9	144.9
	Improved	1177.1	102.9	20.0	511.7	894.5	85.3	1727.5	820.8

Under the roadmap scenarios, the ratio of improved cows to total cow population are set equal to targets defined under the TLSA. These take values of 60% for the highlands districts and 27% for the coastal district of Mvomero (URT 2017b, Table 44 p.108). In Rungwe the base year % of improved cattle of 68.4% is above the TLSA target, therefore a target of 85% is set. Improving feeding practices is an essential component of the dairy roadmap, in order to reach the potential milk yields of both local and improved cattle (Michael *et al.* 2018). Livestock simulations under the roadmap scenarios are based on recommended practices to reduce seasonal feed deficits and optimize lifetime milk production per cow (Maleko *et al.* 2018), following the supplementation strategies by modelling and empirical literature (Bwire and Wiktorson *et al.* 2003, Rufino *et al.* 2009). Practices involve ensilaging Napier grass for dry season feeding, greater availability of forages year-round, and concentrate supplementation. Feeding of forages and concentrates are set at higher levels for improved cows to meet their higher milk yield potential. Diets are summarized in Table S5.4 and Table 5.2 summarizes the herd populations and milk yields for each simulation unit.

Improved cattle adoption rates. The 70% production target is simulated under three scenarios involving respectively historical consistent changes in the ratio of improved to total cattle (*Status quo*) and then full realization (*Inequitable, Inclusive, Middle road*) of the breed targets for each district (Table 5.1). The percentage of dairy households adopting improved cattle (the 'adoption rate') are assumed to occur up to the values listed by the TLSA: 60% for the highland districts and 45% for the coastal district (URT 2017B p. 144 Table 4). Scenario *Inclusive* is consistent with the TLSA adoption rate, thereby representing the objective of the roadmap which seeks to promote inclusive adoption of improved breeds (Michael *et al*. 2018). The others are set at respectively one half this adoption rate (*Status quo* and *Inequitable*) and mid-way between the highest and lowest values (*Middle road*). The TLSA makes no reference to the number of improved breeds adopted by newly adopting (*Adopting*) households. The herd sizes for *Adopting* households are set to range from 2 – 6 under *Inequitable* and *Status quo* and 4 – 11 under *Inclusive* and *Middle road* (Table 5.1). As a result of these herd sizes at household level, scenarios *Inequitable* and *Inclusive* involve both a lesser number of households adopting improved cattle and a lesser number adopted by new households. Scenario *Inclusive*, while equivalent to *Status quo* in breed percentages at district level, involve a greater number of households adopting and a greater number of improved cattle adopted. Finally *Middle road* involves 'middle road' assumptions on the rate of adoption of improved breeds and the number of households adopting, set mid-way between *Inclusive* and *Inequitable*.

5.2.4 Life cycle assessment of milk production

The methods and procedures used in the LCA are described in full detail in SI 5.2. Direct emissions from cattle and feed production are based on IPCC equations. The fossil energy carbon dioxide emissions associated with feed and N fertilizer inputs are calculated based on the amount of maize bran and sunflower cake consumed by the dairy herd in each simulation unit. N fertilizer application rates are set at 20 kg N ha^{-1} yr^{-1} for maize and sunflower for concentrate, and 10 kg N ha^{-1} yr^{-1} for food crops, which are consistent with typically observed N fertilizer application rates for the south and coastal regions of Tanzania (Hutton *et al.* 2017, IFDC 2012). Results for soil N_2O fluxes per land use type are summarized in Table S2. Emissions are allocated to FPCM (fat and protein corrected milk) and meat using mass allocation (i.e. according to the total production of FPCM and meat expressed in kg). *LivSim* calculated milk production is converted to FPCM by standardizing to 3.3% fat and 4.0% protein (IDF 2010). Meat production from the dairy herd is estimated as carcass weight of culled adult females, male calves, and juvenile males, as determined from liveweight estimates from *LivSim* and using a dressing percentage of 52% (Mruttu *et al.* 2016).

Land use accounting

LUC as part of changes to the dairy land footprint are divided into two transition pathways: *cropland expansion,* in which croplands replace grasslands, and *grassland expansion*, in which grasslands replace native ecosystems. The CO_2 emissions resulting from each pathway are based on carbon stock differences between respective land uses, as calculated from spatially explicit land cover and carbon density data, described in SI 5.2 and reported in Table S5.2. The direct emissions from LUC transitions as part of the dairy carbon footprint include *cropland expansion* and *grassland expansion*. The actual amount of grassland converted from native ecosystems is calculated by relating the area required for each simulation unit, and relating this to spatially explicit availability of grasslands (Bruzonne *et al*. 2021), described further in SI 5.3.

5.2.5 Income accounting

Income at household level is calculated using mean characteristics for three household aggregates (hereafter 'types'). These types are defined as: *traditional,* stratum 1 households that do not adopt improved cattle and continue to rear local cattle throughout the simulation period; *adopters*, stratum 1 households that adopt improved cattle in the base year; and *modern*, stratum 2 households that rear improved cattle throughout the entire simulation period. Income for each household type is computed as the sum of income from dairy plus all other household income, minus the cost of capital expenditure and opportunity cost of substituting land dedicated to food or cash crops to meet increased Napier production on farm. Description of how non-dairy household income and net crop margins are calculated is provided in SI 5.4 and the results are summarized in Table 5.3. The projected non-dairy income is calculated based on the product of average household size (# of people) (Table 5.3) and the projected income growth per capita throughout the 12-year simulation period, using the national average per capita GDP growth rate between 2014-2019 of 3.2% (World Bank 2021a). Income for each household type is reported as the average value over the 12-year period, calculated as (first year income + final year income)×(0.5). Per capita income is determined by dividing by the number of people per household. Results are then reported as averages for each of *traditional*, *adopters*, and *modern,* as averages over all households per district, and finally as the average across all four districts.

Table 5.3: Household characteristics by stratum across districts. Non-dairy income includes all farm and off farm income sources other than from production of milk. Crop margin represents an aggregate indicator of the average returns from food and cash crop production. ± denotes standard deviation.

District (sample size)	Strata	% sample	Herd size (head)	Household size (people)	Non-dairy income (10^3 USD yr^{-1})	Mean net crop margin (USD ha^{-1} yr^{-1})
Mufindi (n=145)	1	84.8	15.0 ± 10.9	6.2 ± 2.2	3.1 ± 2.4	214.3 ± 155.1
	2	15.2	3.0 ± 2.6	6.0 ± 2.0	3.1 ± 2.4	366.8 ± 173.5
Mvomero (n=134)	1	80.6	37.3 ± 58.7	7.8 ± 5.4	5.0 ± 5.6	214.3 ± 123.6
	2	19.4	3.9 ± 3.8	5.5 ± 1.5	4.0 ± 3.3	366.8 ± 170.8
Njombe (n=301)	1	14.6	8.7 ± 3.7	5.8 ± 2.1	4.1 ± 3.2	199.0 ± 141.5
	2	85.4	3.1 ± 3.3	5.1 ± 1.8	4.1 ± 3.2	167.0 ± 152.3
Rungwe (n=260)	1	23.5	5.2 ± 3.9	5.8 ± 2.1	1.7 ± 2.1	332.4 ± 154.1
	2	76.5	2.8 ± 2.1	5.7 ± 2.2	2.1 ± 1.7	444.1 ± 174.3

Source: Greening livestock survey (GLS 2019).

Income from dairy is calculated with mean number of cattle per household type for each district and stratum for each simulation unit and simulated milk yields per cow (Table 5.2). Income for each district is calculated using weighted average milk yields of MRT and MRH systems per district, based on the relative production between the two systems (Table 5.2). Milk income is calculated as the market value of annual milk production per household, net of costs related to acquiring improved animals (for *adopters*) and variable costs of feeding and animal husbandry. Adoption of improved cattle is assumed to occur by purchasing improved heifers. Discounted cash value of production from the dairy enterprise is estimated using a net present value (NPV) formula that accounts for one-time costs of improved heifers (for *adopters*), and annual feed and animal husbandry expenses:

$$NPV_{d,s} = \sum_{y=1}^{10} \frac{Milk\ value_{d,s} - cash\ expenses_{d,s}}{(1+i)^{\ y}} - Heifers_{d,s} \quad \text{(Eq. 5.3)}$$

Where NPV is the annual cash value of production at the dairy enterprise level in USD yr^{-1}, Milk value is the annual monetary value of milk production from all cows in the herd in USD yr^{-1}, cash expenses are the variable cash expenses for the herd in USD yr^{-1}, i is the discount rate, and Heifers is the cost of acquiring new improved heifers in USD for *adopters*. The discount rate is set at 0.17 reflecting the national average interest rate of 17% (World Bank 2021b). The discount period used in the NPV equation is set at 5 years. The result of equation 2 is then converted to annual dairy income by dividing by 5.

For *adopters*, parameters in the NPV equation are based on stratum 2 households, thus accounting for changes in input use intensity associated with rearing local *versus* improved cattle. 'Milk value' is thus based on the number (head) of cows in the herd multiplied by milk yield per cow (Table 5.2), multiplied by the farm gate milk price in USD litre^{-1}. Milk yields (Table 5.2) are converted to litres using a factor of 0.97 litres kg^{-1}. Table S5.11 summarizes the farm gate milk prices and other variable input expense parameters used in equation 3, obtained from the survey (GLS 2019). The change in variable costs associated with growing more Napier grass is based on a sowing rate of 10 kg seeds ha^{-1} and a local price of seeds equal to 28 USD kg^{-1} (Nkombe *et al*. 2016; Ngunga and Mwendia 2020). Opportunity cost of growing more Napier grass is calculated as the mean net crop margin estimated for each district (Table 5.3) and stratum multiplied by land required to grow additional Napier grass for each scenario. Land dedicated to Napier grass per household type in the base year is based on base year herd sizes (Table 5.3) per household and level of Napier feeding (Table S5.3). The change in Napier grass demand per household is then used to calculate the increase or decrease in cropland area for each scenario using a regionally representative yield of Napier grass of 13.0 Mg ha^{-1} yr^{-1} (Maleko *et al*. 2019).

Monetary values reported in the survey in local currency (Tanzanian shillings, Tsh) are converted to USD based on the average exchange rate for the first half of 2018 (2,263 TSh USD^{-1}). Prices used in income accounting are set equal to the average of the base and final model year prices. Prices in 2030 are estimated based on the national average inflation rate of 4.1% (FAO 2021f). The base year market price of acquiring an improved heifer is based on reported values from survey respondents. These take values of: Mufindi, 1,082.7 ± 968.4; Mvomero, 254.1 ± 78.1; Njombe 540.1 ± 133.8; Rungwe, 397.7 ± 200.0 USD head^{-1} (GLS 2019). The initial year market prices of sunflower cake and maize bran are 0.25 and 0.21 USD kg^{-1} respectively, based on the sample of feed processors conducted for south and coastal regions of Tanzania by Kilimo Trust (2017).

5.2.6 Uncertainty

Uncertainty in GHG emissions and household income are quantified using Monte Carlo uncertainty analysis. Variability of individual GHG emission sources are based either on IPCC defaults or by taking into account uncertainty in emission factors used (Table S5.6). Under the *Baseline,* uncertainty included emission factors, feed on offer per head, biomass yields, and cattle populations. In each subsequent simulation, for which cattle populations and feed intakes were specified in relation to *Baseline*, only emission factor and biomass yield uncertainty are accounted for.

Income uncertainty

Hierarchical uncertainty quantification is applied to account for uncertainty in parameters used to calculate absolute and percentage growth in income for the three household types, and for all dairy households at district and region level. This includes uncertainty in total household income dairy and non-dairy sources, and in the number of households per district. Uncertainty in income calculations per household type is based on the standard deviations of the parameters in the NPV equation, as derived from the survey (Table S5.7). Uncertainty in parameters not derived from the survey included: crop margin uncertainty based on standard deviations reported in Table 5.3, changes in forage land allocation per household based on the relative standard error of 7.5% of Napier grass yields reported by Maleko *et al.* (2019), and the standard deviations of prices for improved heifers (see section 5.2.5). Uncertainty in non-dairy household income is estimated jointly based on the standard deviation of household sizes and of the growth in income per capita per household member. Both are based on the values derived from the survey as shown in Table 5.3. Uncertainty in household income and aggregate population level income is based jointly on uncertainty in income per household type, and uncertainty in the number of each household type within the population. The standard error of the proportion of household types within the population is specified as $\sqrt{p\,(1-p)\,/n}$, where p is the sampled proportion of a given household for either stratum 1 or 2 in one of the four household samples (Table 5.3), and n is the sample size for a given district as reported in Table 5.3.

5.3 Results

5.3.1 Milk and GHG emissions across roadmap scenarios

Milk yield under the roadmap scenarios increases by between 12.2 and 128.0% for local cows and 86.3 and 184.5% for improved cows across districts (Table 5.1). Under the 70% production target scenarios total herd size increase by 119.2% for *Status quo*, and by 54.8% for *Inclusive* and *Inequitable* across all districts. Under *Middle road,* herd size increase by 89.5%. The *Baseline* GHG emission intensity (Fig. 5.3a) is estimated to be 9.7 ± 1.7 kg CO_2eq kg^{-1} FPCM (± 95% confidence interval). Of this total value, which includes carbon dioxide emissions from land use change, 37.1% ± 6.4 are non-LUC emissions from enteric fermentation, manure, agricultural soils, and fossil energy use. The other 62.9% ± 10.9 are CO_2 emissions from crop and grassland expansion. GHG emissions and emissions intensities, excluding LUC and disaggregated by local and improved cattle are provided in Figure S5.3. Land use and feed intake variables are presented in Figure S5.2.

