Improved animal genetics deliver low emissions development in East Africa's dairy sector

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Analysis

Keywords:

Posted Date: April 13th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1536934/v1

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Abstract

Smallholder farm-households produce most of the crop and livestock products consumed in developing countries. Equitable transitions to low emissions food production will depend on policies that promote a reduction of greenhouse gases (GHGs) whilst improving these farmers' livelihoods. Here, using survey data and simulation modelling, we show that Tanzania's public programme to reduce import dependence through efficiency gains in the dairy sector increases farmer incomes (+12-20%) whilst reducing GHG emissions consistent with the Nationally Determined Contributions pledge (21-39%). Scenario analysis demonstrates that incrementally higher proportions of improved cattle (*Bos taurus* crosses) in the herd lead to greater reductions in GHGs over the *Baseline*, while benefitting producers through higher marketable surpluses and household income. As East Africa has the highest population density of indigenous *Bos indicus* cattle in Africa, genetic gains will be a key lever for reconciling food sovereignty with climate mitigation pledges throughout the region.

Introduction

Smallholder farms across the tropics are confronted with the need to adapt to a warming climate, including changes in growing seasons and heat stress limiting cattle productivity[1,2]. Yet, due to their importance for food security from local to regional scales across much of the developing world, these farms could play a crucial role in future transitions to low emissions food production systems. In Sub-Saharan Africa (SSA), agricultural productivity growth on smallholder farms has stalled in recent years; growth in crop and livestock production instead has mainly come through increases in cultivated areas and livestock populations[3,4]. Models have shown that productivity gains in crop and livestock supply chains will be crucial if future food demand is to be met with reductions in greenhouse gas (GHG) emissions[5,6]. International funding agencies can play important roles supporting climate mitigation pledges of African countries, because these countries' Nationally Determined Contributions (NDCs) are typically conditional on external funding and technologies[7]. The effectiveness of climate finance can be enhanced by quantitative evidence linking domestic policy to reductions in GHGs and positive development outcomes, such as enhanced food security or farmer income. Presently, concerns over high costs of mitigation and lack of standardised frameworks for quantifying benefits are major barriers preventing climate policy uptake [8,9].

Within the African continent, East Africa is relatively highly dependent on livestock -- especially bovine dairy animals -- which are present here in the highest density (heads sq. km^{-1}) on the continent, contributing as much as 23% to national agricultural GDP[10,11]. Tanzania has been endowed with the second largest herd in East Africa[12], yet like most countries in the region, the dairy sector is poorly developed. This is attributable to multiple factors operating across scales. On farm, poor feeding practices, reliance on unproductive breeds, and low uptake of external inputs/services limits productivity and results in low and highly seasonal surpluses[13]. Within the dairy value chain, poor handling and improper refrigeration results in frequent contamination and spoilage, which has led processors to commonly opt for imports over domestically produced raw milk[14]. Whilst factors such as these are common in Africa, in the case of Tanzania, low cost-competitiveness of the domestic dairy sector has resulted in particularly high reliance on imports for processed, value-added dairy products, equal to a net trade deficit of over 23 Million USD in 2020[15].

The 2016 'Dairy Development Roadmap' (DDR) was conceived as part of a broader 'Livestock Master Plan' to reduce import-dependence by improving productivity of the domestic dairy sector, allowing more cost competitive domestic production to substitute for imports[16]. Animal genetic gains are a prominent feature of the DDR's strategy; because of the low milk yield potential of the prevailing local *Bos indicus* breeds, promoting higher-than-historical adoption rates of improved *Bos taurus x Bos indicus* crosses was deemed essential for meeting production targets. In an accompanying feasibility study, the Tanzanian Livestock Sector Analysis (TLSA) projected that adoption rates leading to up to 60% improved cattle in high priority regions would enable Tanzania to reach self-sufficiency in dairy production by 2030, whilst additionally increasing income among households that adopt improved breeds. Consultations with sector stakeholders have confirmed genetic gains rank high among alternative interventions enabling the sector to fulfil production goals concurrent with other development benefits, indicating the validity of the DDR goals in fulfilling priorities of dairy farmers and sectoral stakeholders[18]. Breeds with high feed conversion efficiency are estimated to produce milk with up to 35% lower GHGs per litre, implying Tanzania's genetic improvement goals have inherent potential to reduce the dairy sector's carbon footprint[19]. Previous national-level assessments of these outcomes however have omitted the potential for avoided land use change to contribute to dairy's GHG mitigation potential, thus under-estimating the sector's climate mitigation potential[20,21]. In this way, an assessment to quantify the full magnitude of GHG reductions to be realised through improved breeds and the potential contribution to national development goals could be useful to inform climate mitigation policy in Tanzania's dairy sector, and by extension other sectors facing similar challenges.

Here we consider the potential for the animal genetics targets of the DDR to concurrently fulfil development objectives in Tanzania's dairy sector whilst reducing GHG emissions relative to the 'Business as usual' (*Baseline*) scenario. Development outcomes relate specifically to the fulfilment of 2030 milk production targets defined by the DDR, and the impacts on welfare of rural dairy producers through changes in household income. Simulations are conducted for the 2018 to 2030 period which allows calibrating our model with a 2018 household survey, and of aligning development and GHG outcomes with the DDR and Tanzania's official NDC mitigation pledge, which targets a 10% or more reduction in emissions from 'Business as usual' by 2030[22]. Four scenarios are evaluated which represent plausible outcomes of the DDR, differing only in the fulfilment of milk production targets, and the magnitude of animal genetic gains and associated adoption rates of improved cattle among households. Scenarios are conducted for four districts -- three in the southern highlands and one in Tanzania's coastal region, and the production and breed targets in these districts are aligned with the projections and targets of DDR for highlands and coastal regions, respectively. The main features of the scenarios, as differing from "Business as usual" (*Baseline),* were defined as follows (see Methods for additional details):

Status quo

Diets for improved and local cattle improve through greater provision of forages and concentrate feeds raising milk yields relative to the base year. Yet few households not already owning improved cattle adopt (< 3%); breed percentages thus remain fixed relative to 2018. Milk production growth equal to 70% of the 2030 targets are therefore met through higher milk yields per cow, but also relatively large increase in the dairy herd size (see Extended Data Table 1) due to the high proportion of local cattle in the herd.

Middle road

As in *Status quo*, milk yields improve through better feeding. A higher proportion (10-13%) of dairy households adopt improved breeds, leading to 50% realisation of the breed targets of the TLSA. Due to more improved cattle, the total dairy herd increases less than under *Status quo*, yet still fulfilling 70% of milk production targets.

High ambition

Differing from *Middle road* in higher breed adoption and associated genetic gains across districts. The percentage of dairy households adopting improved cattle are in line with the TLSA projections, leading to full realisation of the animal genetics targets in each district simulated. Because of higher a percentage of improved cattle, the increase in herd size is the smallest among scenarios.

High ambition ++

Differing from all other scenarios in that milk production targets are fully realised across districts. This is accomplished through ambitious animal genetic gains consistent with the targets defined under the TLSA for each region (highlands and coastal, respectively) and relatively high improved breed adoption rates.

For each scenario, the household income accounting considers changes in herd management (herd size and breeds) and feeding practices for three dairy household types, henceforth defined as:

(i) *Local-only*, households owning only local cattle in the base year of 2018 who do not adopt improved cattle,

(i) *New-Improved*, households adopting improved cattle in 2018 in place of local cattle, and

(iii) *Extant-improved*, households who own only improved cattle throughout the 12-year simulation period.

Results

Milk yield and GHG footprints

The adoption of improved feeding practices leads to higher dry matter intake and more nutrient dense diets for local and improved cows under the roadmap scenarios (see SI Table 5 for dietary changes in reference to the 2018 base year diets). These changes result in increases in milk yields for local cattle by as much as 179% to a regional average of 736 kg FPCM yr^{-1} in the highland districts, and as much as 141% to an average of 701 kg FPCM yr^{-1} in the coastal district of Mvomero (Extended Data Table 1). For improved cattle milk yields increase by up to 137% in highlands districts to a region-wide average of 2,861 kg FPCM yr^{-1} (+93%). In Mvomero they increase to a district average of 2,414 kg FPCM yr^{-1} (+135%).

Relative to historically extrapolated herd population growth under *Baseline*, the feeding and genetics gains under the roadmap scenarios lead to the fulfilment of production targets with small to moderate reductions in herd sizes relative to the *Baseline* (see full results in Extended Data Table 1). Under *Status quo* where genetics proportions remain fixed in the base year, the feeding improvements would allow meeting production targets with a 18% reduction in the dairy herd size (Extended Data Table 1). As a result of increases in proportions of improved animal genetics under *Middle road* and *High ambition,* the total dairy herd would decrease by 30 and 38%, respectively. Under *High ambition* ++ herd sizes would decrease by 21% relative to *Baseline*. Overall the results of herd scaling outcomes suggest goals to fulfil production targets are achievable and indicate that improved genetics could help reduce the total herd size by up to 20% relative to the counterfactual scenario with breed compositions fixed at their base year values.

