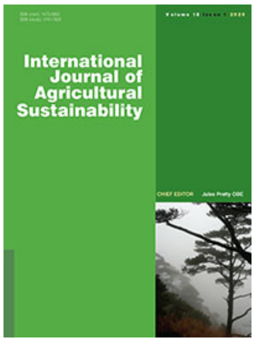

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Reducing agro-environmental trade-offs through sustainable livestock intensification across smallholder systems in Northern Tanzania

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ABSTRACT

Livestock productivity in East Africa, and especially in Tanzania, remains persistently low, while greenhouse gas (GHG) emission intensities are among the highest worldwide. This mixed methods study aims to explore sustainable livestock intensification options that reduce agro-environmental trade-offs across different smallholder farming systems in Northern Tanzania. A smallholder livestock systems typology was constructed, and representative farms simulated with a whole farm multi-objective optimization model. Livestock contributed more than 90% of on-farm GHG emissions, and DAIRY had the lowest GHG emission intensity (2.1 kg CO_2e kg^{-1} milk). All livestock systems had alternative options available to reduce agro-environmental trade-offs, including reducing ruminant numbers, replacing local cattle with improved dairy breeds, improving feeding through on-farm forage cultivation, and minimizing crop residue feeding. Three obstacles to adoption of these technologies became apparent: they require a skillful re-organization of the entire production system, result in loss of some multi-functionality of livestock, and incur higher production risks. Sustainable livestock intensification can be a key building block to Tanzania's climate-smart agriculture portfolio, providing synergies between productivity and income increases, and climate change mitigation as co-benefit. A better understanding of the institutional settings, incentives and coordination between stakeholders is needed to sustainably transform the livestock sector.

KEYWORDS

Sub-Sahara Africa; climate-smart agriculture; improved livestock feeding; ex-ante impact assessment; bio-economic household modelling

1. Introduction

Two-thirds of smallholders in eastern and central Africa rely on mixed crop-livestock systems as a source of income and nutrition, employment, insurance, traction or clothing (Herrero et al., 2012). The rise in population and urbanization is expected to result in higher demand for livestock products, which increases pressure on natural resources. Environmental impacts

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include effects on climate, water, nutrient cycling, biodiversity, land degradation and deforestation (Herrero et al., 2015). In particular, livestock production systems in the region have one of the highest greenhouse gas (GHG) emission intensities, thus GHG per unit livestock product, worldwide due to poor diets, genetics, health, and husbandry (Herrero et al., 2013). Climate-smart agriculture (CSA) is presented as one of the pathways to transform agricultural systems, aiming to sustain food security under climate change, while reducing greenhouse gas (GHG) emissions. Although CSA strives to simultaneously improve three pillars of food security, adaptation and climate change mitigation, it acknowledges that not every recommended practice applied in every place can achieve such a triple win. Mitigation in developing countries is seen as a co-benefit, while food security and adaptation are the main priorities (Lipper et al., 2014).

Tanzania has the third largest cattle population in Africa (25 million heads) after Ethiopia and Sudan. 50% of Tanzanian households keep livestock, contributing 14% to their income. However, livestock productivity remains low. 98% of the total cattle herd is indigenous Tanzania Shorthorn Zebu whose adult body weight lies at only 200–350 kg, annual off-take rate at 8–10%, and 400 l milk is yielded per lactation. Milk production in the dry season is only half of the amount produced in the rainy season. Tanzania's current milk consumption of 45 l $person^{-1}$ $year^{-1}$ is low when compared to Kenya (80 l), India (68 l), USA (261 l), and the FAO recommendation (200 l) (Katjiuongua & Nelgen, 2014; Kurwijila, Omore, & Grace, 2012). Following the ratification of the Paris Climate Agreement in November 2016, Tanzania has committed to reduce GHG emissions by 10–20% by 2013, conditional on sufficient financial support. This commitment is anchored in the National Climate Change Strategy (2012) which elaborates adaptation and mitigation options. Agriculture and livestock are sectors for intended adaptation contributions including increasing crop yields and sustainable pasture management systems (United Republic of Tanzania, 2015). Agricultural research for development needs to align closely to policy interests on climate and agriculture at the national and sub-national level. In doing so, research can critically support evidence-based design and implementation of policy, leading to climate-smart development outcomes and impacts (Thornton et al., 2017).

Several sustainable intensification options have previously been proposed to increase the climate-smartness of livestock production. Feed use efficiency, the amount of dry matter feed required to produce a unit output such as milk or meat, has been identified as key to both increasing livestock productivity and reducing GHG emission intensities. Feed rations can be improved through planted forages, energy-dense concentrates, and treatment of low quality feeds such as crop residues. Improved animal management, including improved breeds, animal health, and reproductive management, can drastically increase herd productivity. Manure management and safe storage could reduce emissions as well (Herrero et al., 2016). Planted forage options have been developed and adapted to various agro-ecologies, farming systems and production objectives. In addition to improving feed digestibility, they can increase soil organic carbon (Peters et al., 2013). A combination of such approaches – improved animal nutrition, management, manure – has been shown to increase productivity, decrease herd size, and therefore lower overall emissions (Herrero et al., 2016).

Finding a balance between multiple objectives and potential trade-offs, and forging synergies between agricultural production and environmental quality, lies at the heart of sustainable intensification and CSA (Campbell, Thornton, Zougmoré, van Asten, & Lipper, 2014). The field of agricultural trade-off analysis is growing, for trade-offs operating on many different scales, and affecting different stakeholders (Klapwijk et al., 2014). Since smallholder farming systems in sub-Saharan Africa (SSA) are highly diverse and dynamic, trade-offs play out differently. Understanding and classifying such complexity and diversity is the basis to understanding impacts and trade-offs (Giller et al., 2011; Tittonell et al., 2010). There is a wide array of indicators and metrics to assess productive, economic, environmental and social functions of farming systems, and to evaluate trade-offs between them (Smith et al., 2017). To address those multiple dimensions in one approach, trade-off analysis often employs interdisciplinary, bio-economic models. Multi-objective optimization in particular is considered a useful approach, as farmers are not ultimate profit maximizers (Kanter et al., 2018). Integrated, systems-oriented impact assessments and realistic consideration of adoption constraints are crucial to inform decisions for improved adaptation and mitigation of mixed crop-livestock systems in SSA (Descheemaeker et al., 2016). This study aims to explore sustainable livestock intensification options that reduce agro-environmental trade-offs across different smallholder livestock systems, taking Babati in Northern Tanzania as study case. Specifically, its objectives are to:

(1) Describe and classify the diversity of livestock feeding and husbandry systems;
(2) Quantify environmental efficiencies and agro-environmental trade-offs of different ruminant livestock systems;
(3) Explore livestock intensification options that reduce these agro-environmental trade-offs.

2. Materials & methods

Data were collected and analyzed in three steps. (i) A rapid household survey among 96 respondents was conducted in April 2013, and analyzed with exploratory statistics for description of general farming systems, and multivariate statistics to construct a smallholder livestock systems typology. (ii) Based on the typology, a sub-sample of 12 farms were characterized in detail including an intensive household survey, tree measurements and soil analysis in February 2015. (iii) From these 12 households, four were further selected for participatory bio-economic modelling and multi-objective optimization. Data were collected in January and February 2017 through in-depth discussions following a list of semi-structured questions to validate model input data and preliminary results, and evaluate farming objectives and constraints, and discuss farmers' perspectives on proposed livestock intensification options.