Validation of GHG emissions intensities (excluding land use change emissions) for local and improved cattle can be done by comparing the results with those of FAO's GLEAM (Global Livestock Environmental Assessment Model) (FAO New Zealand 2019). For improved cattle, emissions intensities estimated here as 2.0 kg CO_2 eq^{-1} kg FPCM are consistent with those estimated by FAO, which ranged from 1.9 to 2.2. For local cattle, emissions intensities estimated here as 8.3 kg CO_2eq kg^{-1} FPCM are lower than the national average estimates by FAO of 20.3 to 28.8. The FAO values for local cattle were higher as a result of the high percentage contribution of cattle raised in arid and pastoral production systems in their nationally representative figures. The lower productivity of dairy production within these systems leads overall to a lower nationally representative productivity level and higher GHG footprint. GHG emissions from land use change (62.9% of the total GHG footprint) correspond well with estimates by the global biosphere model (GLOBIOM). Using GLOBIOM Gerssen-Gondelach *et al.* (2017) estimate land use change to contribute 48 to 62% of total GHG emissions from dairy production systems in the sub-Saharan Africa region throughout the 2009 to 2017 period.

The *Status quo* scenario results in a reduction in emissions intensity by 54.2% ± 9.2 to 4.6 ± 0.9 kg CO_2 eq kg^{-1} FPCM. Scenarios *Inequitable*, *Inclusive*, and *Middle road,* with the same district breed compositions and feeding practices, result in reductions in emission intensity of 66.4% ± 6.7 to 3.4 ± 0.7 kg CO_2 eq kg^{-1} FPCM. With the exception of *Status quo*, all scenarios simulated result in reductions in absolute emissions on a par with or surpassing the NDC target range of 10 to 20% reduction from the *Baseline* (Figure 5.3c). *Status quo* results in reductions in absolute emissions by 3.6% ± 19.3 from *Baseline*, 6.4% higher than the minimum NDC target of 10% reduction from *Baseline*. *Inequitable* and *Inclusive* result in absolute emissions reductions by 29.6% ± 13.4, surpassing the low end of the NDC target range by 9.6%. *Middle road* results in absolute emissions reductions by 13.8 ± 17.1%, surpassing the low end of the NDC target range by 3.8%.

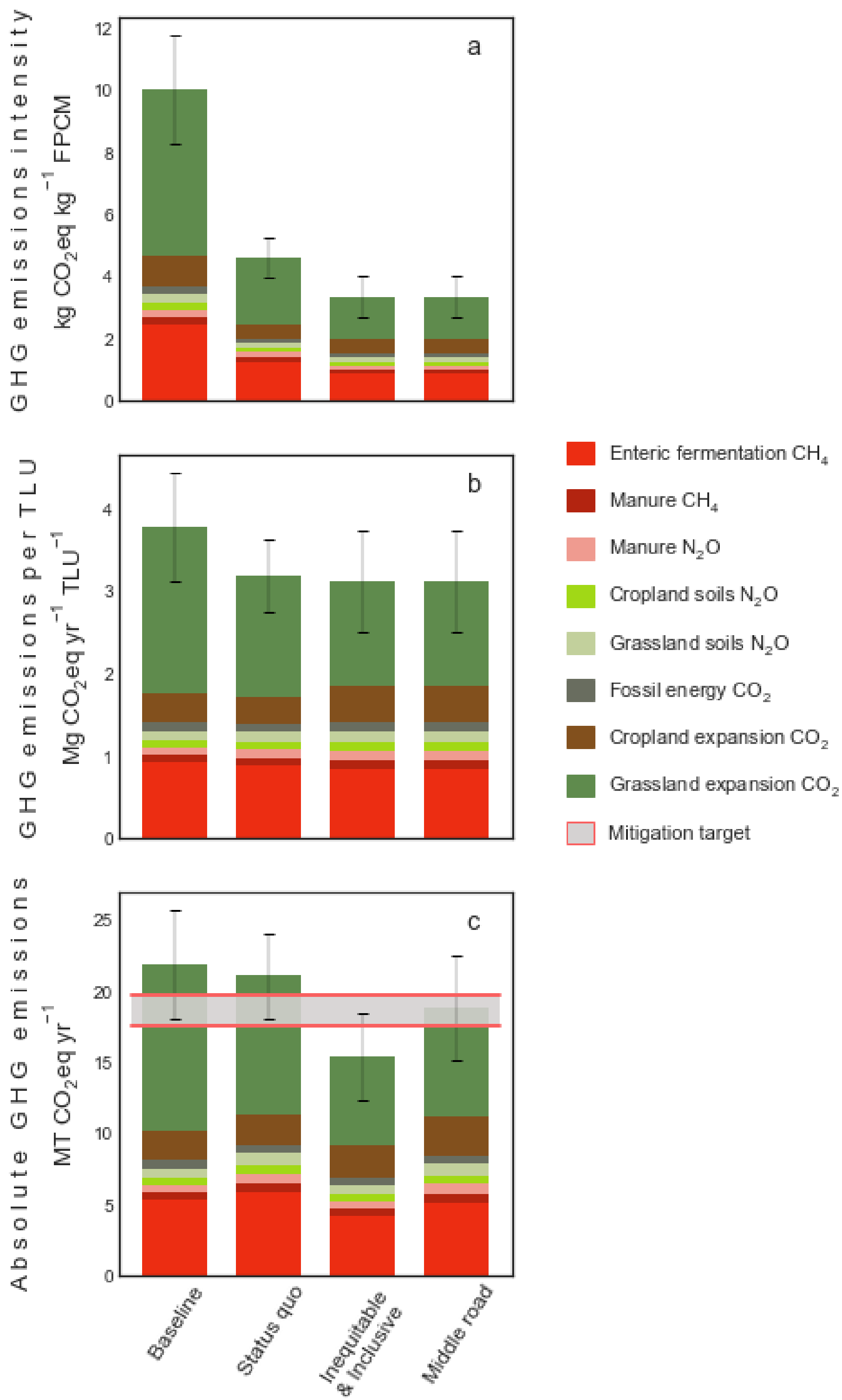

Figure 5.3: Greenhouse gas emissions. Error bars indicate 95% confidence interval. Grey shaded area on panel c indicates 10-20% mitigation target range of NDC

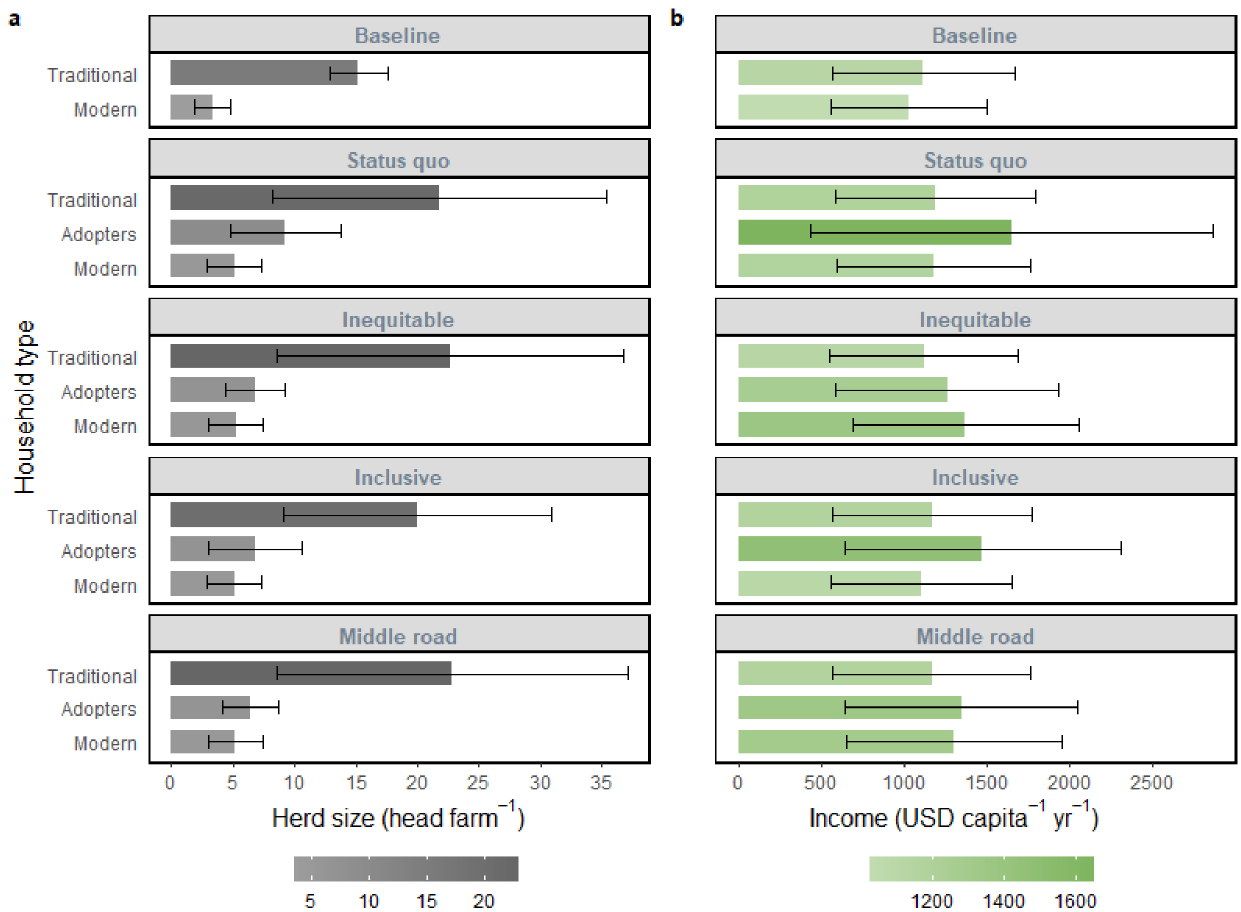

Figure 5.4: Mean herd size (a) and annual income per capita (b) across household types for each scenario. Household types defined as: 'Traditional' – households rearing local cattle that do not adopt improved cattle, 'Adopters' – households rearing local cattle that adopt improved cattle in the base year, and 'Modern' -- households already owning improved in the base year onwards. Scenarios include *Baseline* ('Business as usual'), *Status quo*, involving 70% of the production target with *Baseline* breed proportions, *Inclusive* and *Inequitable*, with 70% of the production target and the TLSA target breed proportions but different adoption scenarios, and *Middle road*, 100% of the production target and TLSA breed target and moderate adoption rates among dairy households. Error bars indicate one standard error

5.3.2 Welfare effects of scenarios

Income growth across dairy households

Mean herd sizes under *Baseline* for *Traditional* (local cattle rearing) households range from as low as 5 (Rungwe) to as high as 35 head (Mvomero) (Figure 5.4). For *Modern* (improved cattle) households herd sizes under *Baseline* range from 3 (Rungwe) to 6 (Mvomero) head. Relative to *Baseline,* herd sizes increase for *Traditional* by between 4 to 8 head per household across scenarios and by about 2 head for *Modern* for each of the roadmap scenarios. For *Adopters* (households adopting improved cattle in the base year) herd sizes decrease by between 6 and 8 head across scenarios. However, under the roadmap scenarios these households adopt improved in place of local cattle, and the higher income from dairy thus increases household income by between 144 to 535 USD capita^{-1} yr^{-1} across scenarios. Under the roadmap scenarios, *Traditional* households (not adopting improved cattle) experience declines in income by up to 13% from *Baseline* in the district of Rungwe. In Njombe, Mvomero, and Mufindi the declines are more modest (up to a maximum of 9%) and in some scenarios (*Inclusive, Status quo, Middle road*) increase by up to 13% (Mvomero). As the average for all *Traditional* households income growth is lowest under *Inequitable* where the change is negligible, and under the other scenarios increases by 55 (*Inclusive*), 72 (*Status quo*) and 53 (*Middle road*) USD capita^{-1} yr^{-1}.

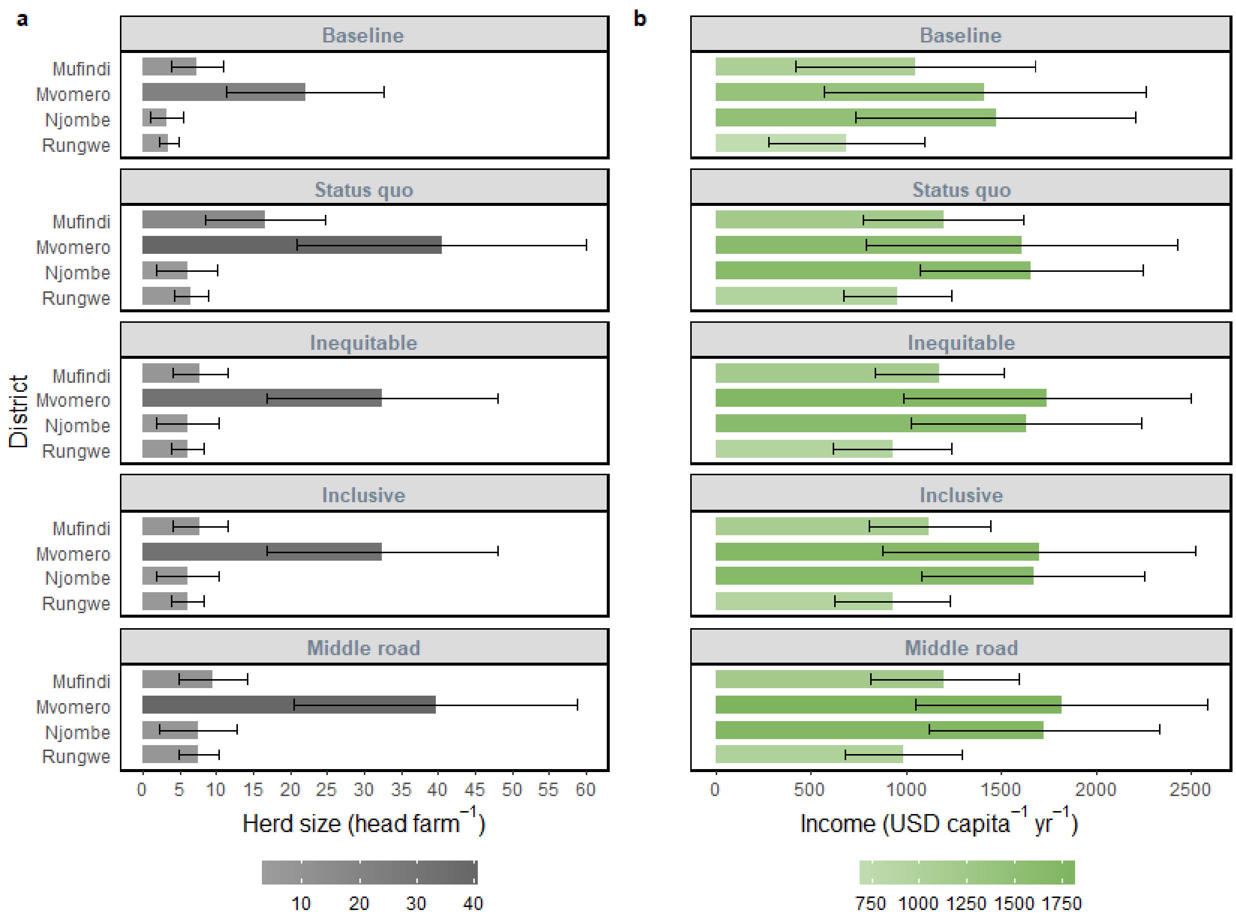

Figure 5.5: Mean herd size (a) and annual income per capita (b) for dairy households across districts for each scenario. Scenarios include *Baseline* ('Business as usual'), *Status quo*, involving 70% of the production target with *Baseline* breed proportions, *Inclusive* and *Inequitable*, with 70% of the production target and the TLSA target breed proportions but different adoption scenarios, and *Middle road*, 100% of the production target and TLSA breed target and moderate adoption rates among dairy households. The districts of Mufindi, Njombe, and Rungwe are located in the southern highlands and Mvomero is located in coastal region. Error bars indicate one standard error.