The *Baseline* GHG emission intensity is 9.5 ± 1.5 kg CO_2eq kg^{-1} FPCM (fat- and protein-corrected milk) (Fig 1a). Of the total GHG footprint, 37.1% ± 6.4% is from direct sources, including enteric fermentation, manure, crop and grassland soils, and fossil energy use. Crop and grassland expansion to supply the dairy herd accounts for the other 62.9% ± 10.9 of the CO_2 emissions. GHG emissions and emissions intensities, excluding land use change (LUC) and disaggregated by breed are provided in Extended Data Fig. 2. Emissions intensities for improved cattle estimated here as 1.9 ± 0.4 kg CO_2eq kg^{-1} FPCM are consistent with those estimated by FAO which ranged from 1.9-2.2 kg CO_2eq kg FPCM^{-1} excluding LUC emissions[23]. For local cattle, emissions intensities estimated here as 9.1 ± 1.1 kg CO_2eq kg^{-1} FPCM are 55-68% lower than the national average estimates by FAO of 20.3-28.8 kg CO_2eq kg^{-1} FPCM[23]. These higher intensities by FAO result from the high proportion of cattle raised in the less productive arid and pastoral production systems. Our estimates of GHG emissions from LUC at 63% of the dairy GHG footprint correspond well with the 48-62% estimates by the GLOBIOM model for dairy in sub-Saharan Africa, using comparable land use emissions accounting methods[24,25].

Scenario *Status quo* reduces emissions intensity by 50.6% ± 6.6% to 4.7 ± 0.6 kg $CO_2eq\ kg^{-1}$ FPCM due to higher milk yields and reductions in dairy land use (Extended Data Fig. 1). Scenarios *Middle road* and *High ambition* result in reductions in emission intensity by 56.5% ± 5.3% to 4.1 ± 0.5 kg $CO_2eq\ kg^{-1}$ FPCM and by 61.4% ± 4.3% to 3.7 ± 0.4 kg $CO_2eq\ kg^{-1}$ FPCM, respectively. Scenario *High ambition ++* similarly results in a reduction in emissions intensity by 61.5% ± 5.7% to 3.7 ± 0.5 kg $CO_2eq\ kg^{-1}$ FPCM. All the scenarios considered result in absolute emission reductions on par with the 10% reduction target of the NDC (Fig. 1b, c). These reductions are in the amount of 21.4% ± 10.4% (*Status quo*), 30.8% ± 8.6% (*Middle road*), 38.6% ± 7.4% (*High ambition*), and 22.7% ± 11.4% (*High ambition* ++).

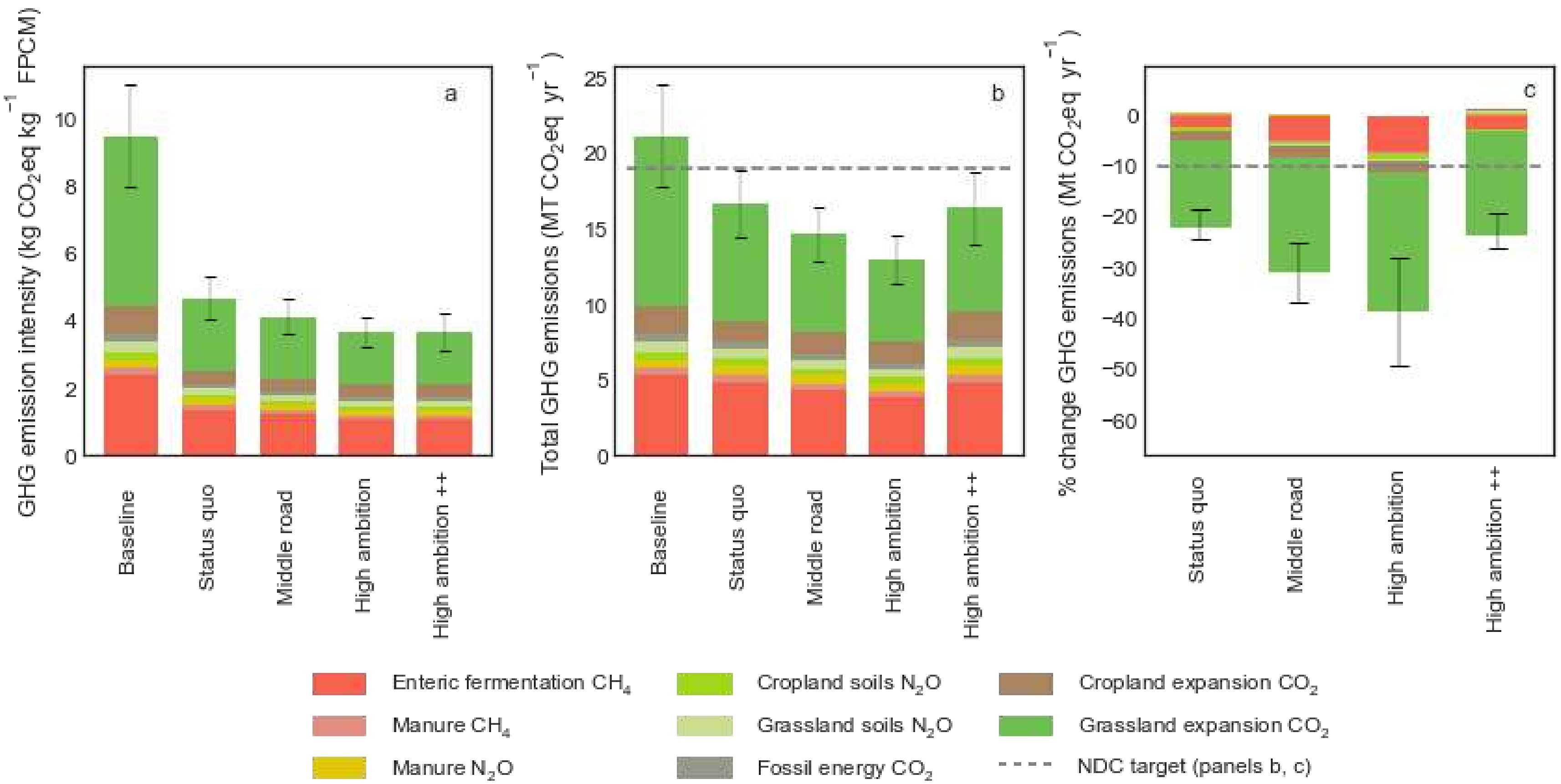

Figure 1: Greenhouse gas emissions from different scenarios: *Baseline*, *Status Quo*, *Middle road, High ambition, and High ambition ++.* (a) Emissions intensities expressed in kg CO_{2eq} per kg of fat and protein corrected milk (FPCM), (b) Absolute emissions for the simulated region expressed in Megatonnes of CO_{2eq} (1Mt =10^6 tonnes), (c) Percent change in absolute emissions relative to *Baseline* scenario. Error bars indicate 95% confidence interval based on uncertainty analysis (see Methods). Dotted lines on panels b and c indicate targeted reduction level of Tanzania's Nationally Determined Contribution which is defined as a 10% reduction from *Baseline*. FPCM = fat- and protein-corrected milk.

Effects on dairy household income

Under the roadmap scenarios, herd sizes (Fig. 2a) for *Local-only* households increase the highest under *Status quo* (4 head), followed by *High ambition ++* (3 head), and *Middle road (2 head).* Under *High ambition* they decline by 1 head as this scenario leads to the smallest herd size increase and the smallest quantity of local cattle. Herd sizes for *Extant-improved* households (maintaining improved cattle) are on average small for the *Baseline* (mean = 3 head) and increase by relatively small amounts (0 to 1 head) across the scenarios. For *New-improved* households, herd sizes decrease by 6 to 8 head across scenarios. As these households substitute herds of local for improved cattle, higher milk production increases income by between 21% (*Status quo*) to 71% (*High ambition*), for a growth in income of 151 to 534 USD capita^{-1} yr^{-1} among these farming-households. For *Local-only* households, increases in income are highest under *Status quo* (+138 USD capita^{-1} yr^{-1}) (+18%), followed by *Middle road* (+99 USD capita^{-1} yr^{-1}) (+13%), and *High ambition ++* (+78 USD capita^{-1} yr^{-1}) (+4%). Under *High ambition* income remains relatively constant with the *Baseline* (< 1% change). For *Local-only* households income increases are inversely correlated with the rate of genetic gains, because higher proportions of improved cattle results in less local cattle per household (Fig. 2a), implying lower income due to less milk production for these households (Fig. 3a). For New-*improved* households, income increases across all scenarios, ranging from +21% (+140 USD capita^{-1} yr^{-1}) under *Status quo* to 71% (+205 USD capita^{-1} yr^{-1}) under *High ambition* (Fig. 3a).

Impacts on all dairy households

As the average for all dairy households in the simulated region, the roadmap scenarios result in herd size changes ranging from small declines under *High ambition* to increases of up to 2 head per household under *Status quo* (Fig. 2b). Average income among dairy farm households increases from 941 USD capita^{-1} yr^{-1} for *Baseline* to 1,053 USD capita^{-1} yr^{-1} (+12%) for *High ambition*, 1,087 USD capita^{-1} yr^{-1} (+16%) for *Middle road*, 1,106 USD capita^{-1} yr^{-1} (+18%) for *Status quo*, and 1,132 (+20%) for *High ambition ++.* Thus the roadmap scenarios result in positive aggregate impacts in income or nutrition benefits among dairy households, despite trade-offs with respect to capital expenditures and land allocation associated with adopting improved cattle and changing feeding practices (see Methods for how cash expenses and land use trade-offs are considered for dairy farming households).