2.1. Study area

Babati is one of the five districts in the Manyara region, Northern Tanzania, representing a high agro-ecological and socio-economic diversity. Altitude ranges from 950 to 2450 m above sea level, and precipitation varies between 500 and 1200 mm year^{-1} (Figure 1). Soils include sandy loams to clay alluvials, have a pH around 6.5, and P, S and Zn availability is generally low. Mineral fertilizer application in the area is insignificant (Kihara, Tamene, Massawe, & Bekunda, 2015). Maize (*Zea mays*) is intercropped with pigeon pea (*Cajanus cajan*) and beans (*Phaseolus vulgaris*) in the long rains from February to May, and beans are planted in the short rains from November to January. A wide range of cash crops are grown. In 2012, Babati district had almost 64,000 farming households and 420,000 heads of cattle. 40% of the population are ethnic Iraqw, and 30–35% Gorowa, and both communities count as indigenous nowadays. The Iraqw settled in the area 200 years ago from Kenya, when population pressure was low in Babati. Availability of fertile land attracted more in-migration in the 1950s, leading to the high current ethnic diversity. More recently, population pressure has been increasing up to 180–200 people per km^2, limiting the availability of farming land and pasture (Bishop-

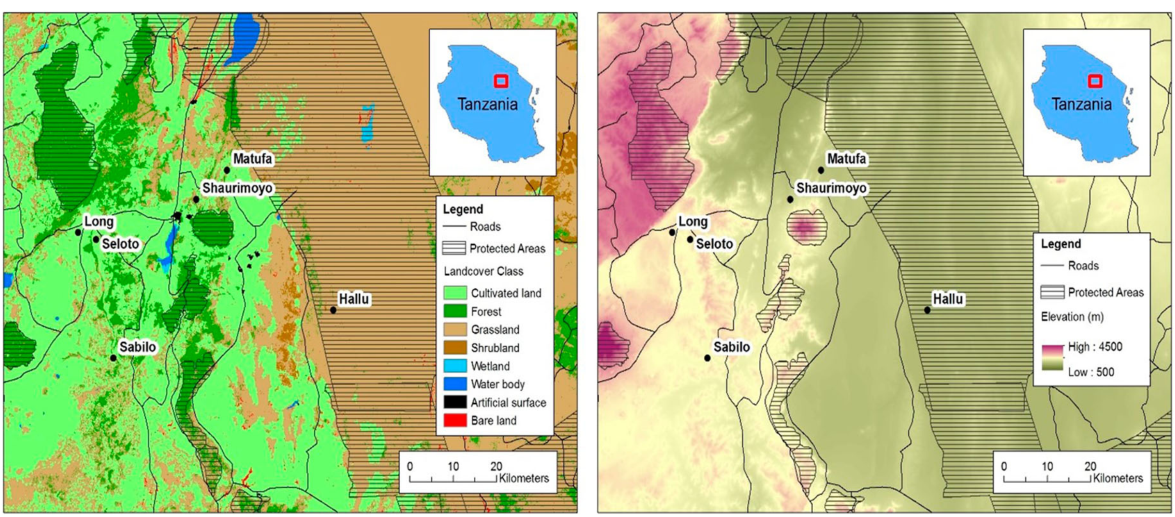

Figure 1. Maps of the six study villages with land cover (left) and elevation (right). Data sources: Land cover (Chen et al., 2014), district boundaries (GADM, 2015), elevation (Jarvis, Reuter, Nelson, & Guevara, 2008), protected areas (UNEP-WCMC and IUCN, 2016).

Table 1. Variables with units used in typology construction.

Variable	Unit
Household size	number
Farm size	ha
Livestock herd size	TLU
Improved cattle	number
Local cattle	number
Small ruminants	number
Poultry	number
Cereal residue used as feed	kg FW year^{-1}
Legume residue used as feed	kg FW year^{-1}
Other residue used as feed	kg FW year^{-1}
Livestock family labour	hours day^{-1}
Grazing time	hour day^{-1}
Purchased concentrates	kg year^{-1}

Notes: Livestock family labour referred to the total daily family labour required for the livestock herd per farm, excluding hired labour. Purchased concentrates was the sum of locally available, purchased supplements for any livestock type, e.g. maize bran, sunflower cake and maclick. Cereal, legume and other residue fed was computed by multiplying the crop areas per farm with average crop yields, the harvest index per crop, and the farmer-reported percentage of residue fed to livestock.

Sambrook, Kienzle, Mariki, Owenya, & Ribeiro, 2004; Hillbur, 2013).

2.2. Household survey, statistical analysis and typology construction

A rapid household survey (96 respondents) was conducted by eight trained enumerators in April 2013 in the villages of Hallu (1224 m), Mafuta (1022 m), Shaurimoyo (1002 m), Seloto (1646 m), Sabilo (1664 m), and Long (2154 m) (Figure 1). The survey assessed farm resources, management strategies, farm productivity and household economy, aiming to identify initial entry points for sustainable intensification in Tanzania (Timler et al., 2014).

Exploratory statistics with the R statistical programming software (R Core Team, 2013) were conducted to describe the general farming systems. A quantitative, multivariate statistics method was used to construct a smallholder livestock systems typology (Alvarez et al., 2018). Expert knowledge and literature review resulted in the selection of 12 variables for the typology construction, which were extracted or calculated from the dataset (Table 1). Cattle number was closely correlated with total TLU ($R2 = 0.93$) and therefore not included. As multivariate analyses are sensitive to exceptional observations, the dataset was curated for missing and outlying data (Alvarez et al., 2018). The following farms were removed: five farms without livestock (TLU = 0), two farms with missing data, and six farms with exceptional data (two farms with >4 improved cattle, two farms with >25,000 kg cereal residue fed, one farm with >1000 kg other residue fed, and one farm with >3000 kg legume residue fed). A total of 83 out of the original 96 households were retained for analysis. We first ran a principal component analysis (PCA) to reduce the dimension of the dataset, and then used the scores of the PCA to obtain homogeneous groups of farms using hierarchical cluster analysis (Ward method) (e.g. Tittonell et al., 2010). All analyses were executed in R, using the *ade4* package (Dray, Dufour, & Chessel, 2007, version 1.6–2) and the *cluster* package (Maechler, Rousseeuw, Struyf, Hubert, & Hornik, 2016, version 1.15.2). The household typology was validated with local extension officers, and found to be adequately representing the existing livestock system diversity.

2.3. Detailed household characterization, tree measurements and soil analysis

A sub-sample of 12 farms were chosen from the 96 respondents of the rapid household survey in discussion with extension officers to represent the targeted smallholder livestock system types. A detailed household characterization was administered in February 2015, using the IMPACTlite survey tool (Rufino et al., 2012). Trees on the farms were counted and diameter at breast height (DBH) measured if >2.5 cm. In case trees were too remote to measure, only the number of trees was recorded and the average DBH of the farm applied. Aboveground biomass of live trees was estimated using the following empirically derived allometric equation from Kuyah et al. (2012):

$$AGB = 0.091 * DBH^{2.472}$$

where AGB is the aboveground biomass in kg dry weight (DW), and *DBH* tree diameter at breast height in cm. The carbon content of woody biomass was assumed to be 0.48 kg C kg DW^{-1} (Thomas & Martin, 2012) with which the total C stock of trees on farms and per hectare was computed. Annual growth and removal of C stocks were not taken into account.

A total of 26 topsoil (0–20 cm) composite samples were taken from different land uses (cropland, grassland and fallow). The soil samples were air-dried and transported to the CIAT soil laboratories in Nairobi, Kenya for analysis. Total C and N were analyzed by total combustion technique using an elemental macro-analyzer (Elementar Vario Max Cube). PH was measured in water (1:2.5), soil particle size (sand, silt, clay) by the hydrometer method, and extractable phosphate was determined by Bray-P.