Income growth across districts

All roadmap scenarios have positive effects on average dairy household income (*Traditional, Adopters, and Modern*) across districts relative to *Baseline* (Figure 5.5). For the 70% production target scenarios, income grows by between 70 (Mufindi) to 400 (Mvomero) USD capita^{-1} yr^{-1}, a growth rate in per capita income of between 7 and 31% across districts. Under *Middle road*, income increases by between 149 and 483 USD capita^{-1} yr^{-1}, for increases in percentage terms of between 14 and 36% across districts. Growth in income under all roadmap scenarios is relatively high in Mvomero and Rungwe where under *Middle road* it grows by an average of 403 USD capita yr^{-1} (+28%) in Mvomero and 300 USD capita yr $^{-1}$ (+44%) in Rungwe. In Njombe and Mvomero it is significantly lower, growing only by 253 capita yr $^{-1}$ (+17%) in Njombe and and 149 capita yr^{-1} (+14%) in Mvomero. In both Mvomero and Mufindi the adoption rates for improved cattle are higher, and in Mvomero this translates to among the largest growth in income among districts. This is because of the difference in returns between breeds. Local cows have returns per unit milk between 0.20 – 0.30 USD litre^{-1} compared to improved cattle, which have returns up to as much as .35 USD (excluding the opportunity costs of forage production, for full results of income calculations see NPV sheets of 'interpolation' excel sheets provided through data availability statement). In the district of Mvomero, where there is substantial growth in improved breeds by 16.5% of the total herd, this results in significant income growth among *Adopters.* In Mufindi the growth in improved breeds was even higher, by 43.2%. However income growth among *Adopters* in Mufindi is offset by a relatively high cost of acquiring improved breeds, based on the market price for heifers obtained from the survey of 1,082.7 USD (GLS 2019). This high price implied *Adopters* experienced in every scenario a decline in household income ranging between 3 and 10%. The percentage growth in improved cattle in Rungwe of 16.6 is comparable as Mvomero. However in Rungwe the price per heifer is the least among all districts, 397.7 USD, therefore *Adopters* experience among the largest increases in income. In Njombe while the heifer price is reasonable (540.6 USD), the growth in % of improved cattle is only 1.8 relative to *Baseline*. Therefore income grows only between 11 and 17%.

Region wide impacts of roadmap scenarios

Relative to *Baseline*, the roadmap scenarios lead to mean increases in the quantity of cattle per household by 4 head (+81%) for *Status quo*, 2 (+36%) head for *Inequitable* and *Inclusive*, and 3 head (+66%) for *Middle road* (Fig 5.6a). These changes in dairy herd sizes increase mean household income for dairy producers by 217 USD capita^{-1} yr^{-1} (+22%) for *Status quo*, 203 USD capita^{-1} yr^{-1} (+21%) for *Inequitable*, 195 USD capita^{-1} yr^{-1} (+20%) for *Inclusive*, and 261 USD capita^{-1} yr^{-1} (+26%) for *Middle road* (Fig. 5.5b and Fig. 5.6). The net effect of the larger herd sizes and better feeding practices under the roadmap scenarios therefore is to increase average dairy household income by between 20 and 26%, and reduce total dairy GHG emissions throughout the study region by between 4 and 30% (Fig. 5.7).

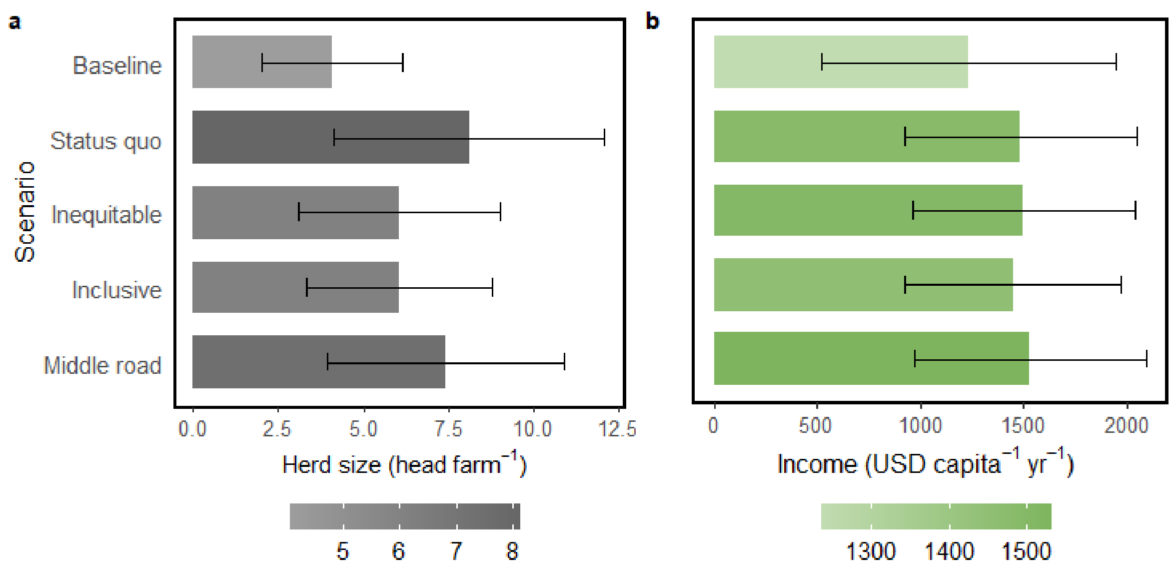

Figure 5.6: Mean change in herd size per farm (a) and annual income per capita (b) for all districts and for each scenario Scenarios include *Baseline* ('Business as usual'), *Status quo*, involving 70% of the production target with *Baseline* breed proportions, *Inclusive* and *Inequitable*, with 70% of the production target and the TLSA target breed proportions but different adoption scenarios, and *Middle road*, 100% of the production target and TLSA breed target and moderate adoption rates among dairy households. Error bars indicate one standard error.

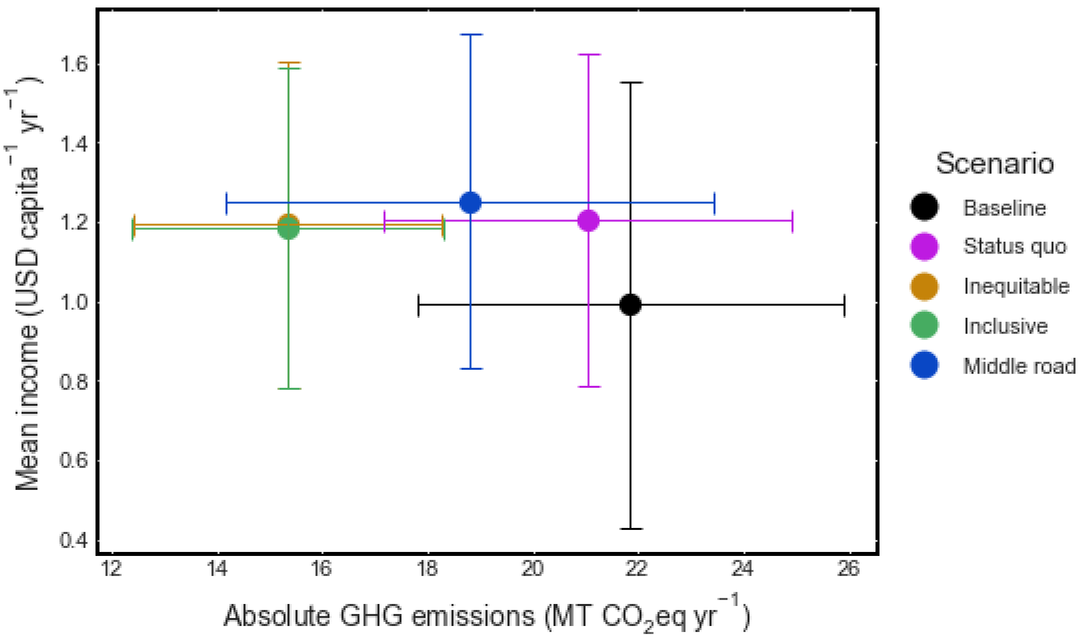

Figure 5.7: Trade-offs plots between income per capita among dairy producing households and greenhouse gas emissions, across a *Baseline* and four roadmap scenarios. Error bars for GHG emissions denote 95% confidence interval and for income indicate one standard error.

5.4 Discussion

The study assesses the potential whereby the modernization of Tanzania's dairy could be realised consistent with both climate mitigation and poverty reductions for rural producers. By explicitly assessing the role of improved breeds as an enabler of improved productivity, this study presents the 'transformative' potential which breed improvements demonstrate in delivering climate mitigation and national development objectives in the livestock sector. Scenarios considered here would improve aggregate dairy household income by 70 to 483 USD capita^{-1} yr^{-1} across the four districts (Figure 5.5b), increasing income by as much as 50% across dairy households and districts (Figure 5.6b). The four roadmap scenarios lead to growth in income for dairy households by 20 to 26% on average (Fig. 5.6b and 5.7), however large uncertainty in income accounting implies these results are not statistically robust.

Among scenarios, those that involved the breed targets proposed by the Tanzania's Livestock Sector Analysis -- *Inclusive*, *Inequitable*, and *Middle road* – would result in absolute reductions in GHGs 14 to 30% relative to the *Baseline*. Uncertainty analysis suggests a high likelihood that scenarios *Inclusive* and *Inequitable* would result in emissions reductions consistent with the mitigation target, with less than a 1% probability emissions surpass this 10% value. Under *Middle road*, the probability emissions surpass the 10% mitigation target are 36%. Therefore in summary, the results suggest a reasonable likelihood that improved breeds, feeding, and animal husbandry could lead to production increases consistent with the national target with GHG reductions consistent with Tanzania's NDC.

This evidence of mitigation potential on a par with Tanzania's NDC target differs from previous studies evaluating feeding and feed crop yield interventions (Brandt *et al.* 2018, 2020 and Hawkins *et al.* 2020) which found negligible absolute emissions reductions. The production growth represented by *Status quo*, following unambitious historically consistent genetic gains, would fail to deliver on GHG mitigation in the range targeted by the NDC, suggesting that realising mitigation targets and the roadmap priorities will depend crucially on the adoption of improved breeds. This study therefore provides the first national level evidence of potential synergies between dairy development to deliver both rural poverty alleviation and climate mitigation. These results are particularly relevant for other countries with herds predominantly comprised of indigenous (*B. indicus*) cattle breeds. While genetic gains have been studied previously in Tanzania by Notenbaert *et al.*, that study overlooked the risks associated with land use change on GHG emissions quantification, which are key components for mitigation (Gerssen-Gondelaach *et al.* 2017, Herrero *et al*. 2016).

Breed improvements: farm and sector dynamics

In this assessment, adopting improved cattle involves two costs for farm-households: (i) the capital costs from acquiring a heifer and of expending more on its maintenance, and (ii) the opportunity cost of diverting land from crop production to grow forages required for feeding improved breeds. For the 5-year horizon over which this investment decision is modelled, these costs are offset by the value (monetary or otherwise) of higher milk production. Households that adopt improved cattle are thus better off on average (Fig. 5.5b). The scenarios evaluated here, by design, involve significant changes in the proportion of local and improved cattle in district herd compositions. *Traditional* households not adopting improved cattle would experience in some cases declines in household income, as a result of a smaller herd (and therefore lower income from milk) (Fig. 5.5b). This finding draws attention to the inherent tradeoff that would arise in meeting breed targets. In particular, rural households depending on local cattle in subsistence production systems could undergo declines in income if the rate of adoption of improved cattle does is not sufficient enough to offset the nutrition and income derived from local cattle. However, households which have herd reductions 'imposed' under this framework (since household herd sizes correspond with sector herd compositions) may in reality opt to continue rearing local cattle, in subsistence-oriented, and therefore high GHG footprint production systems. Farming and agropastoral households, especially those which are resource poor and have poor market access, may be unwilling to adopt improved breeds in the absence of an adequate 'enabling' policy environment and secure market access. Therefore, in order for Tanzania's dairy roadmap to achieve realistic development outcomes, policy initiatives should focus on reducing obstacles farmers may face in adopting improved cattle. In this regard, Kenya's dairy NAMA (Nationally Appropriate Mitigation Action) may serve as guidance for policy makers in Tanzania for which key elements involve provision of extension services, development of input and service-related industries, and promoting greater access to credit (GOK 2017). All of these initiatives are expected to support technology adoption, improve on-farm productivity and market access (GOK 2017).