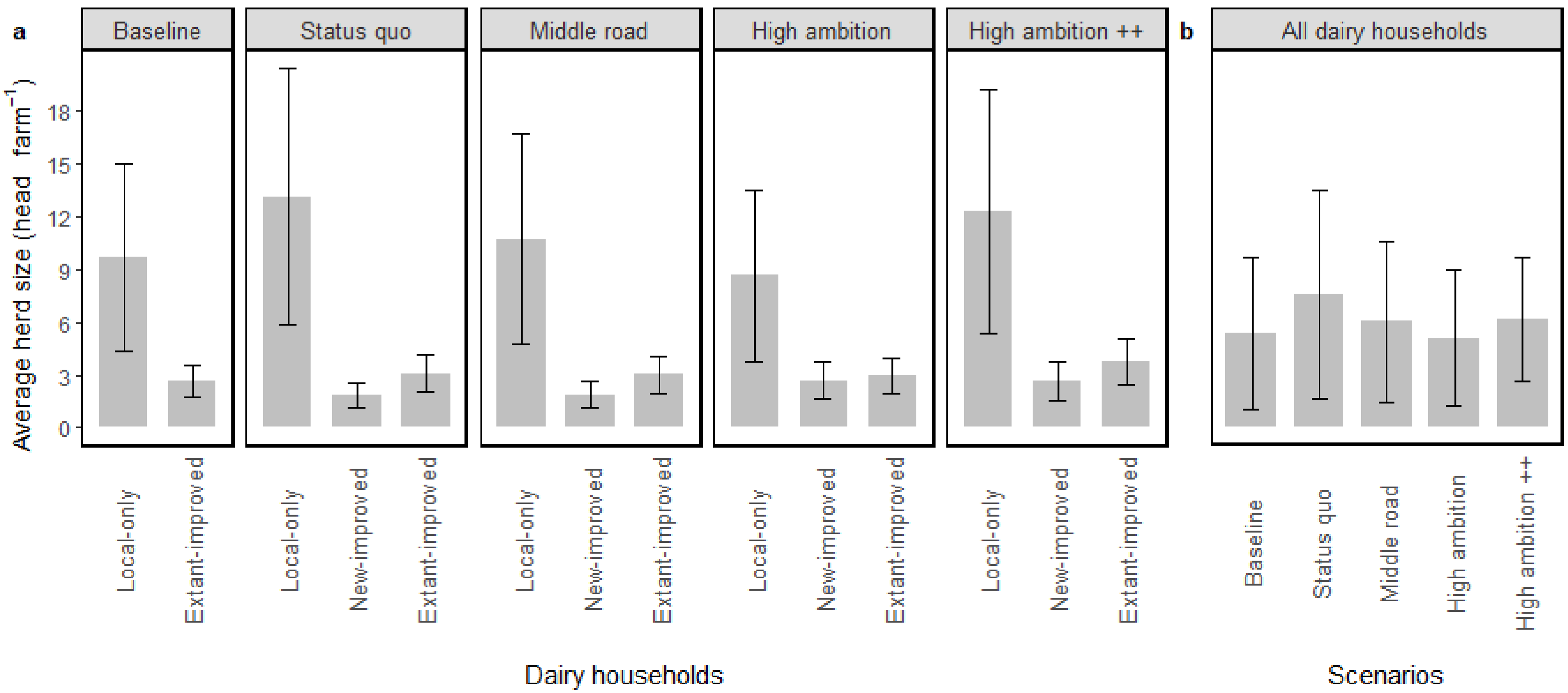

Figure 2: Herd sizes associated with dairy development scenarios. (a) shows mean herd size for each dairy household type, and (b) shows mean herd size for all dairy households accounted for in the simulations. Household types defined as: 'Local-only' – households rearing local cattle who do not adopt improved cattle, 'New-improved' – households rearing local cattle who adopt improved cattle in 2018, and 'Extant-improved' – households already owning improved cattle in 2018 and who maintain the same breed throughout the simulated period. Error bars indicate one standard error of Monte Carlo simulations (see Methods Uncertainty).

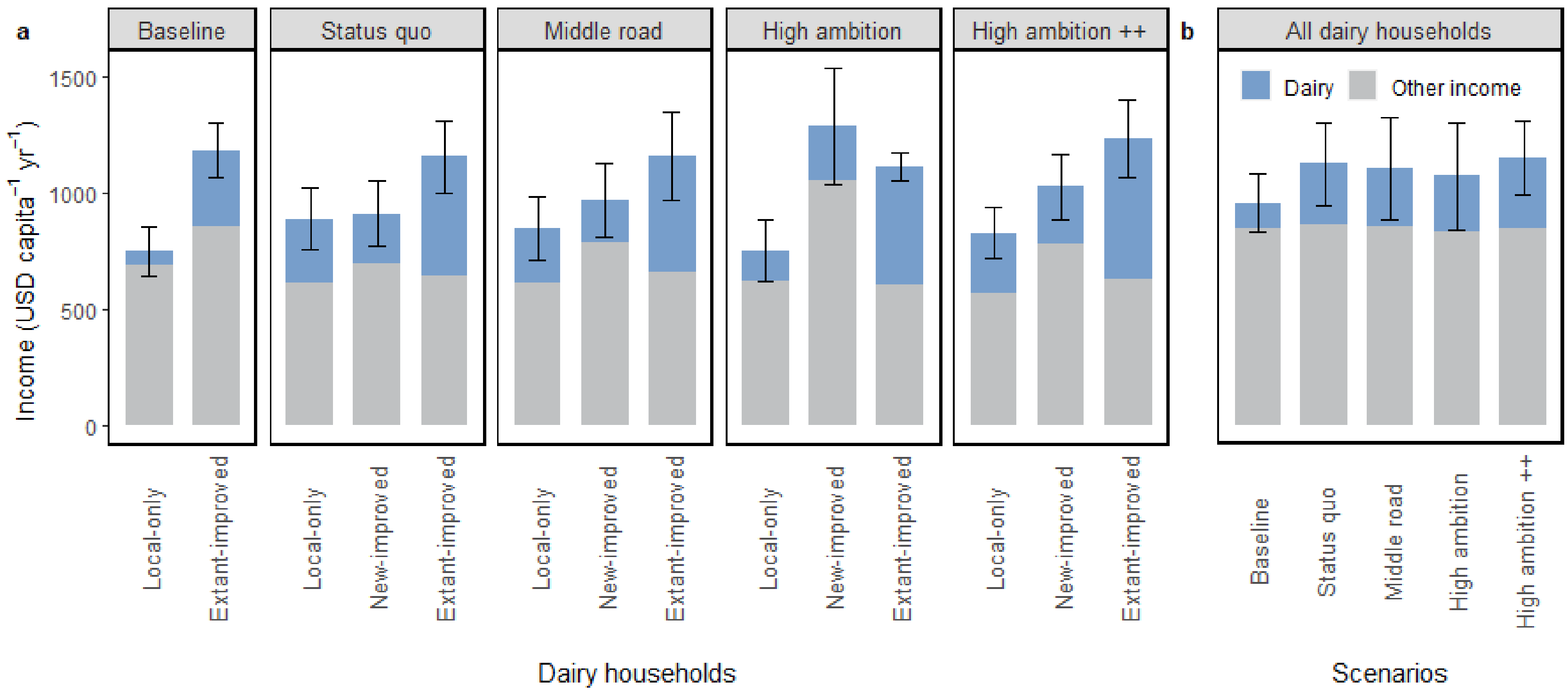

Figure 3: Dairy household income across scenarios. (a) Shows mean income per capita for the three dairy household types. (b) shows average income per capita for all dairy households included in the simulation. Household types defined as: ‘Local-only’ – households rearing local cattle who do not adopt improved cattle, ‘New-improved’ – households rearing local cattle who adopt improved cattle in 2018, and ‘Extant-improved’ – households already owning improved cattle in 2018 and who maintain the same breed throughout the simulated period. Error bars indicate one standard error of Monte Carlo simulations (see Methods Uncertainty).

Sensitivity to milk and concentrate prices

Broad-based uptake of productivity enhancing practices among dairy farmers may lead to market feedbacks including reductions in the price of milk and/or increases in input prices. As this study does not evaluate such outcomes explicitly in a market equilibrium framework, the potential impacts of reductions in milk prices and increases in concentrate feed prices are estimated using sensitivity analysis. Prices for the respective inputs/outputs are assumed to change by +/- 20% for the partial (70%) milk production target scenarios and by +/- 35% for scenario *High ambition*++. Income changes among dairy households are evaluated against these price changes implemented first on a *one-at-a-time* basis and then *two-at-a-time* (changes in multiple variables)(Table 1).

Results indicate that dairy household income is most sensitive to changes in milk prices, with reductions in income by up to 8% under the 70% milk target scenarios, and as much as 15% under *High ambition++*. When milk price reductions are combined with increases in concentrate feed prices, income declines as much as 9% (70% milk target scenarios) and by 18% (*High ambition*++). As these income reductions are relatively consistent with the income gains resulting from the roadmap interventions, the results of sensitivity analysis suggest that such price changes would in the most extreme case nearly negate the income gains from the DDR interventions.

Table 1: Sensitivity analysis. Impacts of declines in milk prices and increases in feed prices on dairy household income across scenarios.