2.4. Participatory bio-economic modelling and multi-objective optimization

A further sub-sample of one representative farmer of each type was selected in discussion with extension officers. In-depth discussions followed a semi-structured list of questions, and were conducted together with Babati extension officers in January and February 2017. In addition to evaluating model input data and preliminary results, general farming objectives and constraints were explored, and farmers' perspectives on alternative climate-smart livestock intensification options were discussed. These four case study farms were simulated with FarmDESIGN, a bio-economic farm model that calculates the impacts of various farm configurations on a large set of agro-environmental and socio-economic performance indicators. Applications of FarmDESIGN in the Netherlands (Mandryk, Reidsma, Kanellopoulos, Groot, & van Ittersum, 2014), Zambia (Timler, Michalscheck, Alvarez, Descheemaeker, & Groot, 2017), and Mexico (Cortez-Arriola et al., 2014, 2016; Flores-Sanchez et al., 2011, 2015; Groot, Cortez-Arriola, Rossing, Améndola Massiotti, & Tittonell, 2016) have suggested the model is robust enough to accommodate contrasting farming systems and agro-ecologies. FarmDESIGN has been evaluated in terms of design-, output- and end-user validity. However, uncertainty lies in the quality of input data, as well as parameterization of degradation, nutrient losses and OM breakdown (Groot, Oomen, & Rossing, 2012). The inputs required for the model can be grouped into: (i) biophysical environment (e.g. soils, climate); (ii) socio-economics (e.g. input costs, labour price); (iii) crops and crop products yield, composition and use; (iv) livestock and livestock products yield, composition and use; (v) manure types and degradation, and mineral fertilizer use; (vi) household members and labour availability.

Model input data were derived from the detailed characterization (Section 2.3) and triangulated with information from the semi-structured interviews (Appendix 3), as well as literature-derived or expert-estimated parameters (Appendix 4). Farm performance was evaluated in FarmDESIGN in terms of livestock feed balance, organic matter (OM) balance, farm nitrogen (N) balance and cycle, GHG emissions, species richness, income, and labour requirements. Species richness relied on the Margalef index (M) by Oyarzun, Borja, Sherwood, and Parra (2013), which was computed from the number of crops and the farm area. Feed balances were calculated for energy and protein by matching available feeds with animal requirements and dry matter intake capacity. Animal requirements were related to body maintenance, growth, pregnancy and milk production. Feed intake was determined by the feed intake capacity saturation value of feeds. We used the Dutch VEM (feed unit milk) and DVE (intestinally degradable protein) systems (Tamminga et al., 1994; Van Es, 1975). Household net income calculations included revenues from all crop and livestock production, based on their production and prices minus production costs such as feeding, inputs, hired labour and land (Groot et al., 2012). Prices and costs were reported in Tanzanian Shilling (TSh), and converted to US dollar (USD), using an exchange rate of 2235 TSh. Off-farm income was not taken into account.

A GHG emission estimation module was added to FarmDESIGN, including the following sources: (i) methane (CH_4) from livestock enteric fermentation, (ii) CH_4 and direct and indirect nitrous oxide (N_2O) from manure storage and application, (iii) N_2O from

Table 2. GHG emission factors on an annual production basis.

Emission source	Unit	Factor
(i) Enteric fermentation		
Crossbred dairy cow	kg CH_4 animal^{-1}	41
Local dairy cow	kg CH_4 animal^{-1}	31
Local adult bull	kg CH_4 animal^{-1}	31
Steers and heifers	kg CH_4 animal^{-1}	20
Calves	kg CH_4 animal^{-1}	16
Sheep and goats	kg CH_4 animal^{-1}	5
Pigs	kg CH_4 animal^{-1}	1
Poultry	kg CH_4 animal^{-1}	0
(ii) Manure production		
All cattle, pigs	kg CH_4 animal^{-1}	1
Sheep	kg CH_4 animal^{-1}	0.15
Goats	kg CH_4 animal^{-1}	0.17
Poultry	kg CH_4 animal^{-1}	0.02
(iii) Manure storage and deposition/application		
Direct emissions stable and yard manure storage	kg N_2O kg N^{-1}	0.01
Indirect emissions stable and yard manure storage	kg N_2O kg NH_3–N^{-1}	0.01
Manure deposition during grazing	kg N_2O kg N^{-1}	0.02
Manure application to fields	kg N_2O kg N^{-1}	0.01
(iv) Soil emissions		
Inorganic fertilizer application	kg N_2O kg N^{-1}	0.01
Crop residue, N fixation, atmospheric N deposition	kg N_2O kg N^{-1}	0.01
(v) Burning		
Residue burning	kg N_2O kg DM^{-1}	0.00007
Residue burning	kg CH_4 kg DM^{-1}	0.0027
Residue burning	kg CO_2 kg DM^{-1}	1.515

Notes: Factors taken from IPCC (2006).

mineral fertilizer application; (iv) direct and indirect N_2O from soils through N input from crop residue retention, N fixation and atmospheric deposition, (v) CO, CO_2, N_2O, NO_x and CH_4 from burning of organic material. Input data on livestock numbers, manure production, crop residue use, and fertilizer and manure application were multiplied with IPCC Tier 1 emission factors (IPCC 2006) (Table 2). N manure excretion rate was calculated by the model taking into account protein intake by livestock and protein digestibility of the feed basket, so that manure related N_2O emissions can be considered an IPCC Tier 2 method. Calculated N_2O and CH_4 emissions were converted into CO_2 equivalents (CO_2e) by multiplying by their respective global warming potentials (GWP) – 21 for CH_4 and 310 for N_2O.

FarmDESIGN contains a multi-objective Pareto-based optimization algorithm that can evaluate and minimize trade-offs between several production objectives. Based on available resources and provided with a limited room to reallocate these resources, the model generates clouds of alternative farm configurations. For this study, the objectives were set to: (a) maximize annual income (USD farm^{-1}); (b) maximize the annual farm N balance (kg N ha^{-1}); (c) minimize annual greenhouse gas emissions (t CO_2e). These indicators were chosen to represent the three pillars of CSA – food security, climate change adaptation, and mitigation. In a systematic review of impacts of CSA technologies, Rosenstock et al. (2016) acknowledge that for each of the three pillars, there are many possible dimensions and indicators. Income and GHG emissions are included as indicators for food security and climate change mitigation respectively, while adaptive capacity is more difficult to approximate. Higher farm N balances was chosen represent increased farm and soil resources, and they increase the buffer capacity of households against shocks. Constraints were set to not exceed the current farm size, observe livestock feed balances, and keep the organic matter balance within ranges. Decision variables were based on options for sustainable intensification of livestock, namely (a) varying numbers of livestock species, and option of introducing improved dairy breeds; (b) choice in crop residue use between livestock feeding and soil cover, and (c) room for changes in livestock feeding, including Napier grass (*Pennisetum purpureum*) as introduced forage and local concentrates (Table A11, Appendix 5). The optimization was run for 1000 iterations to attain a stable model outcome. From the obtained trade-off curves for GHG vs. N balance, four alternative configurations per farm type were selected for further investigation and comparison to the baseline (B), representing very high (V), high (H), medium (M) and low (L) income and GHG emissions.

3. Results

3.1. Smallholder livestock systems typology

Livestock feeding and husbandry in Babati was predominantly extensive with relatively large local cattle herd sizes, few improved breeds, day-time grazing, little purchased feed, wide-spread crop residue feeding and low productivity. Soils exhibited a moderate to good level of fertility. Differences between villages were apparent, reflecting varying agro-ecologies. Hallu had the lowest level of soil fertility, and Long the highest (Tables A1–A4, Appendix 1).