Policy implications

Decision makers should consider three key points in order to use the results provided here to inform national policy making in Tanzania or sub-Saharan Africa countries. (i) The results pertain specifically to high potential, mixed crop livestock, tropical and humid production systems in East Africa. A significant fraction of cattle production in Tanzania occurs in arid and semi-arid regions, which are characterised by lower milk yield potential. By focusing on high potential systems in the southern highlands region and in proximity to Dar Es Salaam, this study demonstrates productivity gains and GHG mitigation in areas 'strategically important' for national food security. However, this does not preclude that mitigation in pastoral production systems could also contribute to national targets while preserving livelihoods of rural poor as shown by Henderson *et al.* (2015) and Thornton and Herrero (2010) for grazing systems. (ii) This study considers only the direct economic impacts accruing to dairy households from higher milk production under the dairy roadmap scenarios. These policy objectives could spill over onto the broader rural economy, through employment generation in farming and service/input related industries as discussed by Michael *et al.* (2018). An additional positive impact arising from reduced dependence on external markets would be lower consumer prices for processed dairy products (Michael *et al*. 2018). However, while these additional benefits were not explicitly considered, various negative trade-offs were also discounted (e.g. associated with labour re-allocation, dependency on purchased inputs, and required investments in on-farm infrastructure), which should be considered in future studies. Further, while this study accounts for potential negative welfare impacts associated with different pathways towards meeting district breed targets, the study does not conduct a thorough analysis of distributional impacts of the scenarios. Income impacts are accounted for by considering the means of households rearing local and improved cattle, respectively, which overlooks the dispersion of these variables and hence the number of households living above (or below) the poverty line. Mean incomes for the base year calculated from the household survey are not significantly different between stratum 1 and 2 households, and therefore different adoption patterns do not result in statistically significant differences in net welfare impacts. Distributional impacts could have been accounted for more robustly by, for example, estimating the distribution of the indicator variable (household income, in this case). Doing so could allow the population distribution in this indicator to be compared to a standard benchmark, such as a poverty line, and therefore population percentages living below the poverty line could be accounted for. Future studies conducting such an analysis should consider that key household characteristics such as farm size or income may not be well described using a normal distribution, and therefore an alternate statistical approximation should be used. (iii) This study using attributional LCA does not consider the GHG emissions implications resulting from substitution between domestically produced dairy products and those produced internationally, nor of substitution between dairy and beef products produced domestically or internationally. The substitution of imported dairy for domestic production in particular could represent a net negative for the GHG balance of the scenarios considered. Further, while the impacts of the roadmap scenarios on dairy-beef production are not included here, a preliminary assessment suggests that meeting the milk production targets through a larger dairy herd would result in higher dairy-beef production. This additional dairy-beef output could therefore offset domestic beef production, contributing further to reductions in national GHG budgets. Future studies conducting consequential LCA are therefore warranted, and could quantify these indirect impacts in relation to the direct impacts within the domestic dairy sector. Lastly,this study models reductions in land use by the dairy sector, under the scenarios considered, thus demonstrating that the dairy sector could additionally contribute to broader mitigation in the land use sector through reforestation on spared croplands or grasslands. While the potential for carbon offsets on avoided land use was not explicitly quantified, this represents an additional indirect potential contributor to national GHG reductions of relevance to Tanzania, a country also embracing REDD+.

5.5 Conclusion

Scenarios in this chapter assess the potential for improved dairy breeds and feeding to contribute to Tanzania's national milk production target of ~ 2.5 times 'Business as usual' consistent with GHG reductions on par with the country's NDC target of 10 to 20%. The development objectives stipulated by Tanzania's Livestock Sector Analysis could have repercussions for dairy producers as a result of the substitution between local and improved cattle in order to meet breed targets at district level. The results of income simulations suggest that meeting the milk production and breed targets would improve average dairy household income, expressed in per capita terms, by between 20 to 26%, or 195 USD $capita^{-1}$ yr^{-1} to 265 USD $capita^{-1}$ yr^{-1}. However *Traditional* households rearing *Bos indicus* (local) cattle could experience declines in income by up to 13% due to lower income from a smaller herd. As a result of a dairy sector with a larger percentage of *Bos taurus* (improved) cattle, GHG emissions from the dairy sector could be reduced by 14% consistent with full realization of the national milk production target, and up to 30% at 70% of the production target. These findings are the first to provide quantitative evidence of synergies between climate change mitigation and rural poverty alleviation for dairy producing households in the East Africa region. For other countries in the region with high proportions of *Bos indicus* catle breeds and agro-climatic conditions suitable to dairy, adoption of improved breeds may offer significant potential for both reducing GHG emissions and improving livelihoods of rural households. Future studies could thus seek to better understand the tradeoffs households face when adopting improved breeds and how policy frameworks can be best designed to and targeted to producers who will benefit the most.

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Supplementary information 5

SI 5.1 Livestock simulations

For each of the four districts, feed intakes among local and improved breeds are evaluated, disaggregating based on the two livestock production systems, using results of GLS (2019). In semi-intensive and extensive systems where cattle consume biomass while grazing, the grazed biomass intake is estimated and included as 'grazed feed intake', in addition to feed on offer from farm harvest and market purchases. This intake level is assumed to be sufficient to realise a daily dry matter intake at least as great as 2.5% of bodyweight. To estimate feed intake during the alternate season of the survey, relative feed availability parameters are derived from Mwendia *et al*. (2019) and Wassena *et al*. (2013) to account for the differences in intake of feed categories between dry and rainy seasons. From these values, the total annual feed intake for the herd is then estimated as the average of dry and rainy seasons (Table S5.2).

The monthly feed on offer specified for *LivSim* is determined taking into account practices influencing seasonal availability of feed (Table S5.3). This framework takes into account the seasonality of feed production based on the monthly biomass availability from each feed category, accounting for grazing practices, harvest dates, and rationing practices. The seasonal variation in yield of forages are obtained from Silveira Pedreira *et al*. (2005).

Crop stovers are available during the dry season, through either grazing on crop land or from harvested and rationed crops on farm (Mbwambo *et al*. 2016). Concentrate feeds acquired off farm are the only feeds not affected by seasonality (i.e. they are available year-round). However, their feeding to cows is specified in *LivSim* in relation to the production stage of the animal (early lactation, late lactation, other).

Heat stress

As a result of a warming climate, heat stress is expected to negatively impact milk yields of dairy cattle in East Africa (Rahimi *et al.* 2021). The impacts of heat stress are considered only for improved cattle as indigenous breeds have higher tolerance to heat stress (Santana *et al*. 2015). The modelled impact of heat stress on improved cattle in MRH systems is based on changes in the temperature-humidity index and the expected impact of such on milk yield and fat and protein content (described in detail in SI 5.5). These results in estimated declines in milk yields by 3.1%. Fat and protein are estimated to decline by

19.7 and 4.6%, respectively. These modified estimates of milk yield and composition are thus taken into consideration in estimation of GHG emissions and dairy income for MRH systems.

Table S5.1: Breed parameters used in *LivSim*

Parameter	Local	Improved	Source
Maximum body weight female (kg head^{-1})	450	600	Kashoma *et al.* (2011)
Maximum body weight male (kg head^{-1})	500	600	Ojango *et al*. (2016) Galukande *et al*. (1962)
Maximum milk yield (kg lactation^{-1} cow^{-1})	970	4450	Ojango *et al*. (2016) Galukande *et al*. (1962)
Daily milk yield at maximum (litres)	8	15	Gillah *et al*. (2014) Njau *et al*. (2013)
Lactation length (days)	210	300	Mruttu (2016)
Milk fat content (g kg^{-1})	55	41	Rege *et al*. (2001)
Milk crude protein content (g kg^{-1})	41	35	Rege *et al*. (2001)
Calf birth weight (kg)	30	32	Beffa (2005)
Minimum age at first gestation (months)	30	20	Meaker (1980)
Pregnancy length (months)	9	9	Ojango *et al.* (2016) Mwambene *et al*. (2014)
Dry period (months)	11	2	Mruttu (2016) Chenyambuga and Mseleko (2009)
Postpartum length (months)	12	3	Mruttu (2016) Chenyambuga and Mseleko (2009)
Maximum lifetime (years)	13	13	Rufino *et al*. (2009)

Table S5.2: Biomass productivity, nitrous oxide fluxes, and carbon density parameters for feed and land use categories in model

Land Use	Feed	Annual yield	Available feed biomass	Use efficiency	Nitrous oxide flux	Carbon density		
		Mg DM ha^{-1}	Mg DM ha^{-1} yr^{-1}	Fraction	kg N_2O ha^{-1} yr^{-1}	Mg C ha^{-1}		
						Soils[b]	Other pools[e]	Total
Croplands	Maize	1.46 [d]	0.44 (bran) 2.18 (stover)	0.95	0.73 (stover) 1.03 (bran)	38.0	3.5	41.5
	Sunflower	1.03 [d]	0.36 (cake)	0.95	0.90			
Grasslands	Napier grass	13.04[a]	13.04	0.75	0.51	48.0	4.5	52.5
	Pastures	10.00[c]	5.00	0.50	0.08			
	Grasslands	3.00[c]	1.50	0.50	0.13			
Wetlands						42.0	4.4	46.4
Shrubland						41.0	16.6	57.6
Forest						69.0	37.8	106.8

Sources:
[a] Maleko *et al.* (2019)
[b] Kempen *et al.* (2018)
[c] URT (2017a)
[d] FAO (2021e)
[e] Mauya *et al.* (2019)

Table S5.3: Diets under Base scenario for local and improved cattle across districts. Values represent % dry matter intake on an annual basis. Ranges represent variability across districts and livestock production systems and entire year (both seasons).

Feed	*Mufindi*		*Mvomero*		*Njombe*		*Rungwe*	
	Local	Improved	Local	Improved	Local	Improved	Local	Improved
Grass	30-67	34 - 43	71-75	59-60	63-69	29-57	30-68	34-43
Pasture	<1 - 30	10 – 20	<2	6-7	<1	6-44	<1-30	9-21
Napier grass	<1 - 12	6 - 25	<1	6-7	<=1	6-9	<1-12	6-25
Maize stover	21 - 22	8 - 17	15-17	11-12	21-22	<1-12	21-22	8-17
Maize bran	5 - 11	3 - 22	8-11	10-11	4-9	9-10	5-10	3-22
Sunflower cake	<1	<1 - 11	<1	4-5	<1-11	8-10	<1	<1-11

Source: GLS (2019)

Table S5.4: Conditions affecting seasonal availability of feeds

Feed type	Seasonality conditions
Grass	Can be harvested or grazed year-round.
Pasture	
Napier grass	Can be harvested or grazed year-round. Fed as silage in dry season.
Maize stover	Available during dry season, by either grazing cattle on croplands after harvest, or harvesting and providing to cattle *via* cut-and-carry.
Sunflower cake & maize bran	Available year round from the market. Can be fed to cows according to production cycle: early lactation (first 150 days), late lactation, or other.

Table S5.5: Feeding practices under intervention scenarios (cows only)

Breed	Feeding practices
Local	Receive 25% of feed on offer as Napier grass; fresh Napier in the rainy season and ensilaged Napier in the dry season. Receive a total of 2 kg d^{-1} concentrate during early lactation, 1.0 kg d^{-1} during late lactation, and 0.5 kg d^{-1} during other periods. Concentrates are fed in the proportion 1/3 sunflower cake and 2/3 maize bran.
Improved	All forage* on offer is received as Napier grass; fresh Napier in the rainy season and ensilaged Napier in the dry season. Receive a total of 6 kg d^{-1} concentrate during early lactation, 3 kg d^{-1} during late lactation, and 1 kg d^{-1} during other periods. Concentrates are fed in the proportion 1/3 sunflower cake and 2/3 maize bran.