No.	Variable	Percent change	Scenario	Change in income (relative to scenario) (all dairy households)	
				Absolute value (USD $capita^{-1}$ yr^{-1})	Percent
1	Farm-gate milk price	*-20*	Status quo	-88	-8.0
			Middle road	-81	-7.4
			High ambition	-76	-7.2
2		*-35*	High ambition++	-167	-14.8
3	Maize bran, sunflower cake prices	*+20*	Status quo	-19	-1.7
			Middle road	-17	-1.6
			High ambition	-16	-1.5
4		*+35*	High ambition++	-20	-1.8
5	1 and 3 combined		Status quo	-107	-9.7
			Middle road	-98	-9.0
			High ambition	-92	-8.7
6	2 and 4 combined		High ambition++	-203	-17.9

Source: This study

Aligning development goals with mitigation pledges

Findings indicate that incrementally higher proportions of improved breeds in the herd, demonstrated through scenarios *Middle road* and *High ambition*, lead to progressively lower GHG emissions for a given production level (Fig. 1b, c). Higher proportions of improved breeds allow production targets to be fulfilled with lower total herd increases under scenarios *Middle road* (-8%) and *High ambition* (-20%) compared to scenarios where breed proportions are fixed at their base year values (*Status quo*) or based on historical projections (*Baseline*) (Extended Data Table 1). Smaller herd sizes in turn result in lower GHG emissions relative to the less ambitious targets of *Status quo* and *Baseline*, in large part because of avoided emissions from land use change associated with a smaller, more efficient herd. GHG accounting results (Fig. 1c) show that 45-70% of the total mitigation potential across the scenarios is a result of avoided crop and grassland expansion, which is consistent with continent-scale modelling analyses conducted for dairy and beef production in Africa using the GLOBIOM model[23,24]. While these studies have demonstrated the influential role of land sparing in realizing climate mitigation potentials in the dairy sector, they have omitted entirely the role of genetic gains in contributing to such GHG mitigation potentials. The present study therefore is the first to find that development ambitions focussing on production targets and positive impacts on producer livelihoods can fulfil such goals consistent with mitigation pledges in a national context for any country in the region.

Costs, benefits of improved dairy breeds

Farm-level affordability has been highlighted as one of the largest barriers to scaling low emissions development practices in Africa's livestock sector[26]. Previous analyses in Tanzania have noted a significant time lag -- as long as 10 years -- between adoption and the break-even period when the dairy enterprise reaches profitability[27]. Further, technology adoption that is broad-based may lead to market impacts that reduce the (producer) price of milk, or increase prices of common inputs, in turn negating income gains from adopting new technologies, especially for late-adopters[28]. Results of this analysis clearly show that adopting households *New-improved* and *Extant-improved* benefit more than non-adopting *Local-only* (Fig 3a). This implies inherent distributional outcomes from fulfilling breed targets under Tanzania's dairy development roadmap. As breed targets necessitate a reduction in local cattle populations, it can be expected they will have inherent impacts on livelihoods of farmers dependent on local breeds who do not adopt improved. Thus, whilst the interventions prioritized by the DDR may represent a viable pathway for the low emissions development of Tanzania's dairy sector, these targets and priorities may not necessarily be 'pro-poor', based on current understanding.

Policy implications

Quantitative evidence provided here demonstrating the potential for transitions to herds with improved genetics to contribute to fulfil GHG targets hold broad significance for achieving development-friendly climate mitigation in East Africa. The region has the highest concentration of indigenous cattle in all of Africa[2]; the two largest herds of Ethiopia and Tanzania, with respectively 70 and 28 Million head[13], are both comprised of over 95% *Bos indicus* breeds[30,31]. Investment programmes targeted to support genetic gains in production systems high agro-ecologic potential and good market access could support domestic ambitions to reduce import dependence whilst improving livelihoods of rural livestock producers, in line with GHG reduction pledges under the Paris agreement.

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Methods

Milk production in south-coastal Tanzania

The study simulates milk production for three districts in the Tanzanian southern highlands region (Rungwe, Njombe and Mufindi), and one district (Mvomero) in proximity to the major dairy consuming region of Dar Es Salaam (the Tanzanian capital) (Fig. 4a). The study region is categorised as mid to high agro-ecological potential for dairy, namely mixed rainfed tropical (MRT) and humid (MRH) systems, following Robinson *et al.* (2011)[32] (Fig. 4d), which cover 11,700 km^2 (MRT) and 8,200 km^2 (MRH) for a total area of 19,900 km^2. Between 20-35% of rural households in these regions own cattle[28]: smallholder farmers are the predominant dairy producers with herds of up to 10 heads of cattle and agropastoral households own herds of up to 30 heads of mainly local cattle. Milk produced is primarily consumed on farm, with only about 10% being sold in informal supply chains[33]. Cattle feed on diets of grazed biomass, cultivated forages, concentrates purchased on the market, and crop residues provided after the crop harvest[34]. As a result of the unimodal rainfall pattern, resulting in a six-month dry season (May-October), feed quality and quantity is highly seasonal. Crop residues, concentrates, and hays or silages are used to reduce feed deficits during the dry season[34].

Dairy farm-households

To characterise dairy farms, this study uses data from a household survey conducted in 2018, as part of IFAD's Greening livestock project. The 'Greening livestock' survey[35,36] is a survey of 1,147 crop-livestock farm-households rearing dairy cattle, based on stratified random sampling across the four districts. All households in the dataset own at least one of either local or improved cattle, less than 10% of the sample own both. Households are stratified into stratum 1 (39%) with households rearing local cows only, and stratum 2 (61%) with households rearing one or more improved cows. Only 16% of stratum 2 households own local cows. Therefore, to keep the analysis simple this study does not account for revenue and expense streams associated with local cattle for stratum 2 households. Using locations of the farms, data from the two strata provide geo-referenced model inputs for cattle diets, and parameters for income accounting.

Methodology

The modelling framework links spatially-explicit data of livestock production systems[29] and simulation modelling with farm-level income accounting (Fig. 5). Cattle production is simulated with the *Liv*estock *Sim*ulator (hereafter *LivSim*[37]), which simulates feeding, milk production and cattle excreta for eight simulation units: 4 districts x 2 production systems (MRT and MRH). Under the scenarios cattle populations are scaled relative to *Baseline* in relation to the 2030 milk production and breed adoption targets (see Scenarios). In each simulation unit the *Baseline* cattle populations are projected through a 12-year period between the year of the GLS survey 2018 and 2030 using historical growth rates. Land use change and GHG emissions for each scenario are quantified using a land footprint indicator and life cycle assessment[38].

In a second step, the populations of respective cattle breeds are allocated to dairy households under alternative scenarios. The quantity of dairy households in the base year (2018) in each district rearing local and improved cattle are interpolated based on district livestock populations and average herd size per household (see 'Model calibration'). For *Baseline,* households maintain the same cattle breeds throughout the simulation period. The scenarios consider incremental steps towards meeting the milk production and genetics targets provided by the Tanzanian Dairy Development Roadmap, and the economic impacts of the scenarios on dairy households are accounted for as 'imputed income'. This indicator includes the monetary value of food production consumed at home plus cash sources of income (including off-farm). Household income for each scenario is calculated based on the new herd sizes, net costs associated with adopting improved cattle, better feeding and more intensive use of inputs (see 'Income accounting'). Income sources other than from production of milk are treated as exogenous, and total household income is then calculated and divided by the average household size to calculate annual income per capita.

Dairy cattle simulations

LivSim is used to simulate individual cattle representing different cohorts over their lifetime. 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 'Life cycle assessment of milk production') are aggregated across populations of local and improved cattle and simulation units and reported as a total over all simulation units. Table S1 summarises breed coefficients used in *LivSim*, these coefficients are based on *B. indicus* (local) and *B. indicus* x *B. taurus* crosses (improved) within southern Tanzania and the East Africa region [39,40,41,42,43,44,45,46,47]. Feed quality parameters are derived from FAO's 'Feedipedia' database[48] and from representative feed nutrient sources[49,50] (Table S7).