The multivariate analysis identified five principal components (PCs) with an eigenvalue higher than 1.0, of which four were retained to maintain interpretability (Figure A5, Appendix 2). Together, these four PCs explained 63.9% of the variability within the dataset.

Farm area, cereal and legume residues fed, and livestock herd size were negatively correlated with PC1, explaining 30% of the variability in the dataset; grazing time and livestock family labour were positively correlated with PC2 (13%); improved cattle and poultry were positively correlated with PC3 (11%); and purchased feed negatively and small ruminants positively with PC4 (10%) (Table 3). The subsequent cluster analysis resulted in the selection of five clusters, whose meanings were interpreted together with the PCs (Figures A6–A9, Appendix 2). The five types, and the representative case study

Table 3. Correlation matrix between survey variables and the four retained PCs.

Variable	PC1	PC2	PC3	PC4
Farm size	**−0.89**	−0.20	−0.09	−0.15
Legume residue used as feed	**−0.80**	−0.22	−0.12	−0.19
Cereal residue used as feed	**−0.79**	−0.26	0.10	−0.15
Livestock herd size	**−0.73**	0.31	−0.01	0.21
Other residue used as feed	−0.62	−0.16	−0.42	−0.04
Household size	−0.53	0.46	0.32	−0.14
Small ruminants	−0.47	0.27	0.09	**0.57**
Improved cattle	−0.22	−0.32	**0.63**	0.06
Grazing time	−0.21	**0.71**	0.17	−0.34
Poultry	−0.02	−0.31	**0.77**	0.15
Livestock family labour	−0.01	**0.55**	0.10	0.14
Purchased concentrates	0.18	0.07	0.22	**−0.69**

Notes: In bold the strongest correlations per component.

farms for the subsequent bio-economic modelling, could be summarized as follows:

SMALLEST (44.6%) was the smallest by area (1.3 ha), had the second smallest livestock herd (2.9 TLU), did not own improved cattle and only few small ruminants, but had the highest median amount of purchased concentrates (83.5 kg year^{-1}) (Table 4). The case study farm was located in Long and had 1.6 ha divided in various fields under maize and beans, potatoes (*Solanum tuberosum*), eucalyptus treesand pasture. The household had two local cows, four goats and three sheep which grazed six hours day^{-1} off-farm and two hours day^{-1} on farm and otherwise stayed in the yard or stable (Tables A2–A3, Appendix 3).

DAIRY (16.9%) had a medium farm (2.4 ha) and livestock herd size (4.6 TLU). It had the highest median number of improved cattle (1.5 heads), and relatively high purchased feed (52.4 kg year^{-1}) (Table 4). The case study farm was located in Sabilo and cultivated 3.6 ha, of which one field was intercropped with maize, bean, and pigeon pea, 0.53 ha under Napier grass and 1.5 ha under local pasture. The 4 crossbred dairy cows were kept inside, while the six local cattle, five goats, and two sheep grazed ten hours day^{-1} on-farm (Tables A2–A3, Appendix 3).

SHOAT (26.5%) had a medium farm size (1.8 ha), the second-largest livestock herd (7.3 TLU) with 14.6 small ruminants, the longest grazing time (8.9 h day^{-1}), and purchased the lowest amount of feed concentrates (4.5 kg year^{-1}) (Table 4). The case study farm was located in Sabilo and farmed on 8.4 ha, of which 3.1 ha were under several crops including maize, bean, pigeon pea, sunflower (*Helianthus annuus*), 1.6 ha under wheat (*Triticum aestivum*), and the remainder under natural pasture. The case study farm was considerably larger than the median value from the typology construction, as the household had initially not included the natural pasture as his farm land during the household survey, and had rented additional land for wheat cultivation after 2013. The household-owned 20 goats, seven sheep, and seven local cattle that all grazed exclusively on-farm on the pasture or in the open yard around the homestead (Tables A2–A3, Appendix 3).

Table 4. Description of livestock system types.

	Share of farm population (%)	Farm size (ha)	Household members (number)	Livestock herd size (TLU)	Small ruminants (number)	Poultry (number)	Improved cattle (number)	Grazing time (h day^{-1})	Livestock family labour (h day^{-1})	Purchased concentrates (kg year^{-1})
SMALLEST	44.6	1.3	6.4	2.9	4.7	5.7	0.0	7.8	8.5	83.5
DAIRY	16.9	2.4	7.2	4.6	7.4	19.2	1.5	8.3	8.9	52.4
SHOAT	26.5	1.8	8.6	7.3	14.6	11.2	0.0	8.9	9.8	4.5
POULTRY	7.2	1.6	4.3	1.1	3.0	20.2	0.5	0.0	6.5	56.6
LARGE LIVESTOCK	4.8	7.8	10.3	13.7	20.3	5.0	0.5	7.5	6.7	25.0

Notes: Values are expressed in median over the year. The variables are described in Table 3.

POULTRY (7.2%) owned a relatively small farming area (1.6 ha), had the smallest herd (1.1 TLU) and most chicken of all types (20 heads). It had one of the lowest family labour requirements for livestock (6.5 h day^{-1}) and relatively high purchased concentrates (Table 4). This type was omitted for the household modelling as the focus of this study lay on ruminant smallholder livestock systems.

LARGE LIVESTOCK (4.8%) had the largest number household members (10), the largest farming area (7.8 ha) and the largest livestock herd size (13.7 TLU) (Table 4). The case study farm was located in Hallu and had 11.1 ha with a fully mechanized maize, pigeon pea and sunflower field (10.1 ha), and an *Acacia* and *Senna* tree plot of one ha around the house. The 15 local cattle and 5 calves grazed off-farm for 9 h day^{-1}, and otherwise stayed in the open yard around the house. None of the farms applied mineral fertilizer (Table A3, Appendix 3).

3.2. Bio-economic performance of different types

Feed baskets of the four case study farms contained four to eight on- and off-farm items per household. Total DM intake per farm varied between 6619 kg (SMALLEST) and 28,065 kg (LARGE LIVESTOCK), corresponding to average daily values of 18–77 kg DM. SMALLEST and LARGE LIVESTOCK relied on off-farm grazing for more than 50%, while DAIRY fetched around 40% by cutting and carrying natural grasses outside of the farm. DAIRY was the only farm to cultivate on-farm forages (Napier grass), constituting 15% of its feed basket. SHOAT exclusively fed on-farm resources, with 41% constituted by its own pasture. SHOAT and LARGE LIVESTOCK farms were feeding higher proportions of various crop residues (40–50%) when compared to SMALLEST and DAIRY (20–30%) due to their larger farm sizes and crop production. Concentrate feed such as sunflower cake, maize bran and maize grain only made a marginal contribution to the SHOAT farm feed basket in terms of DM (Figure 2a), but contributed 22% of proteins to the diet (Figure 2b). Although DAIRY only had the second-highest TLU and fed the third-largest DM amount, it fed most proteins of all farms.