*Not including maize stover

Table S5.6: Ranges of herd cohort ratios by cattle genetic type, district, and system (% of herd)

Genetic type, cohort	*Mufindi*		*Mvomero*		*Njombe*		*Rungwe*	
	MRT	MRH	MRT	MRH	MRT	MRH	MRT	MRH
Local								
Cows	39.4	36.5	38.6	43.5	40.6	40.6	44.1	44.1
Heifers	14.0	16.9	17.9	13.2	14.9	14.9	7.5	7.5
Bulls	11.3	12.2	13.6	9.8	9.1	9.1	13.6	13.6
F. calves	18.3	14.1	14.7	16.1	15.3	15.3	14.2	14.2
M. calves	14.6	14.3	10.5	11.5	13.4	13.4	15.6	15.6
Juv. males	2.3	6.0	3.0	5.7	4.3	4.3	5.0	5.0
Improved								
Cows	47.5	47.5	46.4	46.4	51.9	51.9	53.0	55.2
Heifers	15.2	15.2	14.6	14.6	8.2	8.2	9.6	7.4
Bulls	5.9	5.9	7.0	7.0	3.5	3.5	4.3	3.9
F. calves	15.5	15.5	17.1	17.1	19.9	19.9	17.4	15.5
M. calves	15.0	15.0	11.4	11.4	12.7	12.7	14.0	14.0
Juv. males	1.0	1.0	3.8	3.8	3.8	3.8	1.8	4.0

Source: GLS (2019)

Table S5.7: Nutrient properties of feed types by season

	Dry matter (g kg^{-1})		Dry matter digestibility (%)		Metabolisable energy (MJ kg DM^{-1})		Crude protein (g kg^{-1})		Acid detergent fibre (g kg^{-1})		Neutral detergent fibre (g kg^{-1})	
	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
Native grasslands[a,c]	850	155	45.1	55.3	5.8	7.7	61	70	495	432	862	712
Managed Pastures[a,c]	850	155	47.0	65.0	6.5	8.6	94	108	481	420	860	711
Napier grass[a]	893	179	53.7	61.4	6.2	8.2	97	103	419	425	711	715
Napier grass silage[a]	195	--	579	--	7.5	--	6.5	--	436	--	726	--
Maize stover[a]	928	296	46.8	56.7	6.9	8.4	39	68	396	496	699	750
Maize bran[a]	887		72.4		11.0		119		145		442	
Sunf. Cake[a]	890		61.1		9.1		324		320		450	

[a] FAO (2021d)
[b] Rubanza *et al.* (2006)
[c] Lukuyu *et al.* (2012)

Table S5.8: Greenhouse gas inventory and estimation methods, production levels, warming potentials, and allocation methods of LCA

Parameters		**Values, sources**
Greenhouse gas inventory	Enteric fermentation CH_4	IPCC 2006 Eq 10.1
	Manure CH_4	IPCC 2006 Eq 10.23
	Manure N_2O	IPCC 2006 Eq 10.25 - 10.29
	Crop, grassland soils N_2O	IPCC 2006 Eq 11.1,4,5,7,8,9,10,11
	Fossil energy CO_2	5.66[a] kg CO_2eq kg^{-1} N 78.6[b] kg CO_2eq Mg^{-1} compound feed
	Croplands expansion CO_2	C stock difference of 11 Mg ha^{-1} (see SI 5.2)
	Grasslands expansion CO_2	C stock difference of 27.3 to 36.1 Mg ha^{-1} (see SI 5.2)
Production variants (from Table 5.2)	*Baseline*	1.63 MT FPCM yr^{-1}
	70% Production target	3.46 MT FPCM yr^{-1}
	100% Production target	4.19 MT FPCM yr^{-1}
Global warming potentials		28[c] kg CO_2eq kg^{-1} CH_4 265[c] kg CO_2eq kg^{-1} N_2O
Functional unit		1 kg FPCM

[a] Kool *et al*. (2012)
[b] FAO (2016)
[c] IPCC (2013)

SI 5.2 GHG emissions

Table S5.9: Emission factors used in life cycle assessment of dairy sector

Emission factor	Value	Source
Y_m	Estimated as in Jaurena *et al*. (2016)	
[a] MCF	0.015 (pasture) 0.04 (solid storage)	IPCC
[a] EF_3 storage (direct manure N_2O)	0.005	IPCC
[a] EF_3 pasture (direct manure N_2O)	0.00105	Pelster *et al.* (2016)
[a] EF_4 (indirect manure N_2O)	0.01	IPCC
[a] EF_5 (indirect manure N_2O)	0.0075	IPCC
[a] Fraction N volatilized – pasture	0.2	IPCC
[a] Fraction N leached – pasture	0.3	IPCC
[a] Fraction N volatilized – solid storage	0.3	IPCC
[a] Fraction N leached – solid storage	0.4	IPCC
EF_1 (soil N inputs)	0.0105 (inorganic N) 0.01 (organic N)	Hickman *et al.* (2016) IPCC
EF_5 (leaching and runoff)	0.0075	IPCC
Fraction gas volatilized (organic N)	0.1	IPCC
Fraction gas volatilized (synthetic N)	0.2	IPCC
Fraction lost manure management	0.4	IPCC

[a] Specified in the model for each production system as a weighted average based on the fraction of manure excreted on pasture vs. managed, as estimated from GLS (2019)

Carbon stock differences

The C densities for a given land use category are equal to the sum of the five following pools: soils, below and above ground biomass, coarse woody debris, and litter (IPCC 2006). Following the practice of LUC accounting in dairy LCA, the CO_2 emissions after land use change are amortized over a twenty-year period (BSI, 2008, IDF 2010). The transition coefficient for *cropland expansion* is based on the differences between grassland and cropland C stocks. The C stocks of the respective land uses are calculated as 41.5 and 52.5 respectively, based on the data of Kempen *et al*. (2018) and Mauya *et al*. (2019). This resultsin a difference of 11.0 ± 2.0 Mg C ha^{-1} between crop and grasslands. To calculate the transition coefficient for grassland expansion, native ecosystem C stocks are estimated using spatially-explicit land cover data at a 100x100m pixel resolution (Bruzonne *et al.* 2020). The C stock density of native ecosystems is estimated as a weighted mean of the shrub, forest, and wetland categories, all of which represent land use categories under threat from anthropogenic activities in Tanzania (Doggart *et al*. 2020, Msofe *et al*. 2019). The C densities of these land categories (for the non-soil C pools) are based on national carbon stock inventory data (Mauya *et al.* 2018) and the topsoil dataset compiled from 1,400 locations across Tanzania of Kempen *et al.* (2018). The weights are based on the proportion of shrub, forest, and wetland in a given grid cell (Bruzonne *et al.* 2020). This data is up-scaled to the same spatial resolution as the LPS data and aggregated to derive a C stock difference between grasslands and native ecosystems representative of both MRT and MRH systems in the study region. The resulting values range from 32.6 to 36.1 and 27.3 to 33.9 Mg C ha^{-1} for MRT and MRH systems respectively.

Table S5.10: Relative standard errors used in Monte Carlo simulations of GHG emissions

Variable	Relative standard error (%)
Grassland yields	+/- 20
Maize yield	+/- 20
Sunflower yield	+/- 20
Cattle populations	+/-20
Feed intake per tropical livestock unit	+/-25
Y_m	+/- 10
Bo	+/- 30
MCF	+/- 20
EF_1 (soil N inputs)	+/- 66
EF_3 storage (direct manure N_2O)	+/- 30
EF_3 pasture (direct manure N_2O)	+/- 7
EF_4 (indirect manure N_2O)	+/- 30
EF_5 (indirect manure N_2O)	+/- 30
Fraction N volatilized -- pasture	+/- 7
Fraction N leached – pasture	+/- 7
Fraction N volatilized -- storage	+/- 7
Fraction N leached – storage	+/- 7
EF_4 (atmospheric deposition)	+/- 30
EF_5 (leaching and runoff)	+/- 30
Fraction gas volatilized (organic N)	+/- 30
Fraction gas volatilized (synthetic N)	+/- 30
Fraction lost manure management	+/- 30

C stock density croplands	+/- 20
C stock density grasslands	+/- 20
C stock density native ecosystems	+/- 20
Embodied feed and fertilizer footprints	+/- 30

SI 5.3 Land use accounting

The percentage of grassland expansion converting native ecosystems is calculated by relating the estimated land demand for each LPS and district with the availability of unoccupied grasslands for each district and LPS (see Figure S5.1d), as estimated using land cover data of the European Space Agency (Bruzonne *et al.* 2021). This data is merged with the GLW data to estimate the available grassland at LPS level for each district, by summing over all raster pixels of the dataset. The fraction grassland use expansion actually converting native ecosystems, defined as Ω, was then estimated as :

$$\Omega = \sum_p \frac{Dairy\ land\ use\ 2031 - Dairy\ land\ use\ 2018}{Total\ available\ grassland\ 2018 - X} \quad \textit{(Eq. 5.4)}$$

Where p represents the raster pixels at 10 by 10 km resolution across respective districts and LPS, 'Dairy land use 2031, 2018' is the total land use, the sum of crop and grasslands in ha, by the dairy sector in a given LPS and district in the final and initial periods of the simulation respectively, Total grassland available is the total unoccupied grassland in the year 2018, and X is the area growth in exogenous land uses in ha. Exogenous land uses included croplands and grasslands for non-dairy ruminants. Total grassland expansion emissions are then reported as Ω x the total land use growth between 2031 and 2018 x the LUC transition coefficient for each LPS (described in SI 5.2).

The availability of grasslands and percentage utilized for grazing and cut and carry feeding are estimated based on the land cover data (Bruzonne *et al*. 2020), the cattle population densities (Gilbert *et al.* 2018), and the parameters specified to reflect productivity and efficiency of grazing/harvesting of grassland species included in the model. The feed categories described in the body of the paper which are included in this framework are all feed categories that are not included under the crop category for the Bruzonne *et al*. (2020) land cover data. This includes Napier grass, managed pasture, and native grasslands. The extent of grassland utilization is calculated with the following equation:

$$\textit{Grassland utilization} = \frac{Cattle\ density \times Grass\ consumption \times Use\ efficiency}{Grassland\ yield} \quad \textit{(Eq. 5.5)}$$

Where grassland utilization (km^2) is the extent of grasslands per spatial unit being utilized for ruminants, cattle density (head km^{-2}) is based on Gilbert *et al.* (2018), grass consumption (Mg DM $head^{-1}$ yr^{-1}) is the grass consumption per animal as specified above, use efficiency is the fraction of grass available that is harvested or consumed by grazing cattle (Table S5.2), and grassland yield is the yield of grassland (Mg DM ha^{-1} yr^{-1}) (Table S5.2).

In the final year of the model simulation period the grassland available for use by the dairy sector is equal to grassland area in the base year (2018) minus the expected use from non-dairy sector sources. These sources include cropland as an aggregate, and the grassland occupied for grazing by non-dairy cattle. Cropland expansion is calculated based on the crop land area in the base year (Bruzonne *et al.* 2020) and the annual growth rate as calculated from FAO data which was estimated as 1.457% (FAO 2021). The growth rate in land needed for non-dairy cattle grass consumption is calculated based on the population and the land requirement for their grass consumption. The former is calculated based on the Gilbert *et al.* data using the ratio of non-dairy cattle from census data (NBS 2016, 2013) which resulted in 0.440 % of the total herd categorized as non-dairy. The latter is calculated assuming a daily dry matter intake of 2.5% of body weight (in kg), and using the grassland yields and use efficiencies provided in Table S5.2.

SI 5.4 Household income computation

This section describes how non-dairy household income is derived from the survey. The resulting values for each district and strata are reported in Table 5.3. Non-dairy household income is inclusive of cash income from farm and off farm sources plus the market value of home produced food products (excluding dairy) following the method of Rufino *et al.* (2013). Production of food, cash and fodder crops, dairy and other livestock products are calculated based on the survey respondent's description of production, and associated variable inputs as outlined in Equations S3-S6 below. Cash expenses on non-dairy livestock inputs by the sampled households is minimal, thus only the expenses incurred on crops were considered. Producer prices of food commodities are obtained from the survey, because households reported both sales and revenue from products sold. For uncommon products, resulting in a small sample size to calculate market prices, producer prices are obtained from FAO databases (FAO 2021). Survey respondents most often reported value of on farm production, sales, etc., in local units, such as debes (8 kg of maize), kisados (5 kg of maize), or gorogoros (2 kg of maize). These are converted to SI units based on the respective conversion ratios (Tittonnell *et al.* 2003). The monetary values are converted from Tanzanian shillings to USD. The reported income sources herein do not include fixed costs (e.g. expenses on capital investments), and therefore only represent the net cash flows (i.e. annual income from sales minus annual variable expenses). Income from the sale of crops are estimated as follows:

$$Crop\ income_{d,s} = \sum_C QCS_{d,s,c} * PP_c - \sum_z CE_{d,s,z} \qquad \text{(Eq 5.6)}$$

Where Crop $income_{d,s}$ is the annual income (USD yr^{-1}) from cropping activities for household s, district d, $QCS_{d,s,c}$ is quantity of crop product c sold (kg hh^{-1} yr^{-1}), PP_c is the producer price of crop c (USD kg^{-1}) and $CE_{d,s,z}$ is the crop expenses for household s and district d and crop expense category z. The types of inputs (z) include (inorganic) fertilizer, seeds, herbicide, pesticides, hired labour for cropping activities, expenses on farm machinery, and rented cattle. In addition to income from crop sales, two additional sources of income are included: income from other non-dairy livestock (poultry, sheep, goats) and from other farm activities (such as from plantation forests in Mufindi district). Because the survey does not consider expenses on these types of livelihood activities, they are solely reported as gross revenue. Finally, off farm income is estimated based on the reported income from non-farm sources for all members of the family:

$$\text{Total off farm income}_{d,s} = \sum_v Off\ farm\ income_{d,s,v} \qquad \textit{(Eq. 5.7)}$$

Where Total off farm $income_s$ is the Total annual off farm income for household s and district d, and Off farm $income_{d,s,v}$ is income from off farm for household s and district d on activity v. These activities included all types of off farm employment, as well as remittances, dividends, pensions paid to household members, as well as any other forms of off farm cash income (e.g. capital gains from the sale of assets). The total household cash income is then approximated as the sum of the above categories:

$$\text{Non-dairy cash income}_{d,s} = \text{Crop income}_{d,s} + \text{Other farm revenue}_{d,s} + \text{Other livestock revenue}_{d,s} + \text{Total off farm income}_{d,s} \qquad \textit{(Eq. 5.8)}$$

Where cash $income_{d,s}$ is the annual cash income for household s in district d from all sources (on and off farm) in USD yr^{-1}, Other farm $revenue_{d,s}$ and Other livestock $revenue_{d,s}$ are the revenue streams for household s in district d as described above. Cash income is then combined with the value of farm produce consumed to estimate the total (cash + non-cash) income of the household:

$$\text{Total non-dairy income}_{d,s} = \text{Cash income}_{d,s} + \text{Value of consumption}_{d,s} \quad \textit{(Eq. 5.9)}$$

Where Total non-dairy income is the total non-dairy income for household s in USD yr^{-1} , and Value of consumption is the value of all on farm produce consumed by household s in district d in USD yr^{-1}. The latter includes from food, cash and fodder crops, and non-dairy livestock products (USD yr^{-1}).