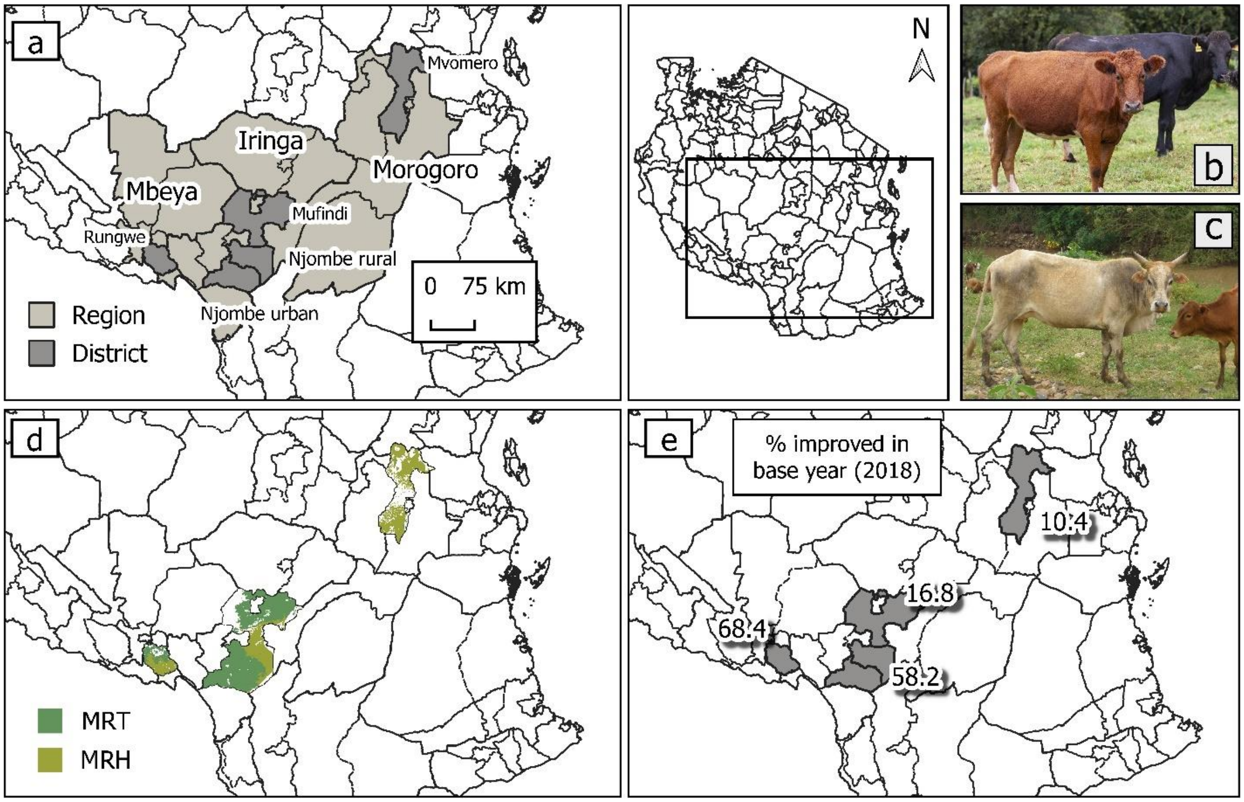


Figure 4: Overview of key geographic data and depiction of main cattle breeds considered in study. (a) location of study region within Tanzania showing regions and districts used in simulations, (b) improved (*Bos taurus* x *Bos indicus)* and (c) local cattle (*Bos indicus*) breeds considered in model, (d), production systems simulated (MRT = Mixed rainfed tropical, MRH = mixed rainfed humid), (e) dairy breed composition for base year (2018) as % improved cattle for each simulated district. Base year herd genetic compositions are based on the Greening Livestock Survey (GLS 2019). Photo credits 'Greening Livestock Project' (panels b, c).

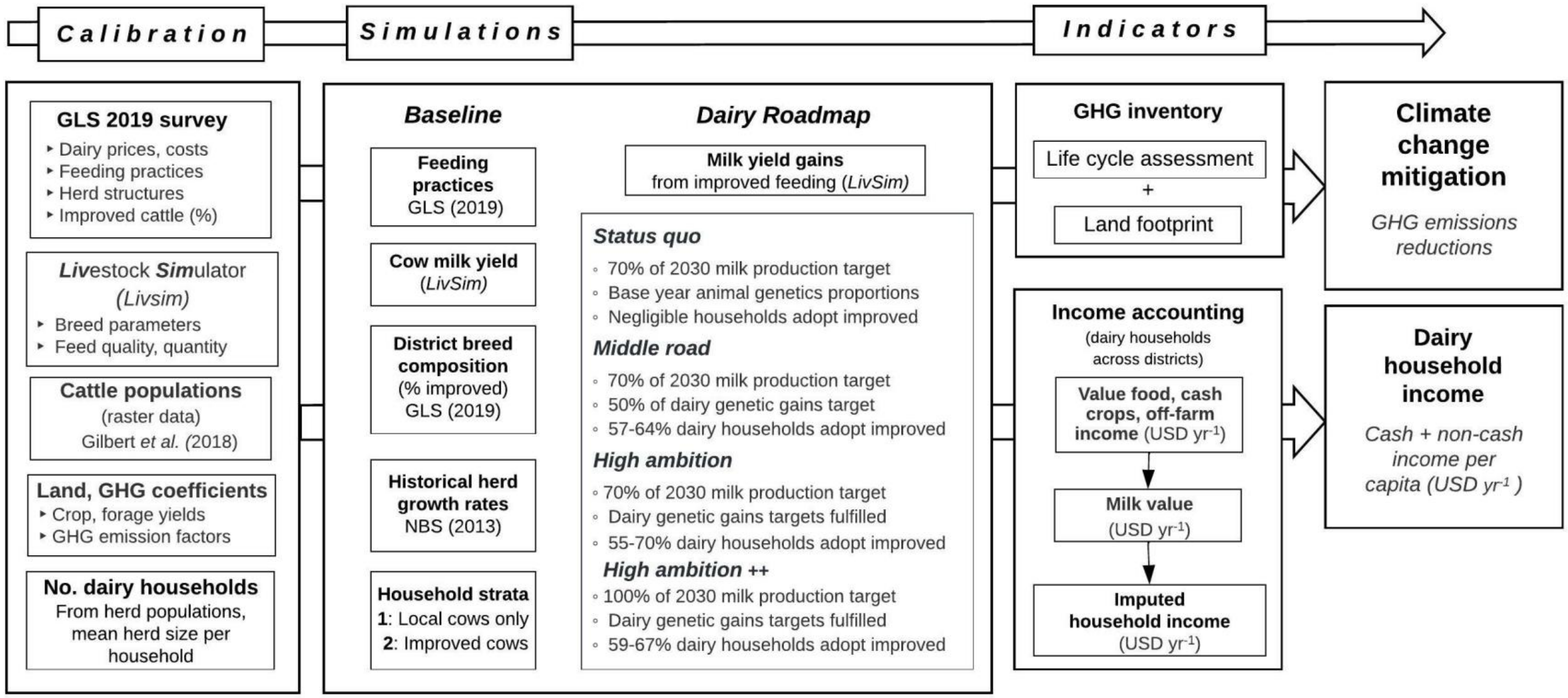


Figure 5: Outline of model workflow simulating GHG emissions and income for dairy households across four districts. Calibration involves specifying parameters from the household survey, for local and improved cattle in the livestock simulation model *LivSim*, herd population and activity data for life cycle assessment (LCA), and number of dairy households per district. Simulations represent respectively a *Baseline* (‘Business as usual’) and four scenarios involving variations of roadmap objectives. Impact indicators include dairy GHG emissions quantified using the LCA and land footprint indicator, and household income based on the milk yield, herd sizes, and input use associated with each scenario.

Dairy land footprint

The land footprint is calculated with feed biomass, land use, yield and feed use efficiencies of each feedstuff[38]. Changes in herd size for each scenario results in changes to the demand for cropland and grasslands and land use transitions which are used to calculate CO_2 emissions in the LCA (see 'CO_2 emissions from land use change'). The land footprint considers main feedstuffs: Maize bran and sunflower cake are the two main dairy supplements in south and coastal Tanzania[34]. Forages include native grasses, managed pasture, and Napier grass (*Pennisetum purpureum*) as the high-quality feed used by dairy households in the region[34,36]. Maize stover is the most consumed crop residue. These feeds are sourced domestically[34,51] 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 (Table S2). Yield growth of feed crops are projected throughout the simulation period following historical growth rates of 3.4% for maize and 4.1% for sunflower[52].

Model calibration

Populations of cattle for base year are obtained from a gridded livestock population dataset[53], extrapolated from the source year (2012) with district-level historical herd growth rates. The ratio of dairy to total cattle is total cattle minus beef cattle and oxen taken from census data[54]. For local and improved breeds, the ratio of each cohort as a fraction of the respective herd are from GLS (2019)[36] (Table S3). Breed composition for 2018 for each district is shown in Figure 4e. This population and herd structure are then mapped to spatial datasets of MRT and MRH production systems 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 agricultural households. Households rearing each breed are therefore triangulated from the cattle population[53] and survey data[36], using respective herd populations, and mean herd size per household strata as:

$$Dairy\ households_{d,s} = \frac{Cattle\ population_{d,s}}{Mean\ cattle\ per\ household_{d,s}} \quad (1)$$

Where *Dairy households*, is the number of households rearing dairy cattle, local or improved, *cattle population* is the population of dairy cattle, *Mean cattle per household* is the average head of cattle in the survey year for a given household, and indices *d* and *s* represent districts and household strata, respectively. The cattle populations for respective breeds, local and improved, in equation (1) map to stratum 1 and 2 respectively. This equation therefore relates the number of households owning a given breed, local or improved, to the number of each breed in the population.

Scenarios

Baseline. Populations of cattle grow at historical annual rates of 3.2% for local and 4.3% for improved calculated from regional census data for the four districts for the 2003-2008 period[55]. Cattle diets used in the *Baseline* are taken from the household survey for households with local *vs* improved cattle. Detailed diets are provided in SI 1 and Table S4.