Annual income per household was between 997 USD (SMALLEST) and 2977 USD (LARGE LIVESTOCK). Except LARGE LIVESTOCK, all farms lay below the poverty line. One third to half of all produce was consumed by the households themselves. When family labour was costed, SMALLEST was operating at a loss, and SHOAT just ran even. Despite its much lower farm area, DAIRY was generating higher income than SHOAT (Figure 3a). Total annual labour hours (Figure 3b) required were 3262 h (SMALLEST), 6327 (SHOAT), 6634 (DAIRY) and 8296 h (LARGE LIVESTOCK). In total, livestock activities required more labour than crop activities, mainly due to grazing time. SMALLEST hired least labour, while LARGE LIVESTOCK and SHOAT hired considerable amounts of labour for crop and livestock activities. Livestock labour intensity (hours TLU^{-1}) was highest for SMALLEST and lowest for LARGE LIVESTOCK, as herding a small herd is less labour efficient than herding a large livestock herd. DAIRY needed the second-highest amount of labour for livestock due to cut and carry feeding. Crop labour intensities were similar across farms.

Enteric fermentation and manure together were responsible for >90% of total farm-level emissions. Therefore, emissions increased with livestock herd size, ranging between 2.9 t CO_2e (SMALLEST) and 16.2 t CO_2e (LARGE LIVESTOCK). Only LARGE LIVESTOCK also had significant crop-related N_2O emissions due to N inputs from crop residue retention on the field and N fixation by legumes. LARGE LIVESTOCK was also the only farm that burned on-farm products such as timber and pigeon pea stalks for fire wood. Emission intensity per litre milk produced was highest for SHOAT (15.3 kg CO_2e l^{-1}) and SMALLEST (9.4 kg CO_2e l^{-1}) due to low production levels, and lowest for DAIRY (2.1 kg CO_2e l^{-1}). Emission intensity per hectare was highest for DAIRY (2.6 t CO_2e ha^{-1}) due to a relatively higher stocking rate, and lowest for SHOATS (1.1 t CO_2e ha^{-1}) because of the large farm size (Figure 4a). SHOAT had the lowest N balance with 0 kg N ha^{-1} as it was the only farm with no nutrient influx from off-farm feeds. All other farms achieved positive farm-level N balances due to the import of grass from outside the farms. DAIRY exported the largest amount of N through milk sale, and SHOAT and LARGE LIVESTOCK through crop sales. None of the farms imported N in the form of manure or mineral fertilizers (Figure 4b).

Overall relative scoring of agro-environmental and socio-economic indicators clearly illustrated differences in performance between the livestock

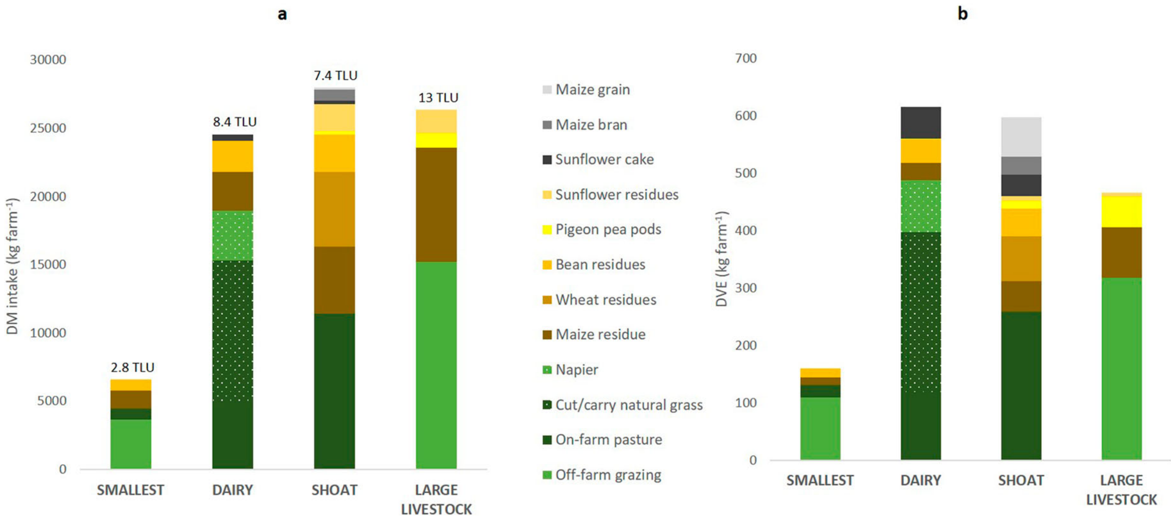

Figure 2. Livestock feed baskets of the four case study farms in (a) total dry matter (DM) intake and (b) intestinally digestible protein (DVE) per livestock system. Fresh grasses are denoted in green colours, crop residues in brown/yellow/orange colours, and grain/seed feed in grey colours. Cut-and-carry fodders were marked with the white dotted pattern.

systems. SMALLEST came out favourably in terms of environmental quality with the highest species richness, low GHG, and good C and N balances but it also generated the lowest income. DAIRY produced high income, highest C and N balances and only medium GHG, but had a relatively high feed and labour demands. SHOATS had medium income and highest tree C stock, but lowest C and N balances, high GHG emissions, and high feed and labour requirements. LARGE LIVESTOCK had the highest income, but low C and N balances, high GHG emissions, low species richness, and high feed and labour requirements (Figure 5).

3.3. Agro-environmental trade-offs

The model optimization runs illustrated that all farms faced trade-offs between income and GHG emissions.

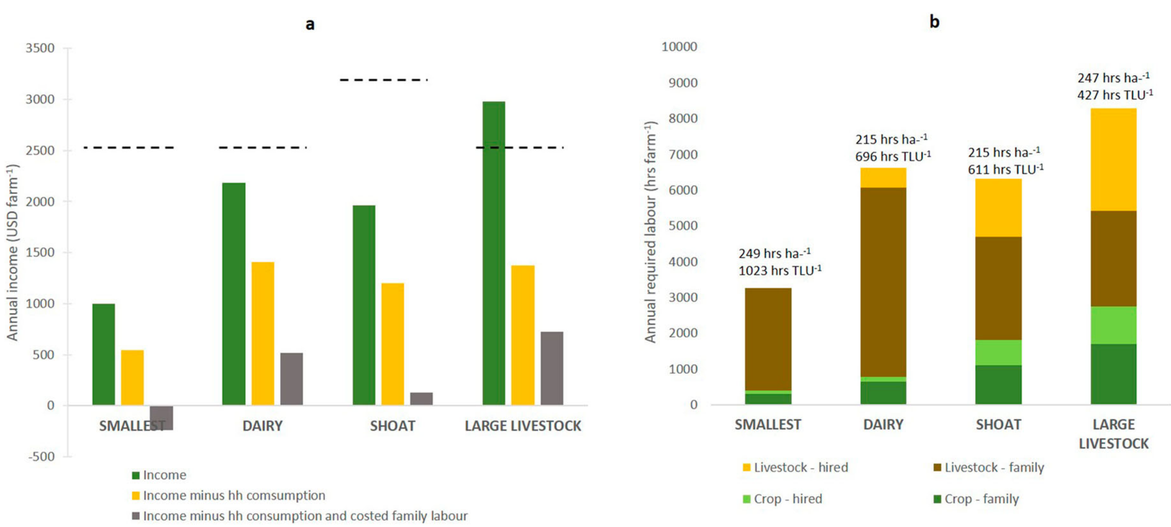

Figure 3. Socio-economic indicators of farm performance per livestock system: Annual income (a); annual required labour (b). The dashed line illustrates the poverty line at 1 USD per household member and day (a), and the numbers above bars denote labour efficiencies – for crop activities per area, and for livestock activities per TLU 9b.