Net crop margin

Net crop margins are calculated as the total market value of all food and cash crops produced by the household divided by total area of land devoted to producing food and cash crops:

$$\textit{Net crop margin}_{d,s} = \sum_C QC_{d,s,c} * PP_c - \sum_z CE_{d,s,z} \quad \textit{(Eq. 5.10)}$$

Where Crop net $\text{margin}_{d,s}$ is the average net crop margin in USD ha^{-1} yr^{-1} for household s in district d, $QC_{d,s,c}$ is the quantity of crop c produced by household s in district d, and PPc and $CE_{d,s,z}$ are as described above.

Table S5.11: Parameters used in income accounting by district and household type. Values are averages plus standard deviation (±) calculated per strata.

District	Strata	Farm gate milk price (USD litre^{-1})	Cash expenses on input use per cow (USD yr^{-1})			
			Purchased feeds	Replacement cattle	Health inputs/services	Reproductive inputs/services
Mufindi	1	0.43 ± 0.05	0.5 ± 2.6	1.5 ± 12	11.6 ± 9.1	0 ± 0
	2	0.43 ± 0.44	11.9 ± 16.4	0 ± 0	17.1 ± 13.1	1 ± 3.4
Mvomero	1	0.26 ± 0.12	0 ± 0.3	0.7 ± 5.7	11.3 ± 19	0 ± 0
	2	0.44 ± 0.08	4.9 ± 10.3	0 ± 0	20.5 ± 19	0 ± 0
Njombe	1	0.43 ± 0.05	25.8 ± 64	0 ± 0	15 ± 19.2	0 ± 0
	2	0.34 ± 0.19	228.9 ± 138.4	8 ± 58.2	17.2 ± 11.7	0.7 ± 3.2
Rungwe	1	0.39 ± 0.06	35.3 ± 88.1	3.9 ± 23.7	8.3 ± 9.7	0 ± 0
	2	0.28 ± 0.13	266.6 ± 291.4	2.5 ± 20.5	8.7 ± 10.1	0.9 ± 4.5

Source: GLS (2019)

SI 5.5 Impact of heat stress on milk yield and composition

For MRH systems the impacts of heat stress on milk yields are estimated by first estimating the Temperature Humidity Index (THI) and then accounting for the impact of a rise in THI on milk yields based on empirically estimated relationships obtained from literature. MRT systems are excluded because temperatures generally do not surpass 20°C in these regions (Mcsweeney, New, and Lizcano, 2006) and therefore heat stress is not likely to be an issue at least in the 2020s timeframe.

The heat stress equation provided by NRC (1971) is used, which is the most commonly used method to assess heat stress conditions for dairy cattle in tropical environments (Nascimento *et al*. 2019).

$$THI = (1.8 \times Tdb + 32) - [(0.55\text{–}0.0055 \times RH) \times (1.8 \times Tdb - 26.8)] \qquad \textit{(Eq. 5.11)}$$

Where THI is the Temperature Humidity Index (an index ranging from 0 to 100), Tdb is the dry bulb temperature (°C), and RH is the relative humidity (%).

In equation 5.11, the Tmax (°C) temperature values estimated by Gebrechorkos, Hülsmann, and Bernhofer (2019) for Tanzania during the 2020s are used for Tdb, following the approach of previous studies such as Rahimi *et al.* (2020).

Using three different climate models, Gebrechorkos *et al*. (2019) estimates the increase in Tmax to vary between 0.2 to 1.50 °C above the historical value over the 2020 to 2030 timeframe for Tanzania. For a historical value, the national mean temperature of 25.36 was used (Gebrechorkos, Hülsmann, and Bernhofer, 2019). The mid range of these values, which is estimated as 0.625, was used as the expected temperature rise during the period. Thus the value for Tdb used was 25.36 + 0.65 = 26.01 °C. This value as well as a Humidity index of 70% for all the Humid zones (MRH) in the study region is used. This results in a THI of 75.5%, for a total increase of 3.5% over the 72% cutoff estimated to result in impaired milk yield by Johnson (1980).

To estimate the impact of a change in THI on milk yields, estimates provided by York *et al.* (2017) are used. These authors find that milk yield declines by 0.76 and 2.19% per unit THI for purebred and crossbred Jersey cattle in India. A value of 1.0 iss used, which is broadly representative of a crossbred (50:50 Zebu and Jersey). For milk fat and protein, the values provided by Bouraoui *et al*. (2002) whereby the milk fat and protein content (g) is found to be reduced by 0.056% (fat) and 0.013 % (protein) for every one unit increase in THI over 72%.

Using these relationships and the above listed values for THI, the estimated impact on milk yield is a decline by a factor of 3.5%. For milk composition, the main simulations result in declines of 19.7 and 4.5% for fat and protein contents, respectively.

SI 5.6 Supplementary results

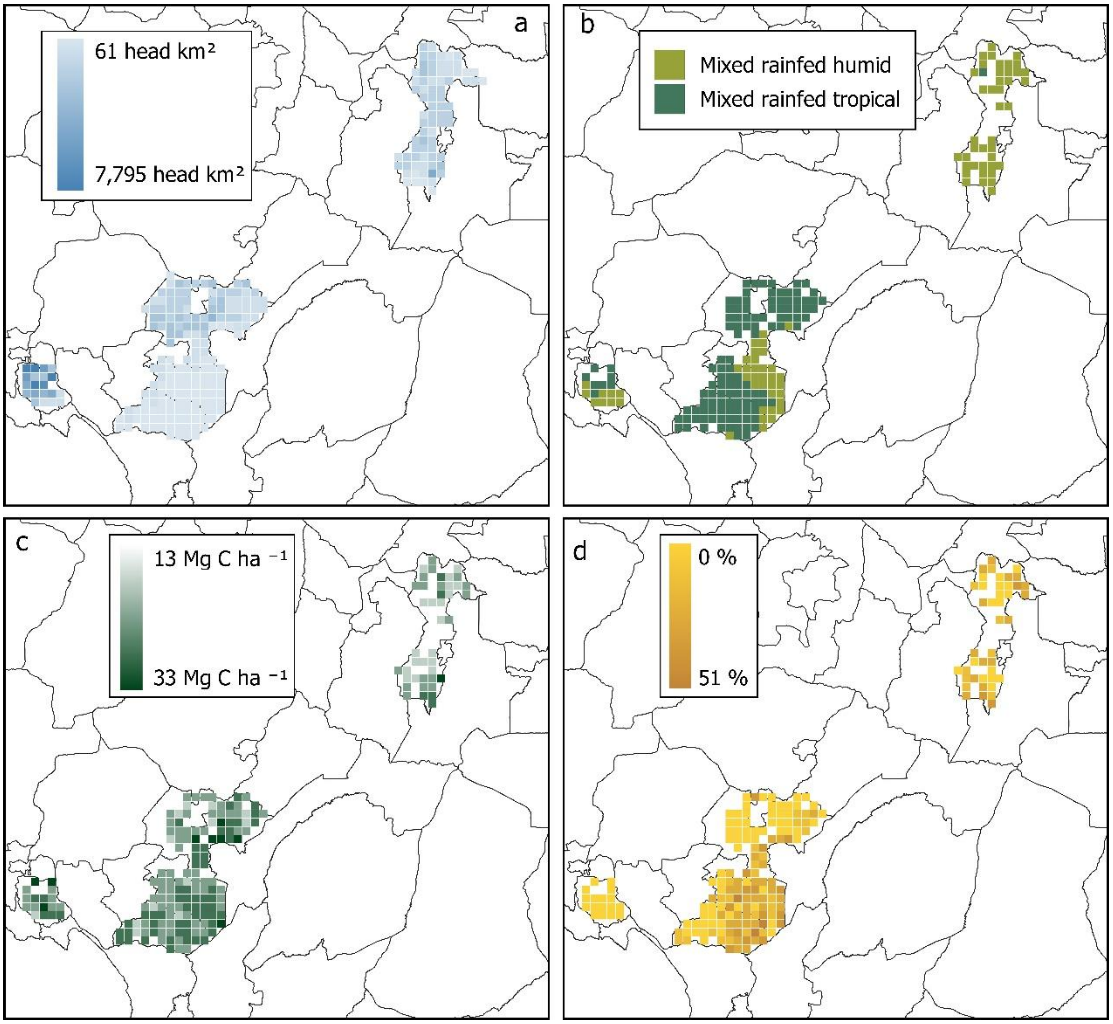

Figure S5.1: Graphical depictions of spatial data used for grid pixels informing simulation units in model. Data includes (a) cattle population densities, (b) livestock production systems, (c) carbon densities of native ecosystems (see SI 2), and (d) grassland availability (% of land surface area) (see SI 3).