Under the roadmap scenarios, herd sizes are scaled based on the requirements to meet milk production targets in each district, given the milk yields and breed compositions per scenario. Scenarios *Status quo*, *Middle road*, and *High ambition* are based on 70% of the milk production targets and *High ambition ++* considers reaching production targets in full in each district. Herd sizes to meet the production target with milk yields and breed composition are determined by multiplying the herd size under *Baseline* by a scaling factor, as follows:

$$H_{d,l} = T_{d,l} \times \frac{\sum_s Cows_{b,l} \times Frac\_s\_b_{s,l} \times Yield_{b,s,l}}{\sum_s Cows_{b,l} \times Frac\_s\_r_{s,l} \times Yield_{r,s,l}} \quad (2)$$

Where *H* is a herd scaling factor for district *d* and production system *l* (MRT and MRH), *T* milk production growth over *Baseline*, *Cows* is the population in each scenario, *Frac_s* are the fractions of local or improved cattle in the *Baseline* ('_b') or roadmap scenarios ('_r'), and *Yield* is the milk yield in kg FPCM cow^{-1} yr^{-1} under the baseline ('b') and roadmap ('r') scenarios for either local or improved cattle in a given simulation unit.

Cattle diets under the roadmap scenarios are designed to reflect the types of feeding practice changes the roadmap has prioritized. These involve increased feeding of silages and hays to reduce seasonal feed deficits, greater year-round provision of high-quality forages, and supplementation with energy and protein concentrates[16]. The diets under all the roadmap scenarios are implemented for cows only and are assumed constant across the four scenarios. Feeding changes involve greater provision of *Napier* grass year-round and as silage during the dry season, and supplementation with maize bran and sunflower cake according to the lactation cycle of the animal (see full summary in Table S4).

Production and genetics targets

Scenarios *Status quo, Middle road and High ambition* simulate achieving 70% of the production growth target to 2030, differing only in the rate of animal genetic gains (% improved to total cattle per district), and the associated adoption rate of improved cattle among dairy households (Extended Data Table 2). Scenarios *Status quo*, *Middle road*, and *High ambition* represent genetic gains outcomes representing the variability between the values observed in 2018 and the targets defined under the DDR, at respectively 0, 50%, and 100% of the targets for scenarios *Status quo*, *Middle road*, and *High ambition* respectively (Extended Data Table 2). Production targets are specified respectively for highlands and coastal districts by extrapolating the DDR projected growth rates for respective regions to 2030 using a linear growth rate. The resultant level of production growth is defined as a percentage increase over the base model year (2018), equal to 234% (highlands) and 152% (coastal) the base year (2018) milk production values.

Animal genetics targets and household adoption are similarly aligned with the DDR which stipulate targets of 60% (highlands) and 27% (coastal) improved cattle as a percentage of all cattle in a given district, and 60% (highlands) and 45% (coastal) of dairy producing households adopting in a given district. The household adoption rates under these scenarios are coordinated with the targets of the DDR: the percentage of the adoption rate fulfilled under each scenario is proportional to the genetics target of the respective scenario. That is, under *Status quo* no households adopt new improved cattle; under *Middle road* the adoption rate fulfils 50% of the DDR target; under *High ambition* the adoption rate entirely fulfils the DDR adoption targets. *High ambition++* is designed to represent a highly optimistic scenario with respect to both production growth and genetics targets, fulfilling the production targets as well as the animal genetics targets in full for each district. The quantity of households adopting are assumed to be the same as under *High ambition*.

Dairy greenhouse gas emissions

Direct emissions from cattle and feed production are based on IPCC equations[56]. The CO_2 emissions associated with the use of fossil energy for feed and N fertiliser inputs are calculated based on the amount of maize bran and sunflower cake consumed by the dairy cattle. Fertiliser application rates are 20 kg N ha^{-1} yr^{-1} for maize and sunflower, and 10 kg N ha^{-1} yr^{-1} for food crops, following typical N fertiliser rates for the south and coastal regions of Tanzania[57,58]. Soil N_2O fluxes per land use type are shown in Table S2. Emissions are allocated to FPCM (fat- and protein-corrected milk) and meat using mass allocation according to the total FPCM production of and meat expressed in kg. Simulated milk production is converted to FPCM by standardising to 4.0% fat and 3.3% protein[59]. Meat production is calculated as carcass weight of culled adult females, and young males either culled or sold as is common practice by Tanzanian dairy farmers[60]. Liveweights at time of culling are based on simulated liveweight from *LivSim* and a dressing of 52%[61] is applied to calculate dairy-meat output. Details on methods and procedures used in the LCA are in SI 2.

CO_2 emissions from land use change

LUC is calculated assuming two transition pathways: *cropland expansion,* where croplands displace grasslands, and *grassland expansion*, where grasslands displace other native ecosystems. Changes in dairy feed demand associated with changes in diets and breeds increase areas dedicated to croplands for the scenarios. However, the decline in grassland areas are higher than the increase in cropland areas, and therefore the total dairy land footprint declines. Dairy feed intake and corresponding land use changes are shown in Fig. S2. The CO_2 emissions resulting from LUC are based on carbon stock differences between land uses, as calculated from spatially-explicit land cover and carbon density data, described in SI2 and reported in Table S2. The actual amount of grassland converted from native ecosystems is calculated by relating the area required for each scenario, and the spatially-explicit availability of grasslands[61], described further in SI 3.

Household income

Imputed income for each dairy household is computed as the sum of gross revenue from dairy and all other household income, minus the cost of cash expenses and the change in crop income from substituting land dedicated to food or cash crops to produce cultivated forages required to meet cattle demand:

$$\textit{Total income}_{d,t} = \textit{Dairy income}_{d,t} + \textit{Crop income}_{d,t} + \textit{Other income}_{d,t} \quad (3)$$

Where $\textit{Total income}_{d,t}$ is all sources of household income for a dairy household of type t in district d, $\textit{Dairy income}_{d,t}$ is the annual cash value of production for the dairy enterprise in USD yr^{-1}, $\textit{Crop income}_{d,t}$ is the cropping income in USD yr^{-1}, and $\textit{Other income}_{d,t}$ is all income other than dairy income or changes in crop income in USD yr^{-1}. The indices d and t represent the four districts (Mufindi, Mvomero, Njombe, Rungwe) and three household types (*New-improved, Local-only, Extant-improved*) respectively.

Dairy income is calculated using mean number of cattle per household type for each district and stratum and simulated milk yields per cow (Extended Data Table 1). 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 (Extended Data Table 1). Milk income is calculated as the market value of annual milk production per household, net of costs related to acquiring improved animals (for *Improved-adopting*) and variable costs of feeding and animal husbandry. Adoption of improved cattle is assumed to occur by purchasing improved heifers. The cash value of production from the dairy enterprise is estimated based on annual feed and animal husbandry cash expenses and (for *Improved-adopting*) the one-time cost of purchasing improved heifers, spread evenly over the 12-year simulation period according to:

$$\textit{Dairy Income}_{d,t} = \textit{Milk value}_{d,t} - \textit{Dairy expenses}_{d,t} - \textit{Cost of Heifers}_{d,t} \times \left(\frac{1}{12}\right) \quad (4)$$

where *Milk value* is the monetary value of milk production from cows in the herd in USD yr^{-1}, *Dairy expenses* are the variable cash expenses for the dairy herd in USD yr^{-1}, and *Cost of Heifers* is the cost of acquiring new improved heifers in USD for *Improved-adopting* households. For New-*improved-adopting*, no revenue is received until a nine month pregnancy has passed representing the period until the purchased heifer(s) delivers a 1st calf. Parameters in equation (4) are then updated reflecting those of 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 of cows in the herd multiplied by milk yield per cow (Table 1), multiplied by the farm gate milk price in USD $litre^{-1}$. Milk yields are converted to litres using a density of 0.97 litres kg^{-1}. Table S11 summarises the farm gate milk prices and other variable input expense parameters used in equation 4, obtained from the survey[32]. The price of an improved heifer is based on values reported by survey respondents: Mufindi, 397.7±78.1; Mvomero, 254.1±57.9; Njombe 479.5±115.6; Rungwe, 397.7±220.7 USD $head^{-1}$. The market prices of sunflower cake and maize bran are based on a sample of feed processors conducted for south and coastal regions of Tanzania[62], which in the base year take values of 0.25 and 0.21 USD kg^{-1} respectively.

Crop income is calculated based on the total area dedicated to crops in the base year, and accounting for the change in crop area associated with an increase (or decrease) in area allocated to planted pasture in the base year (2018), and any associated sowing costs. The *Crop income* for a given household type t in district d is thus calculated as:

$$\textit{Crop income}_{d,t} = \textit{Base year crop income}_{d,t} + \textit{Mean net crop margin}_{d,t} \times \textit{Change in forage area}_{d,t} - \textit{Forage sowing cost}_{d,t} \times \left(\frac{1}{12}\right) \quad (5)$$

where *Base year Crop income$_{d,t}$* is the total income (USD yr^{-1}) from crop production in the base year of 2018, *Mean net crop margin* is the average margin (USD yr^{-1}) per cropping hectare, *Change in forage area* is the change in area (ha) devoted to cultivated forages, and *Forage sowing cost* is the cost of sowing newly planted forages. The crop margins used to calculate foregone crop income are calculated from the survey data based on reported market prices and variable inputs (Table 3). Land dedicated to planted pasture per household type in the base year are based on base year herd sizes (Extended Data Table 3) per household, quantity of feed intakes of the respective forages (Table S3), and their yields (Table S2). The *Forage sowing cost* assumes a sowing rate of 10 kg seeds ha^{-1} and a price of seeds of 28 USD kg^{-1} [63,64].