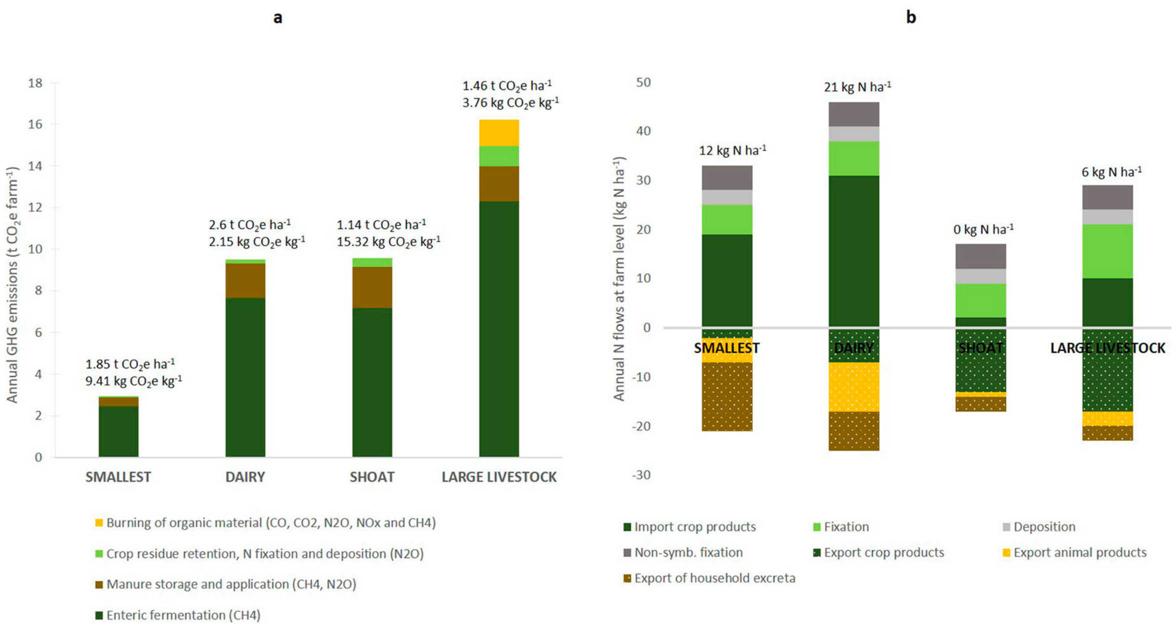

Figure 4. Environmental indicators of farm performance per livestock system: Greenhouse gas emissions (a) and annual N flows at farm level (b). Numbers above bars emission intensities per land area and milk produced (a), and positive values represent imports, and negative value denote exports while numbers above bars denoted the annual N balance per land area (b).

However, all types had alternative options available to increase income while reducing GHG when compared to the baseline, with DAIRY and to a lesser extent SHOAT and LARGE LIVESTOCK having most options available (Figure 6a). When looking at the relationship between income and annual N balance, a trade-off was visible for SMALLEST and DAIRY while for SHOATS and LARGE LIVESTOCK there were only few options to increase their N balance (Figure 6b).

Only a few of the chosen alternatives represented a triple win, thus an improvement on all three objectives when compared to the baseline. Farm constellation M (medium) for SMALLEST increased income by 40%, decreased GHG emissions by 30% and increased N balance by 76%. The overall cattle number was reduced from six to three, and goats and sheep from seven to one. Less maize and bean residues were fed but sunflower cake added, which enabled higher milk production for local and improved cows. The on-farm pasture was eliminated, potato and maize and bean fields slightly reduced and more residues retained in the field instead of fed. Farm alternatives V and H were triple-wins for DAIRY when compared to the baseline. Option V (high income and increased GHG emissions) increased DAIRY income by 109%, decreased GHG by 11% and increased N balance by 38%. This was reached through eliminating the local goats and cows, but increasing improved cows to seven, and raising their milk production to 4.9 kg day^{-1} by increasing the Napier grass field, decreasing on-farm pasture, and doubling the sunflower cake fed. Less maize and bean residues were fed but more retained on the field. Option M increased SHOAT income by 46%, decreased GHG by 39% and increased N balance by 1144%. This was obtained through eliminating local cows and goats, reducing sheep to one, and adding three improved cows with higher milk production of 5.4 kg day^{-1}. A Napier grass field of 0.4 ha was introduced, the on-farm pasture and crop fields reduced so that the total farming area decreased to 5.4 ha. Less maize and bean residues were fed and more retained on the soil. Option H was not a triple-win for LARGE LIVESTOCK but came closest as it increased income by 33%, decreased GHG by 26%, but decreased N balance by 28%. Local cattle were reduced from 15 to eight, and one improved cow at high (5.8 kg day^{-1}) milk production added. Off-farm grazing was reduced, but sunflower cake feeding (354 kg DM $year^{-1}$) and a Napier grass field of 1.8 ha were introduced. Crop residue feeding was reduced but more retained on the field (Table 5).

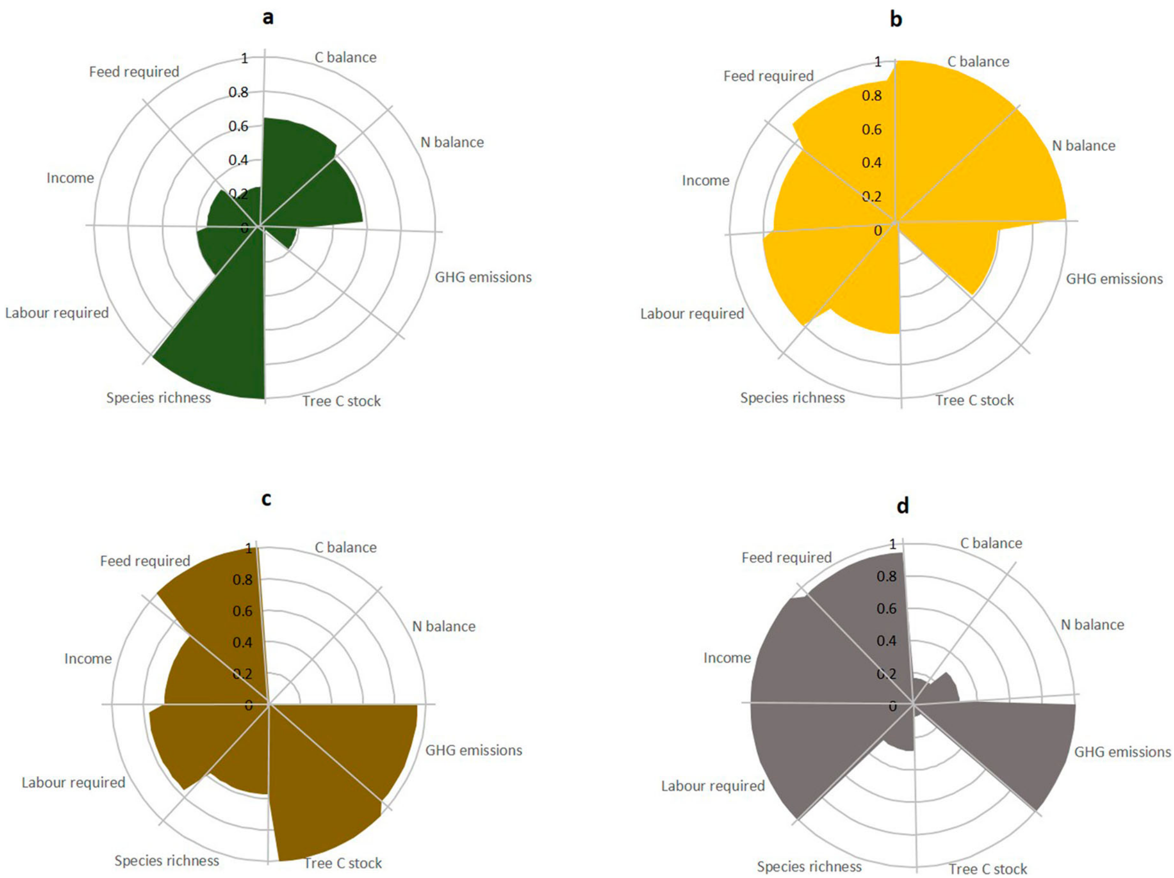

Figure 5. Scoring of SMALLEST (a), DAIRY (b), SHOAT (c) and LARGE LIVESTOCK (d) along socio-economic and agro-environmental indicators. Variables were standardized between 0 and 1, defining he highest value for each variable among the four farmers as 1.