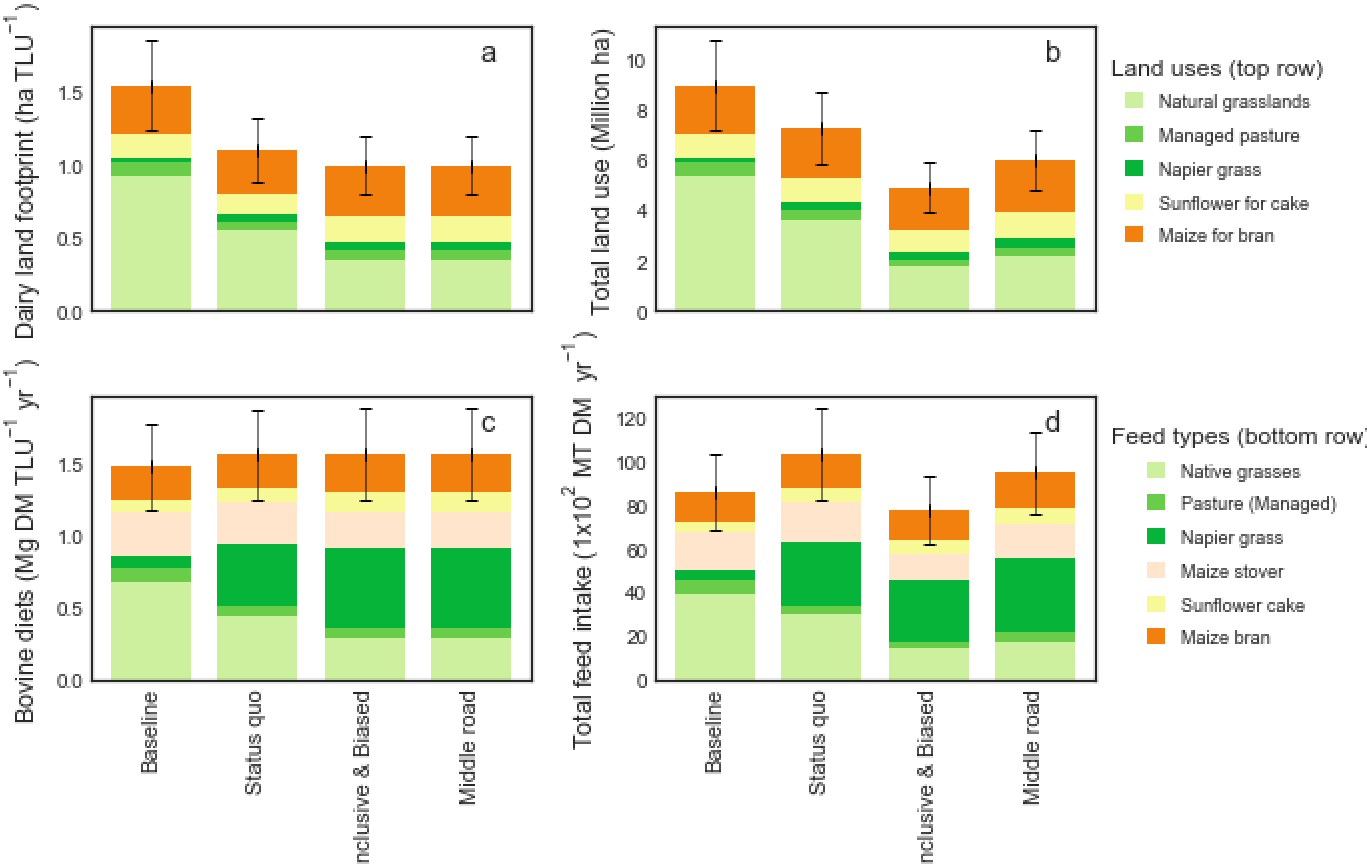

Figure S5.2: Land footprint & feed intake model results

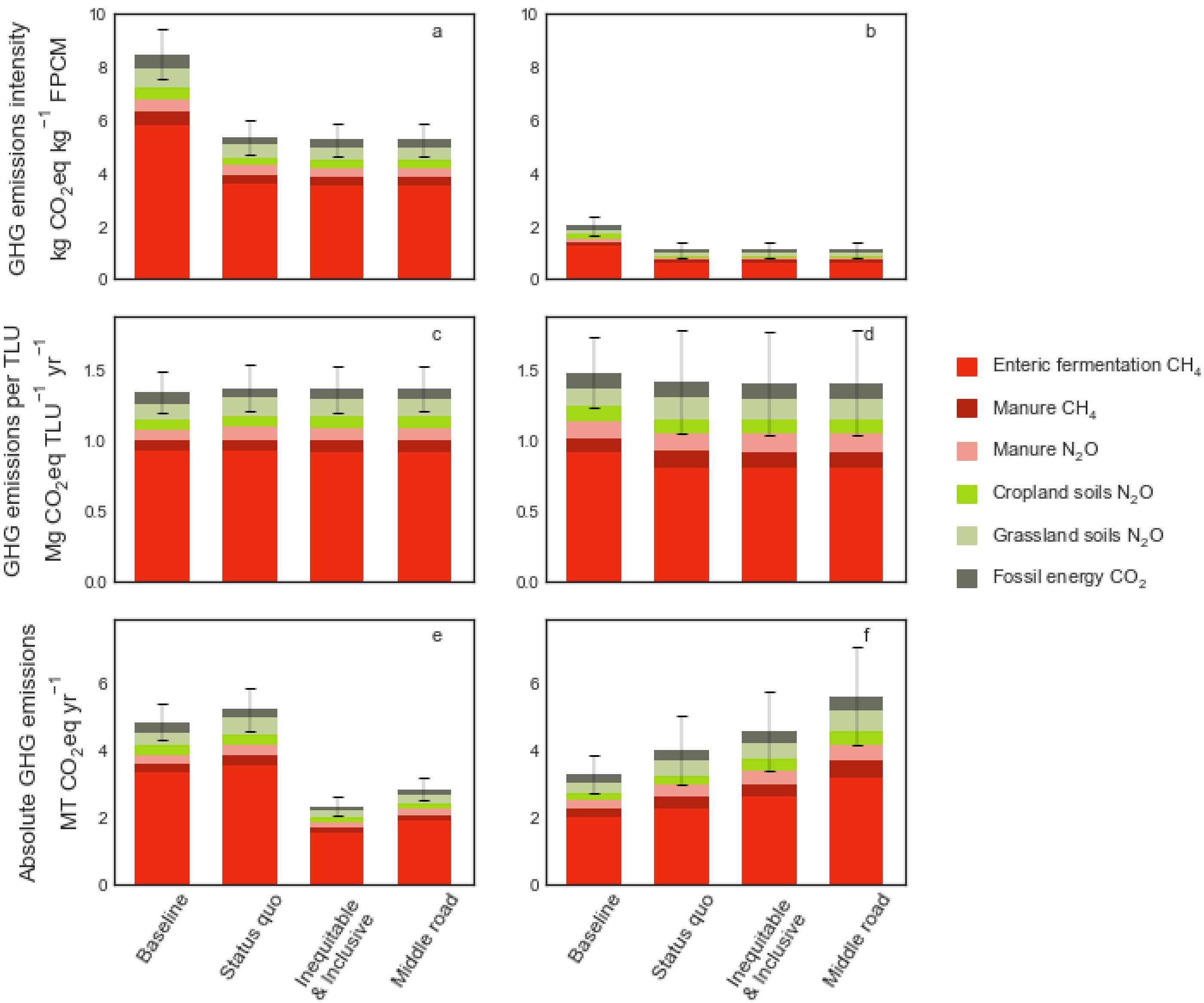

Figure S5.3: Greenhouse gas emissions by dairy sub-sector: local cattle (left panels; a, c, e) and improved cattle (right panels; b,d,f)

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6 General discussion

6.1 Introduction

Development initiatives for both the Kenyan and Tanzanian dairy sectors are designed to achieve efficiency gains from farm to retail level (GOK 2013, Michael *et al.* 2018). These are expected to confer benefits beyond the direct impacts on dairy producers from higher milk income and food security. A more efficient domestic dairy sector is expected to lower the price of milk and increase per capita milk consumption which, at a value of about 35 litres year^{-1} (FAO 2021), is far below the 200 litres recommended by the FAO. There are additional spillovers expected for the rural economy as a result of greater employment and income from input and service-related industries (Michael *et al*. 2018, GOK 2013).

Key strategies for national dairy modernization initiatives to achieve these outcomes include promoting uptake of best feeding practices, through adoption of feed conservation, cultivation of improved forages on farm, and greater access to affordable forage and concentrate feeds through the commercial feed industry (Mbwambo *et al*. 2016, GOK 2013). Uptake of improved cattle breeds is promoted through wider dissemination of AI (artificial insemination) and heifer supply programmes, as well as access to extension, and affordable animal husbandry inputs and services (Mruttu *et al*. 2016, GOK 2013).

While climate change mitigation is not the main objective of these development initiatives, they can be expected to reduce GHG emissions intensities in the dairy sector (CO_2 eq emissions per FPCM). Feeding higher quality diets can increase milk yields per cow and reduce methane emissions per unit of milk (Caro *et al*. 2016, Agle *et al.* 2010), the largest direct contributor to dairy's GHG footprint. Improvements in health and reproduction can reduce mortality, optimize herd structure, and increase the productive lifespan of cows. Modelling studies have shown that these factors can improve productivity at animal and herd level, reducing GHG emissions from not only enteric fermentation but other major sources of GHG emissions within the product life cycle (Knapp *et al.* 2014, Mottet *et al*. 2015). An additional expected result of these productivity gains is the avoidance of native ecosystem conversion, a key component of the GHG mitigation potential from the livestock sector (Gerssen-Gondelaach *et al.* 2017, Havlik *et al*. 2012).

While the priority interventions included in national dairy development programs have the potential to reduce GHG intensities, national climate mitigation policy frameworks, as part of

NDCs, are based on economywide reductions in absolute emissions (Hood and Soo, 2017). Both the Kenyan and Tanzanian dairy policy initiatives will support continued growth in milk production in coming years (Michael *et al*. 2018, GOK 2013). A key knowledge gap therefore concerns how far national milk production targets are consistent with economy-wide targets for reducing GHG emissions.

6.2 Summary of findings

Chapter 3 presents a household typology to understand adoption of low emissions dairy production practices among dairy households in Kenya and Tanzania. Households are stratified by cattle breed (local and improved), and principal component and clustering analysis are used to group these households based on distinct structural and functional traits. Adoption of practices relating to feeding, animal health, reproduction, and manure management are evaluated. Differences in means tests are evaluated across household types and across household strata, thereby testing the effectiveness of the typology and of breed ownership (local *versus* improved cattle) in influencing adoption of the select practices. This results in a total of 60 site x practice pairs (6 sites x 10 practices) for each test. Difference in means tests for household types show statistically significant differences in adoption rates for 36 out of the 60 pairs, for a total percentage of 60%. Breed ownership is statistically significant in explaining differences in adoption rates for 30 out of 60 site x practice pairs. However, breed type is found to result in statistically significant differences in GHG emission intensities (kg CO_2eq kg^{-1} FPCM) for all six sites but Nandi. The typology can therefore aid the design of interventions targeted at households based on baseline GHG emissions intensities of dairy production.

Chapter 4 quantifies the effects of feeding practices and feed crop productivity on sectoral GHG emissions for Tanzania's 'Traditional' (local cattle) and 'Modern' (improved cattle) dairy sectors. As a result of low milk productivity and reliance on unproductive grasslands, the Traditional sector is found to have twice the land footprint (1.25–1.50 ha TLU^{-1} *versus* 0.60–0.70 ha TLU^{-1}), contributing up to 4.5 more CO_2eq emissions per kg FPCM compared to the Modern sector (19.8 to 27.8 *versus* 5.80 to 5.86 kg CO_2eq kg $FPCM^{-1}$). Improved feeding practices, including feed conservation, and higher levels of improved forages and concentrates, may increase milk yield per cow for each respective sector (Traditional and Modern) by up to 52.4 and 38.0%. Gains in yields of feed crops lead to an additional reduction of emissions by 11.4-14.4% (Traditional) and 29.5-34.9% (Modern). However, overall the feeding and feed crop yield scenarios show negligible potential to reduce GHG emissions in absolute terms. These findings suggest that increases in the proportion of improved cattle within the sector will be required for realising absolute GHG reductions consistent with the production growth targets of Tanzania's dairy roadmap.

Chapter 5 analyses the effect of combining both improved diets and improved breeds, based on an increase in the proportion of improved cattle in each of the four districts taken for this modelling exercise. These scenarios are evaluated in relation to the mitigation target of Tanzania's NDC of a 10 to 20% reduction relative to 'Business as usual' (URT 2017a), and assuming growth in milk production by a factor of 2.57 times 'Business as usual', as outlined in the dairy roadmap (Michael *et al*. 2018). The scenarios simulate the district breed proportions and improved breed adoption targets up to the values defined by the Tanzanian Livestock Sector Analysis (TLSA) (URT 2017b). The realisation of district breed targets will result in trade-offs for dairy households, as a result of changes to herd size and breed composition, of changes to land allocation to meet increased forage requirements of the herd, and of changes in capital expenditure. An income-based indicator is used to quantify the net welfare effects from each of the scenarios across the range of households. The indicator accounts for changes in cash plus non-cash income (such as changes in the food crops produced by the household) based on the changes to the size of herd and proportion of improved cattle within it, of capital expenditure and shifts in the opportunity cost of farm land associated with each scenario.

This chapter finds that: (i) the breed targets at district level must be achieved in order to meet dairy production targets and the absolute GHG reductions in the 10 to 20% range stipulated by the NDC. Meeting the district breed targets defined in the TLSA consistent with 70% of the milk production target would lead to emissions reductions exceeding 10% with a high level of certainty; less than 1% probability emissions surpass this reduction target. Meeting district breed targets defined in the TLSA consistent with full realization of the milk production target would lead to emissions reductions exceeding 10% with a 64% probability. By contrast, scenario *Status quo*, in which the proportion of improved cattle per district is consistent with historical growth rates of respective cattle breeds, falls short, only reducing GHG emissions by 3.6% from *Baseline*. (ii) Meeting the district breed targets has net aggregate welfare benefits for dairy producers, because the growth in the value of milk production exceeds the costs associated with adopting improved breeds and feeding higher quality diets. However *Traditional* households (rearing local cattle) would be worse off as the sizes of their herds decline. These households experience declines in income of up to 13% under scenario *Inequitable*. By contrast, the maximum decline in income under scenario *Inclusive* is only 4%. This finding suggests that more households adopting improved cattle can help minimize negative welfare effects associated with this shift towards a dairy herd based predominantly on improved cattle.

To the knowledge of the author, these findings are the first, for any country in sub-Saharan Africa, to demonstrate potential for realizing national dairy sector development objectives with delivery of GHG reductions consistent with national climate mitigation targets. Previously, Notenbaert *et al*. (2020) evaluated the potential for improved breeds, feeding, and animal husbandry (better veterinary care) to contribute to GHG reductions in Tanga region, Tanzania. These authors document that changing these practices jointly could increase gross profits by over 500 and 50 USD $ha^{-1} yr^{-1}$ for mixed crop-livestock and agro-pastoral farming systems respectively. However, the authors overlooked the effects of LUC in both the baseline, as well as the intervention scenarios, confounding the actual magnitude of GHG reductions as a result changes in practices.

As a result of the above findings, the main knowledge contributions of the thesis can be summarized as follows:

(1) Avoided LUC emissions play a key role in contributing to GHG reductions in Tanzania's diary sector and, by extension, in other countries in sub-Saharan Africa, and

(2) Broad-based uptake of improved cattle breeds is required for meeting milk production targets which are consistent with climate change mitigation in Tanzania and, by extension, in other countries characterised by high proportions of *B. indicus* cattle.

As these findings represent the main knowledge contributions of the thesis, the following sections explore in more detail their validity and implications for ongoing policy dialogues and research pertaining to low-emissions dairy development in Tanzania, Kenya, and Africa more broadly. The limitations of my study and suggestions for future work are then summarized, and a concluding statement provided.

6.3 The contribution of land sparing to climate mitigation in the dairy sector

As a result of the methods described in Chapter 4, LUC is found to contribute 45.8 - 65.8% of the base scenario GHG emissions across production systems and dairy sectors (Traditional and Modern). Better feeding improves milk yields but does not result in significant GHG reductions in absolute terms. Most of the reductions in GHG emissions are a result of a change in feed mixes and/or crop yield gains which reduce LUC emissions.

In chapter 5, genetic gains at district level, resulting in substitution of improved for local cattle, lead to growth in milk production up to 2.57x *Baseline* with reductions in absolute GHG emissions of 14% (*Middle road*), and 2.1x *Baseline* with emissions reductions up to 30% (*Inclusive*, *Inequitable*). The GHG reduction potential for these scenarios can be traced to their impact on dairy land occupation. The roadmap scenarios result in a transition to a herd with up to 25% more improved cattle at region level (all four districts combined), and the feed mixes of the dairy herd shift from relying less on low yielding native grasses and more towards higher yield forage crops and concentrate feeds. Figure 6.1 (a) outlines the relative contribution of 'direct' (non-LUC) emissions with land use change emissions for the *Baseline* and four roadmap scenarios. Associated with the changes in breed and diet compositions, the relative contribution of direct emissions to the total GHG footprint increases, while that of LUC decreases (Figure 6.1 a). However reductions in LUC emissions are primarily a result of reduced *Grassland expansion*; the contribution from *Cropland expansion* increases by 3 to 33%. Avoided CO_2 emissions from reductions in *Grassland expansion* forms the largest single contributor to reductions in GHG sources (Fig. 6.1 b), and is large enough to more than negate the increases in other sources.

The roadmap scenarios result in a shift towards higher quality and higher yielding feeds in dairy diets, especially Napier grass, and to a lesser extent maize bran and sunflower cake (Fig. 6 c). While total feed intake per TLU increase (as much as 6%), the dairy land footprint declines as a result of the substitution for low yielding native grasslands for higher yielding Napier grass (Fig. 6 d). As a result, total land occupation declines in absolute terms under the roadmap scenarios (Fig. 6 e), by up to 30% under *Middle road* and 43% under *Inequitable* and *Status quo.* This decline is driven primarily by a reduction in occupation of low yielding (native) grasslands (Fig. 6 e). Overall, the results of the thesis suggest feeding management improvements, including improved diets and productivity gains of staple feeds, have minimal potential to reduce GHG emissions in absolute terms if the populations of dairy herds (for respective breeds) remain unchanged. Instead, a shift to a herd with more improved animal genetics are required to lead to absolute GHG reductions, and this occurs despite higher emissions from direct sources, especially enteric fermentation, as well as expansion of cropland areas. The results of these analyses suggest that this would result in significant declines in *Grassland expansion* and associated CO_2 emissions, which would contribute to significant absolute declines in the dairy sector GHG footprint.