Other farm and off-farm income

Income from non-dairy farm activities and off-farm sources are calculated as:

$$\textit{Other income}_{d,t} = \textit{Other farm income}_{d,t} + \textit{Off-farm income}_{d,t} \quad (6)$$

where *Other farm income* is farm income other than dairy in USD yr^{-1}, and *Off-farm income* is income from off-farm sources for a dairy household. More details on how the latter two sources of income are calculated from the survey are provided in SI 4, and the values are shown in Table 3.

Other income is projected throughout the 12-year period based on the product of average household size (number of people) (Table 3) and the projected income growth per capita, using the 5-year average per capita GDP growth rate between 2014-2019 of 3.2%[65]. Monetary values reported in the survey in Tanzanian shillings (TSh) are converted to USD based on the exchange rate at the time of the survey 2,263 TSh USD^{-1}. All prices in income accounting other than heifers are set equal to the final model year prices which are estimated based on the national average annual inflation rate of 4.1%[66]. Heifer prices are based on the 2018 values, and costs of replacement animals in subsequent years are accounted for in the animal husbandry costs for each household (Extended Data Table 4). Total household income is then divided by average household sizes (Extended Data Table 3) to determine income per capita per year. These results are then reported as averages for each of *Local-only*, *New-improved*, and *Extant-improved,* as averages over all households per district, and finally as the average for all dairy producing households across the four districts.

Uncertainty

Monte Carlo simulations are conducted quantifying uncertainty of the two main outcome indicators of GHG emissions and household income. Parameters used to estimate each indicator are drawn randomly from their probability distributions and the mean and variance of the resulting simulations are used as the basis for uncertainty. As GHG emissions sources used in this study are primarily based on Tier 2 estimates with relatively little uncertainty (see Table S6), GHG emissions uncertainty is reported at the 95% confidence level. Income uncertainty is reported as one standard error from the mean. All input parameters are assumed to be normally distributed and their standard errors (%) are specified based on the expected variability throughout the study region, described below.

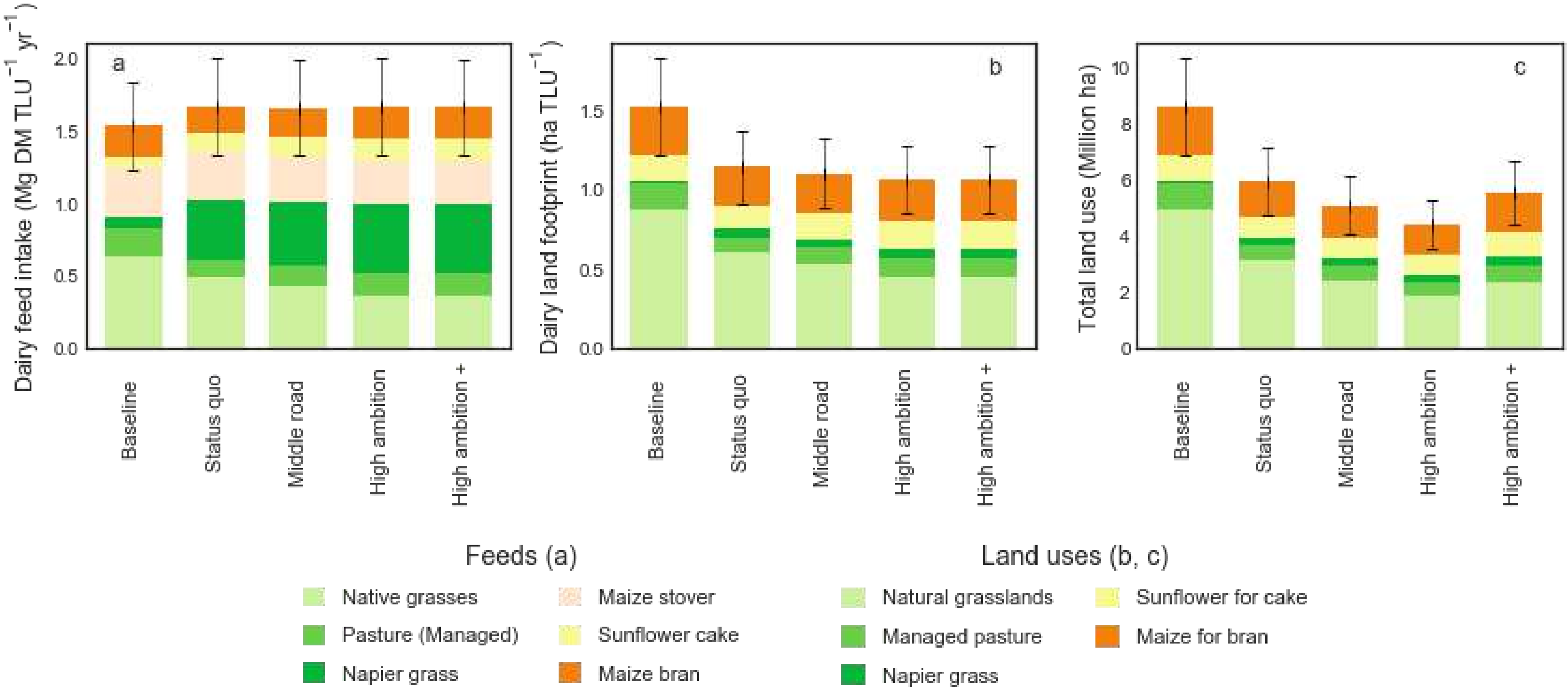
GHG emissions uncertainty

Standard errors of GHG emission factors are based either on IPCC African defaults or based on reported values from sources representative of the southern highlands and coastal regions of Tanzania, summarised in Table S6. Under the *Baseline,* uncertainty includes emission factors, feed on offer per head, biomass yields, and cattle populations. In each subsequent simulation, for which cattle populations and feed intakes are specified in relation to *Baseline*, only emission factor and biomass yield uncertainty are accounted for.

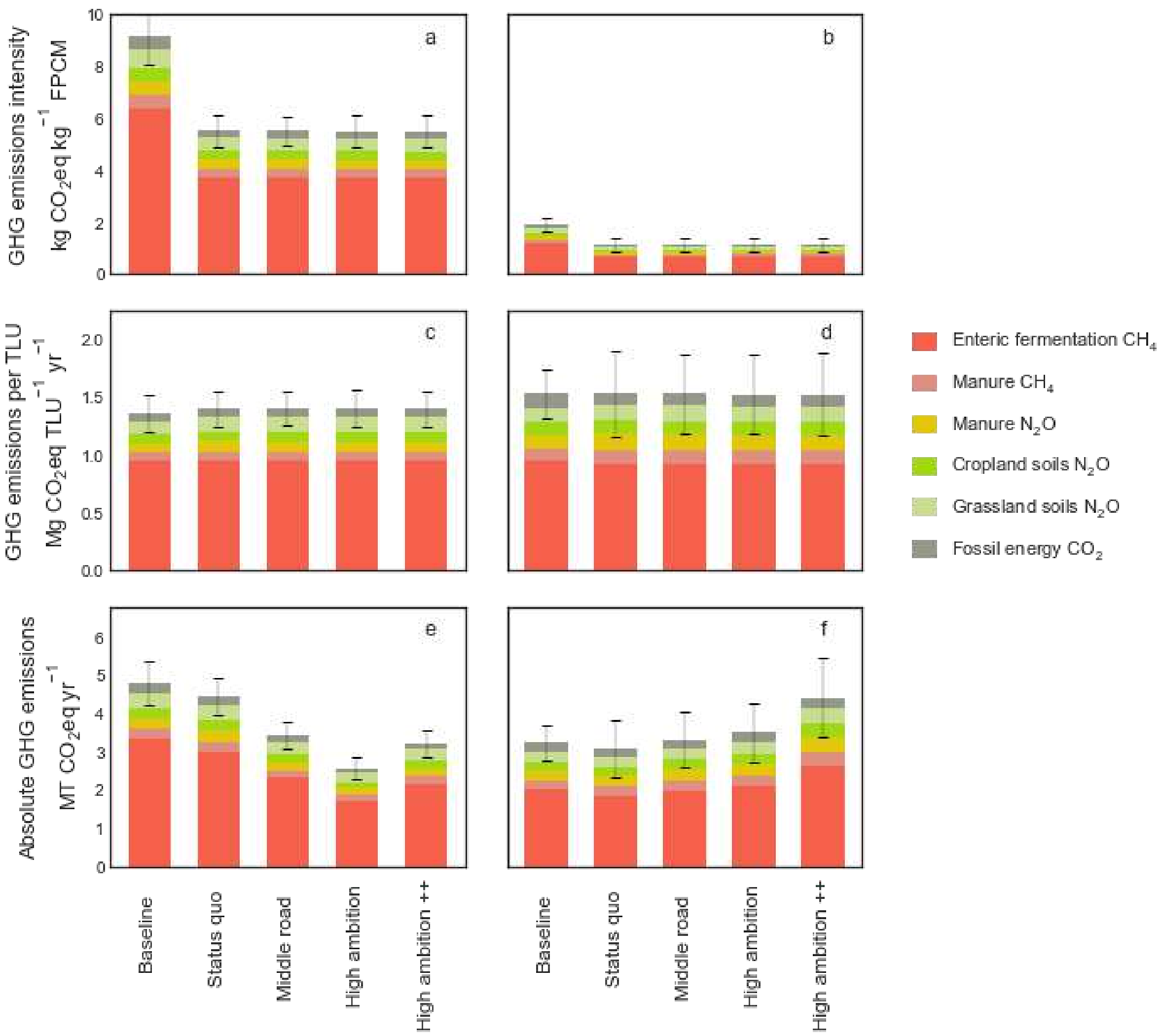
Income uncertainty

Uncertainty in imputed income per household takes into account variability in dairy income and considers sources of income other than the dairy enterprise as constant. Sources of variability in dairy income include the milk price, milk yield per cow (kg yr^{-1}), and dairy expenses as reported in Extended Data Table 4. The standard error of milk yield was set to 14% which is consistent with the performance of *LivSim* evaluated against experimental data[37]. Uncertainty in crop margins are based on standard deviations reported in Extended Data Table 3. Uncertainty is then aggregated for the three household types for the entire region, and as an average for all dairy households in the simulation. When aggregating household income to the population level, error ranges consider both uncertainty in income per household type and number of each household type per district. The latter is calculated based on the standard error of the proportion of household types within the population, calculated 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, and n is the sample size for a given district as reported in Extended Data Table 3.