3.4 Farmers' perspectives on sustainable livestock intensification options

When asked about the relative importance of crop and livestock activities, all four case study farmers underlined cropping as the priority activity for income generation. Livestock was mainly seen as backup asset, insurance or risk buffer for funding events and emergencies such as travel, schooling and medical expenses. Except DAIRY, farmers also expressed the importance of livestock numbers, and not productivity, to elevate status and prestige within their community. DAIRY was the only farm that had experience with improved cattle at the time of data collection in 2015, and was planning to replace the remaining local cattle with improved cows (except one bull for draught power) when the children left home as there would be no herding labour available anymore. All farmers underlined the main advantage of improved cattle, being higher milk and manure production. Several challenges with improved cattle rearing was quoted, especially by SHOAT and SMALLEST: (a) they required a high amount and different type of labour as fetching of cut-and-carry feed and drinking water (around 80 l day^{-1}) was physically demanding and could not be exercised by children or old people who normally herded local cattle; (b) they were susceptible to diseases and decease especially under hard conditions; (c) they could not provide draught power which was essential in the area; (d) they were not easy to sell as they had higher body weight and were more expensive; (e) they were difficult to impregnate naturally, and artificial insemination services and cooling facilities were difficult to access; (f) they required more and higher quality feed which is not sufficiently available from the local pastures; (g) lack of training and successful examples among their neighbours. After the detailed characterization in 2015 (thus not reflected in this study), SMALLEST started experimenting with Napier grass on a small plot, and LARGE LIVESTOCK commenced with

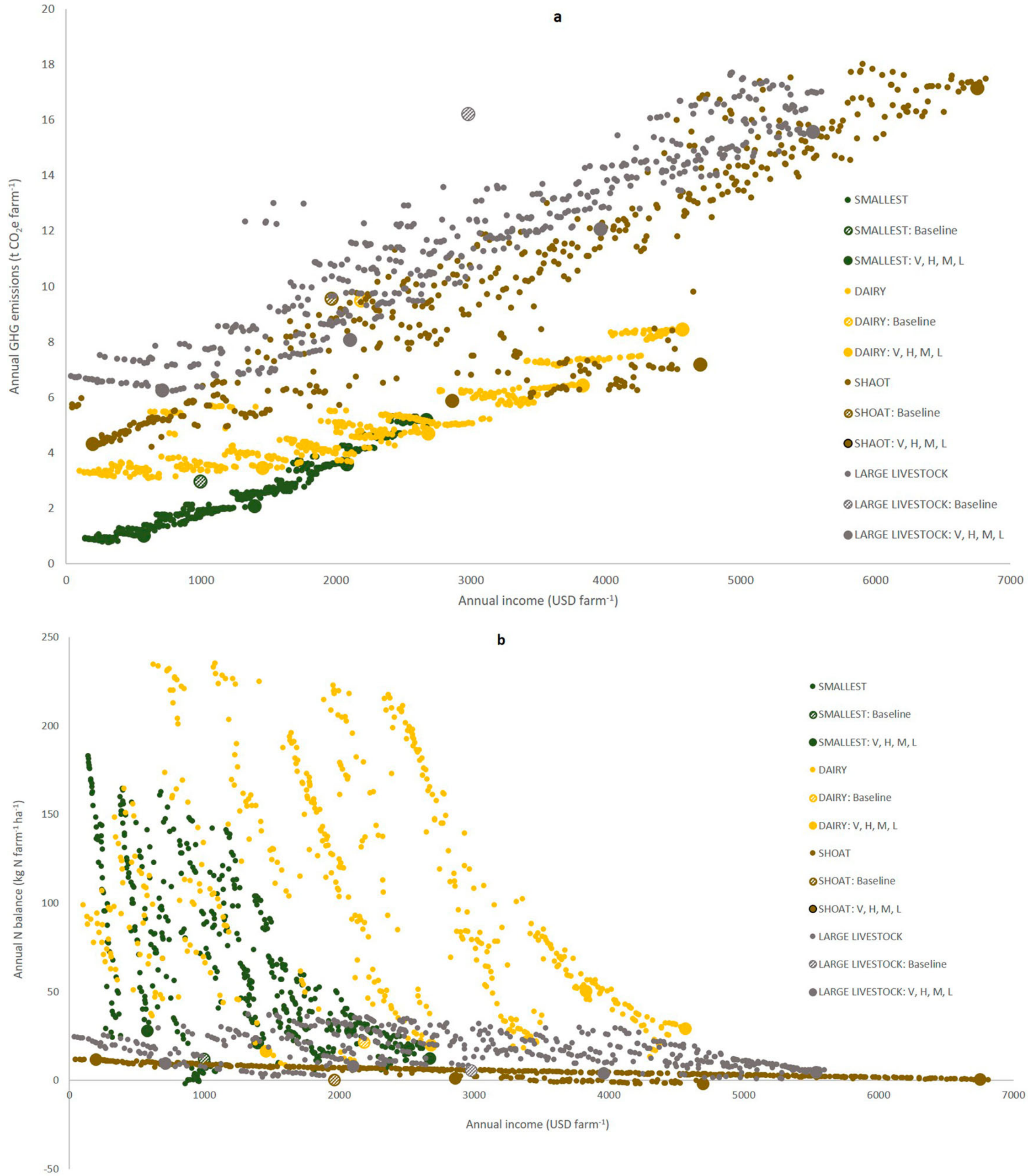

Figure 6. Trade-offs between annual income and GHG emissions (a) and annual income and farm N balances (b) across smallholder livestock systems. The large dots with pattern denote the baseline position, whereas all other dots 377 are model-generated. The large dots denote model-generated farm constellations that are further examined in Table 5. *V* = very high income and GHG, *H* = high, *M* = medium, *L* = low.

one improved dairy cow, which was managed separately from the other cattle. Another commonly mentioned theme was the disappearance of off-farm, communal grazing areas. In Sabilo, there was already no grazing areas available anymore as they had disappeared over the last decade; in Long only the nearby forest could be grazed during parts of the year; only in Hallu, large communal grazing areas were available as recently the community received land from the neighbouring Tarangire National Park in exchange for strictly keeping their cattle outside of its boundaries. Part of this land was used for communal grazing,

Table 5. Outcomes, constraints and decision variables for baselines (*B*) and four alternative farm configurations from optimization run output.