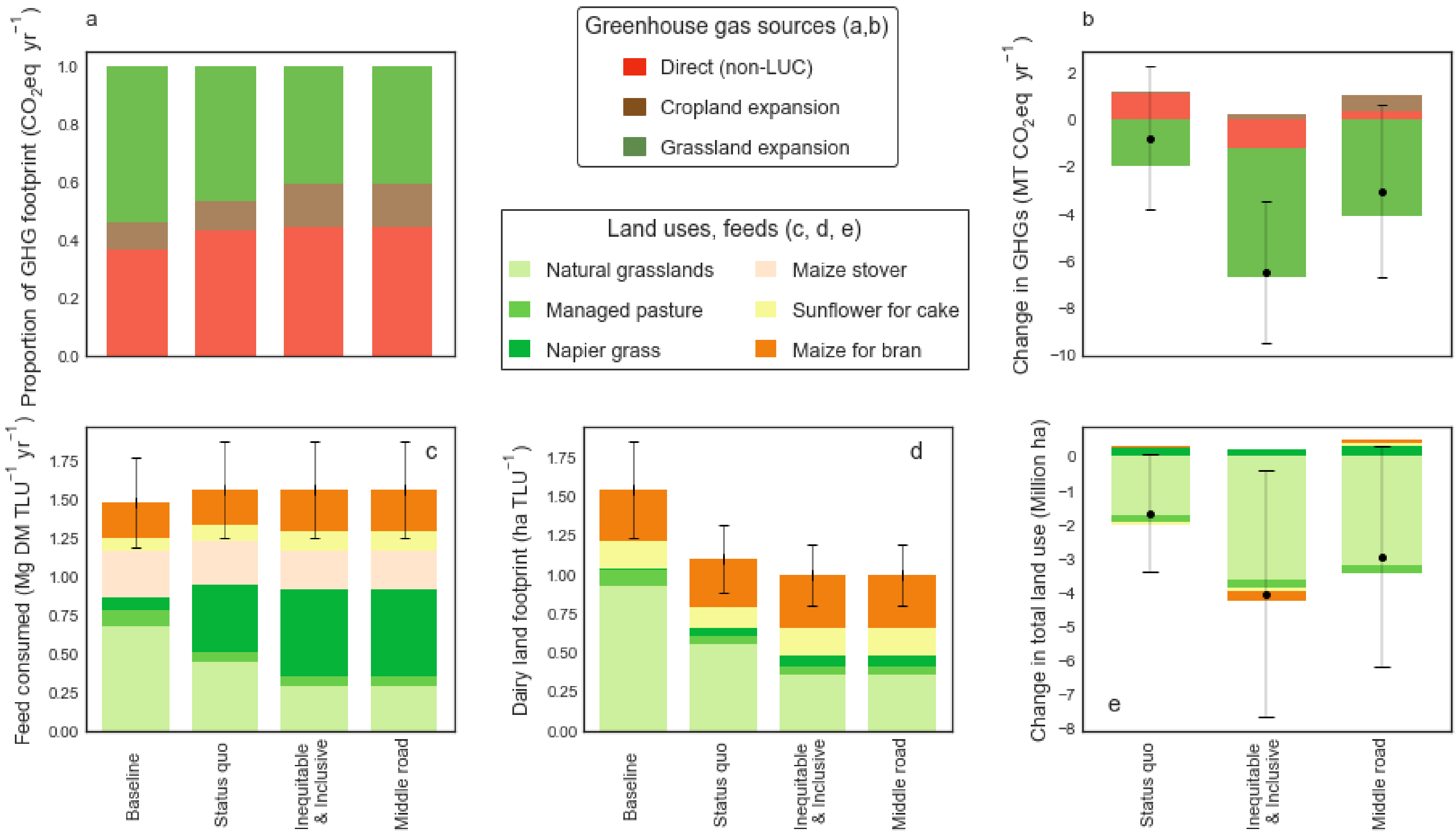

Figure 6.1: Summary of greenhouse gas, feed, and land use implications of dairy sector scenarios (**Chapter 5**). Panels show contributions of individual GHG sources to total footprints (a) and reductions in total emissions from *Baseline* (b), feed consumed by dairy herd (c), the dairy land footprint (d), and total change in dairy land occupation relative to *Baseline* (e). Black circles on panels (b) and (e) represent net changes relative to *Baseline*.

While many studies in sub-Saharan Africa quantify GHG emissions from livestock production to inform domestic agricultural or climate policy, few consider the role of LUC in GHG accounts. For studies based on GLOBIOM (the Global Biosphere Model), a shift in land between agriculture and other uses is accounted for based on a land use transition matrix, and the land allocation solution to the model's objective function (Havlik *et al*. 2014). These studies unanimously find that reduced conversion of native ecosystems forms the largest component of reductions in GHG emissions (Havlik *et al*. 2014, Valin *et al.* 2013, Gerssen-Gondelaach *et al.* 2017). Brandt *et al*. (2018) and (2020) are the only other studies, to the knowledge of this author, which use a bottom-up approach, to inform climate policy in the livestock sector for any country in sub-Saharan Africa in a framework that includes LUC. The former, Brandt *et al*. (2018), study quantifies GHG emissions from converting grazing land to cropland; the latter, Brandt *et al* (2020), quantifies the same emission categories plus CO_2 emissions generated by livestock grazing in forests.

Chapters 4 and 5 of this thesis differ from Brandt *et al*. in that the implications of changes to both cropland and grasslands are included in the base scenario GHG inventory. Land use change is accounted for based on projected changes in demand for crop and grassland associated with the feed requirements of dairy cattle. Changes to feeding practices (chapter 4) and in the proportion of local to improved cattle breeds within each district (chapter 5) lead to changes in demand for crop and grasslands, and associated GHG emissions. In both chapters, interventions to increase the proportion of improved to local cattle, and parallel shifts in feeding practices result in reduced LUC relative to the base scenarios, demonstrating the importance of avoided CO_2 emissions from land sparing in dairy sector GHG mitigation.

A limitation of the methods used herein are that they are based on simplified assumptions about land use transitions. *Cropland expansion* is assumed to displace grasslands, and *grassland expansion* is assumed to displace a combination of land categories including shrubland, forest, and wetlands, jointly representing 'native ecosystems'. These assumptions are supported by analysis of historical land cover change in the study area. Using satellite imagery of Tanzania's southern highlands region from 2004 to 2018, Kayombo *et al*. (2020) found that cropland expansion was primarily a result of the conversion of shrub and grasslands; and grassland expansion was predominantly a result of conversion of shrubland, woodland, and forest. Msofe *et al*. (2020) additionally documented that in the Morogoro region of Tanzania, grassland expansion is the largest driver of the drainage and conversion of wetlands, which has led to 70% of total wetland area being transformed into grassland between 2010 and 2016.

6.4 Realising the mitigation potential: the enabling policy environment

The feeding and breed adoption scenarios evaluated in chapters 3 and 4 involve trade-offs for resource allocation within and amongst dairy producing households. Feeding higher quality diets necessitates households either diverting existing agricultural land to grow forages, or buy concentrate feeds. Adopting improved cattle requires an initial outlay of cash to acquire an improved heifer, as well as continued expenses on health and reproductive related inputs, feeds, and land to grow forages. *B. taurus* breeds are less adapted to high temperatures, which may depress appetite leading to energy deficits and reduced milk yield and fertility (King *et al*. 2006). Compared to *B. taurus*, *B. indicus* breeds are better suited to survive the diseases endemic to Africa, as well as more tolerant of prolonged periods of water scarcity (Mwai *et al*. 2015). As a result of poorer adaptability to the local environment, dairy producers rearing improved cattle must make up for these deficiencies using greater inputs of external veterinary care, and by taking measures to avoid feed shortfalls, such as through conservation or cultivation of additional quality forages.

The economic benefits for dairy producers under the scenarios evaluated in this thesis are first, greater milk production as a result of better-quality diets leading to higher yields per cow (chapter 4 and 5), and second, transition to a herd with higher genetic potential, leading to more milk production with a smaller herd (chapter 5). The results of chapter 5 show that greater milk revenue from improved cattle can offset the capital and opportunity costs of farmland re-allocation associated with improved cattle adoption. These scenarios therefore generally lead to net benefits for dairy households, however the magnitude of these benefits differ depending on the differences in herd sizes between the *Baseline* and roadmap scenarios. For *Adopters* (households adopting improved cattle) the total number of cattle reared declines by between 6-8 head across scenarios. However, the substitution of a herd with improved in place of local cattle leads to an increase in revenue of between 144 to 535 USD capita^{-1} yr^{-1} across scenarios. While chapter 4 does not quantity changes in household income, the benefits from improved feeding of cattle will primarily materialize in the form of increased income and nutritional status as a result of more milk produced per household.

For subsistence-oriented households, the benefits of adopting improved breeds, feeding practices, and spending on veterinary inputs and services are likely to be low. As demonstrated by Oosting *et al.* (2014), owning a large herd of unproductive local (*B. indicus*) cattle may generate the same production levels (milk and meat) as a small herd of improved cattle. However, a smaller herd ranks poorly on auxiliary benefits, such as manure, draught power and transport, and store of capital. The primary impetus for adopting improved cattle is likely to be as a means of increasing household income from the sale of milk. It is for this reason that empirical studies have often observed strong correlations between market orientation and access, with practice and technology adoption (Henderson *et al*. 2015, Duncan *et al*. 2013), and with productivity and GHG emissions intensities (Henderson *et al*. 2015, Hammond *et al.* 2017). As milk is a perishable product, timely access to procurement channels is necessary for farmers to view commercial dairying as an attractive livelihood pursuit. Including the dairy sector in climate change mitigation initiatives will therefore depend crucially on mechanisms which promote broad based and inclusive participation in supply chains.

6.5 Suggestions for future research

The methods for accounting for LUC have the benefit of (i) accounting for land use transition pathways which are corroborated by historical observation in the study region, and (ii) accounting for CO_2 emissions from land use transition pathways using domestically representative C stock data (Mauya *et al*., 2019 and Kempen *et al.,* 2018, as described in chapter 3). A limitation however is that the framework does not account for CO_2 losses or sequestration from land management within a given land use category; another mechanism whereby changes in management practices could lead to carbon losses or sequestration from land use (IPCC 2006). Future studies which aim to improve on these methods could adopt a 'hybrid' approach based on the methods herein and those of Brandt *et al.* (2020). This would have the benefit of both accounting for cropland and grassland conversion while also accounting for the impact of grazing or cropland management on CO_2 losses (or sequestration).

Chapter 5 of this thesis adopts an integrated assessment framework that links simulation modelling at production system level with an income accounting module derived from household survey data. Frameworks such as this have been widely developed in recent years, by studies such as Reed *et al.* (2020) and Salecker *et al*. (2019). However, there is significant statistical uncertainty in extrapolating household level data to regional level, and *vice versa* (e.g. downscaling regional level data to household level, as in chapter 5). Future studies could improve these methods by providing better estimates of the distribution of key model inputs such as herd sizes, input use, and alternative sources of income (farm or off farm). In the present study these variables are assumed to follow a normal distribution, which simplifies the income accounting framework. In reality however many household characteristics such as farm size, herd size, or income may be better approximated using a gamma distribution (many small farms and a few big ones). Another limitation of this framework is the inability to consider the dynamics of farm consolidation and division. The methods used assumed that the number of households rearing dairy cattle remain fixed throughout the period, and instead only the rate of adoption of new dairy breeds changes. Doing so allows the scenarios to be congruent with the *ex ante* simulations of the Tanzanian Livestock Sector Analysis. The TLSA's target population for adoption of improved cattle breeds are households already rearing *B. indicus* cattle breeds (URT 2017a), which provides the opportunity to account for these impacts assuming a fixed total number of dairy households. As a result of this assumption, the economic benefits per household are higher compared to what would have been realized if the entrance of new dairy households were considered (more cows per household, leading to higher dairy revenue). However it is unclear how significant an impact farm 'exits' could have had on these outcomes. Future studies could improve in this respect by accounting for entry and exits of (dairy) farming households in a more rigorous manner. Such an approach would need to take into consideration broader considerations than those considered here, such as the costs of establishing farm infrastructure for new dairy farming entrants, and potentially the economic benefits of liquidating physical assets for households exiting dairy. Another potential improvement in the socioeconomic impact assessment could involve more explicit accounting of farm heterogeneity. Herrero *et al*. (2014) is one example of a study that integrates regional, spatially explit modelling with household survety data, characterizing geographically and socioeconomically differentiated farming systems to explore adaptation to future environmental change. The current study could be improved in this way by, for example, linking the typology developed in chapter 3 to the scenario analysis of chapter 5. Future studies could improve on these methods by, for example, basing scenarios of adoption of improved practices or technologies with differentiation of households based on socioeconomic characteristics, such as the factors informing the typology in chapter 3.

6.6 Conclusion

This thesis has demonstrated the feasibility of linking dairy sector development initiatives with national climate change mitigation commitments. Results of modelling analyses show that an increase in the proportion of improved cattle breeds within the dairy sector is required for realizing milk production growth concurrent with reductions in GHG emission intensities at a rate consistent with Tanzania's NDC target. The modelling analysis included in this thesis is the first known example of an assessment to quantify the potential for improved productivity in the dairy sector to contribute to GHG emissions reductions as a result of a smaller dairy land footprint.

The results can therefore guide the development of climate policy in Tanzania and countries with similar biophysical characteristics, taking into account the potential for avoided LUC emissions and how they contribute to climate mitigation targets. Future studies should seek to better understand additional farm level tradeoffs not accounted for here, such as from household labour or auxiliary functions of livestock (store of capital, draught power, manure) in relation to adoption of improved breeds and feeding practices. The framework developed in this thesis represents one example of an interdisciplinary approach to guide the successful design of mitigation frameworks in the livestock sector, and has particular relevance in regions such as East Africa where LUC is known to contribute a disproportionate share of the livestock sector's GHG footprint.

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