Extended data



Extended Data Figure 1: Feed intake (a) and dairy land use (b,c) for Baseline and dairy roadmap scenarios. All values represent the average across production systems and districts included in the simulations. Error bars denote one standard error from the mean.



Extended Data Figure 2: Direct Greenhouse gas emissions (excluding land use change) by dairy sub-sector: local cattle (left panels; a, c, e) and improved cattle (right panels; b,d,f). Error bars show one standard error from the estimated value based on Monte Carlo uncertainty analysis.

Extended Data Table 1: Milk yield and cattle population to 2030 by breed type (local and improved), district and production system for the *Baseline* and four simulated scenarios: *Status quo, Middle road, High ambition,* and *High ambition ++*. Milk production is simulated with *LivSim* (See Methods). Production increases are set to 70% of the target for all scenarios except for *High ambition ++* with the increase at 100% of the target. The production target is defined in relation to the Base year level of milk production. Breed compositions differ across *Status quo*, *Middle road*, and *High ambition* in accordance with the genetics targets defined by the dairy roadmap.

Scenario	Variable	Unit	Breed type	Mufindi		Mvomero		Njombe		Rungwe	
				MRT	MRH	MRT	MRH	MRT	MRH	MRT	MRH
Baseline ('Business as usual')	Milk yield	kg cow^{-1} yr^{-1}	Local	433	276	300	305	293	322	310	478
			Improved	1,503	1,142	1,741	1,005	1,277	1,014	1,381	1,508
	Herd size	1000 head	Local	321	39	1,625	166	57	1,223	306	157
			Improved	507	61	371	38	8	163	749	384
All roadmap scenarios	Milk yield	% change relative to Baseline	Local	77	179	137	139	141	118	149	53
			Improved	82	116	60	137	147	135	117	101
Status quo	Herd size		Total	-8	-25	-8	-26	-48	-38	-17	-9
Middle road				-9	-26	-31	-43	-54	-47	-27	-19
High ambition				-10	-27	-44	-54	-62	-54	-30	-22
High ambition ++				14	-7	-30	-41	-53	-43	-11	-1

Extended Data Table 2: Description of five scenarios assessed in this study: Baseline, Status quo, Middle road, High ambition, and High ambition ++. 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 relative to Baseline. Highlands regions correspond to Mufindi, Njombe, and Rungwe districts in the model. The coastal region corresponds to Mvomero district.

Scenario	Improved dairy breeds			Milk production in 2030	
	Dairy household adoption (2018)				
	% of households owning local in base year	% of all dairy households[a]	% improved to total cattle per district[b]	% increase over base year (2018)	% of 2030 target[c]
Baseline	--	Fixed at base year Highlands: 47% Coastal: 42%	Consistent with historical annual growth rates: 3.2% local[51] 4.3% improved[51]	Highlands: 57% Coastal: 49%	--
Status quo	Highlands: 3% Coastal: 2%	Highlands: 48% Coastal: 43%	Fixed at base year Highlands: 42% Coastal: 11%	Highlands: 164% Coastal: 106%	70%
Middle road	Highlands: 13% Coastal: 10%	Highlands: 54% Coastal: 47%	Highlands: 51% Coastal: 19%		
High ambition	Highlands: 23% Coastal: 18%	Highlands: 60% Coastal: 52%	Highlands: 60% Coastal: 27%		
High ambition ++				Highlands: 234% Coastal: 152%	100%

[a] Based on targets of 60% and 45% of households adopting improved in highlands and coastal districts respectively by the TLSA.
[b] Based on breed targets as percentage improved per district from TLSA.
[c] Based on extrapolated production values from DDR as linear trend to 2030.

Extended Data Table 3: Household characteristics by stratum and districts. Stratum 1 includes households rearing local cattle only, stratum 2 includes households rearing at least one improved cow. In the model, stratum 1 households map to *Local-only* and New-*improved*, and stratum 2 households map *to Extant-Improved*. Non-dairy income includes all farm and off-farm income sources other than from production of milk. Cropping margin represents an aggregate indicator of the average returns from food and cash crop production.

	Mufindi n = 144		**Mvomero** n = 124		**Njombe** n = 285		**Rungwe** n = 296	
Strata	1	2	1	2	1	2	1	2
% sample (site)	63	37	47	53	27	73	30	70
Dairy cattle								
Main breed	Local	Improved	Local	Improved	Local	Improved	Local	Improved
Herd size in heads (s.d.)	11.4 (6.0)	2.8 (1.2)	10.5 (5.2)	2.8 (1.2)	9.0 (4.8)	2.5 (1.1)	4.8 (3.2)	2.7 (1.1)
Income in 1000 USD yr^{-1}								
Dairy (s.d.)	0.44 (0.38)	1.10 (0.76)	0.53 (0.36)	0.81 (0.95)	0.63 (0.41)	1.64 (0.70)	0.38 (0.12)	1.51 (0.37)
Other (s.d.)	3.86 (8.63)	4.23 (3.76)	1.92 (2.19)	3.17 (3.88)	1.87 (1.54)	5.84 (4.89)	1.03 (1.26)	1.04 (5.39)
Other traits								
Family size (people) (s.d.)	6.0 (2.2)	5.7 (2.0)	6.6 (3.0)	5.5 (1.5)	6.0 (2.1)	5.0 (1.8)	5.7 (2.1)	5.4 (2.2)
Cropping margins (USD ha^{-1} yr^{-1}) (s.d.)	176 (155)	148 (176)	250 (382)	261 (344)	226 (142)	146 (152)	290 (154)	384 (174)
Farm size (ha) (s.d.)	5.9 (6.9)	7.5 (7.5)	4.5 (5.0)	4.8 (5.5)	5.4 (6.0)	5.1 (8.0)	1.8 (1.5)	1.7 (1.3)

Source: Greening livestock survey (GLS 2019)[32] and the analysis of this study. s.d .is standard deviation.

Extended Data Table 4: Milk price and dairy cost parameters used in estimations of dairy income by district and household type. Values are averages plus one standard deviation (±) for a given sample.

District	Strata	Milk price (USD litre^{-1})	Input use (USD cow^{-1} yr^{-1})			
			Purchased feeds	Replacement cattle	Health inputs/services	Reproductive inputs/services
Mufindi	1	0.57 ± 0.07	45.8 ± 92.4	16.6 ± 92.5	21.4 ± 32.8	0.4 ± 3.1
	2	0.58 ± 0.11	164.4 ± 156.7	13.6 ± 100.1	15.4 ± 12.7	1.6 ± 4.9
Mvomero	1	0.41 ± 0.18	17.6 ± 51.4	1.4 ± 8.0	8.3 ± 10.4	0.0 ± 0.0
	2	0.58 ± 0.08	176.9 ± 196.2	7.7 ± 44	18.2 ± 13.3	0.2 ± 0.8
Njombe	1	0.49 ± 0.14	85.4 ± 101.1	4.5 ± 38.9	16.7 ± 17.5	0.2 ± 1.4
	2	0.71 ± 0.09	284.5 ± 851.5	9.2 ± 62	16.3 ± 11.1	0.8 ± 3.2
Rungwe	1	0.50 ± 0.11	83.2 ± 169.4	3.8 ± 22.1	9.4 ± 11.6	0.1 ± 0.9
	2	0.62 ± 0.08	243.3 ± 108.0	9.9 ± 64.5	8.9 ± 10.5	1.0 ± 4.4

Source: Greening Livestock Survey[1]

Acknowledgements

The paper was in part supported by the International Fund for Agricultural Development (IFAD) within the “Greening livestock: Incentive-Based Interventions for Reducing the Climate Impact of Livestock in East Africa" project (grant numbers 2000000994, 2016), implemented by the International Livestock Research Institute (ILRI), the Center for International Forestry Research (CIFOR) and The CGIAR Research Program for Climate Change, Agriculture and Food Security (CCAFS). Special thanks to David Styles, Luke Parry, and Camilla Toulmin for thoughtful comments.

Data availability

Code and excel spreadsheets used as the basis of the analysis are available in a public Github repository from the following link:

https://github.com/James-Hawkins/Tanzania-Dairy-Mitigation-Assessment

Methods references

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