	SMALLEST					DAIRY					SHOAT					LARGE LIVESTOCK				
	B	*V*	*H*	*M*	*L*	*B*	*V*	*H*	*M*	*L*	*B*	*V*	*H*	*M*	*L*	*B*	*V*	*H*	*M*	*L*
Outcome variables																				
Annual income (USD farm^{-1})	997	2670	2081	1394	574	2186	4565	3828	2680	1455	1965	6754	4701	2860	198	2977	5535	3959	2104	711
Greenhouse gas emissions (CO_2e farm^{-1})	3.0	5.2	3.6	2.1	1.0	9.5	8.5	6.4	4.7	3.4	9.6	17.2	7.2	5.9	4.3	16.2	15.6	12.1	8.1	6.3
Annual N balance (kg N farm^{-1})	12.1	12.5	28.1	21.3	27.9	21.2	29.4	50.6	19.8	16.7	0.1	0.4	−2.0	1.3	11.6	5.7	4.7	4.2	8.0	9.5
Constraint variables																				
Organic matter balance (kg farm^{-1})	−0.2	503.0	549.1	109.0	453.0	0.1	147.9	314.6	239.4	171.9	0.1	209.0	115.7	133.4	140.1	0.3	37.4	19.6	14.5	16.0
Labour balance (hours year^{-1})	3620	4948	5542	5638	5837	585	2789	3499	3755	4102	1174	606	2217	3103	3857	1639	447	673	822	3228
Farm area (ha)	1.6	1.6	0.8	1.2	0.3	3.7	3.1	1.8	1.7	1.4	8.4	8.4	8.4	5.4	3.2	11.1	11.0	10.7	9.6	5.0
Decision variables																				
Local cows (number)	2.0	2.0	2.0	1.0	1.0	3.0	0.0	0.0	0.0	2.0	3.0	6.0	1.0	0.0	0.0	11.0	11.0	6.0	0.0	0.0
Improved cows (number)	0.0	3.0	2.0	1.0	0.0	3.0	7.0	5.0	3.0	1.0	0.0	10.0	3.0	3.0	1.0	1.0	2.0	2.0	2.0	1.0
Local bulls (number)	3.0	0.0	0.0	1.0	0.0	NA	NA	NA	NA	NA	3.0	2.0	2.0	2.0	2.0	4.0	2.0	2.0	2.0	2.0
Local young male cattle (number)	1.0	1.0	0.0	0.0	0.0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Local goat (number)	4.0	0.0	0.0	1.0	2.0	5.0	0.0	0.0	0.0	0.0	20.0	0.0	1.0	0.0	0.0	NA	NA	NA	NA	NA
Sheep (number)	3.0	0.0	0.0	0.0	0.0	NA	NA	NA	NA	NA	7.0	0.0	0.0	1.0	7.0	NA	NA	NA	NA	NA
Off-farm grazing (kg DM year^{-1})	3850	3592	3828	3282	1752	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	13350	12028	7673	8464	5598
Maize + bean (+pigeon pea + sunflower) field (ha)	1.0	0.3	0.0	0.9	0.0	1.6	1.6	1.4	1.5	1.3	3.1	0.5	4.9	2.2	0.0	10.1	7.2	7.1	8.2	3.2
Potato field (ha)	0.3	0.3	0.3	0.2	0.1	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Wheat field (ha)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1.6	0.0	0.3	0.0	0.0	NA	NA	NA	NA	NA
Napier field (ha)	0.0	0.9	0.4	0.0	0.0	0.5	0.6	0.4	0.1	0.0	0.0	4.9	0.2	0.4	0.4	0.0	2.0	1.8	0.0	0.4
On-farm pasture (ha)	0.2	0.0	0.0	0.0	0.0	1.5	0.9	0.0	0.0	0.1	3.7	3.0	3.0	2.8	2.8	NA	NA	NA	NA	NA
Bean residues fed (fraction)	1.0	0.9	0.9	0.4	1.0	1.0	0.6	0.1	0.0	0.1	1.0	0.7	0.1	0.6	0.7	NA	NA	NA	NA	NA
Bean residues retained (fraction)	0.1	0.2	0.0	0.1	0.5	0.0	0.6	0.3	0.6	0.6	0.0	0.6	1.0	0.3	0.8	NA	NA	NA	NA	NA
Maize residues fed (fraction)	1.0	0.1	0.4	0.0	0.5	1.0	0.0	0.1	0.2	0.3	1.0	0.4	0.8	0.3	0.8	0.4	0.0	0.0	0.0	0.0
Maize residues retained (fraction)	0.1	1.0	0.6	0.7	0.3	0.0	0.3	0.9	0.8	0.6	0.0	0.3	1.0	1.0	0.2	0.6	0.6	0.7	0.5	0.9
Sunflower residues fed (fraction)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1.0	0.3	0.0	0.2	0.6	0.4	0.1	0.1	0.1	0.4
Sunflower residues retained (fraction)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.0	1.0	0.5	0.3	0.8	0.6	0.8	0.9	0.7	0.6
Sunflower cake fed (kg DM year^{-1})	0	415	342	473	7	900	1936	1931	44	39	NA	NA	NA	NA	NA	0	178	354	912	116
Wheat residue fed (fraction)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1.0	0.5	0.3	0.5	0.6	NA	NA	NA	NA	NA
Wheat residue retained (fraction)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.0	0.4	0.3	0.3	0.1	NA	NA	NA	NA	NA

Notes: *V* = very high income and GHG, *H* = high, *M* = medium, *L* = low.

while other parts were distributed to households as cropping land.

4. Discussion

4.1. Livestock systems diversity and drivers of change

Livestock feeding and husbandry in Babati was predominantly extensive, with relatively large livestock herds, local cattle breeds, reliance on grazing and crop residue feeding, small amounts of fed concentrates, and low productivity. Only few cattle of improved breeds were kept separately from the local cattle herds in zero-grazing units. The quantified feed baskets in Babati are in line with results from Mangesho, Loina, Diyu, Urassa, and Lukuyu (2013) from the same area. According to Hillbur (2013), the cultural history of the Iraqw and Gorowa as pastoralists and later agro-pastoralists can partly explain the current extensive livestock keeping. The experience of zero-grazing is still mainly limited to areas with high population pressure and Heifer Project International (HPI) intervention areas from the 1980s and 1990s (Hillbur, 2013). However, increasing land pressure and degradation is changing the context, leading to disappearance of grazing land, sub-division of farms, and increased conflicts between herders and farmers. Where communal grazing exists, there are by-laws in place within villages. All villages now have defined boundaries, and village land use plans are under way (Bishop-Sambrook et al., 2004; Hillbur, 2013).

The diversity of agro-ecological environment and socio-economic characteristics is large across SSA. Understanding, considering, capturing and classifying the heterogeneity and diversity of smallholder farming systems in SSA is the basis to understanding the dynamics and exploring responses to interventions (Tittonell et al., 2010). Modelling few farming systems, types or classes that are considered representative for a wider area is a well-established approach. Farming system types are a population of individual farm systems that have broadly similar resource bases, enterprise patterns, household livelihoods and constraints, and for which similar development strategies and interventions would be appropriate. Different approaches can be used to construct farm typologies, such as qualitative, participatory, expert-based and quantitative typologies (Alvarez et al., 2018; Kuivanen et al., 2016; Tittonell et al., 2010). In this study, we chose a predominantly structural, quantitative approach to construct a farm typology, validated by local experts, and opted to model 'real' instead of 'constructed' farms. However, this approach has its inherent challenges: livestock holdings turned out to be highly fluctuating, with numbers that could between the farm visits in 2015 and 2017. Land sizes as verified in 2015 were larger as originally reported by farmers in the survey in 2013, especially for SHOATS. The discrepancies in land size were mainly due seasonal renting of land, and inaccuracies of farmers' estimations, e.g. on-farm pasture is often not considered and reported as farm plot during a household survey. This reflects findings from other rural areas with good urban linkages in Kenya and Tanzania, which studied changes in rural livelihoods over periods of three to ten years. Improving livelihoods in the area was called a 'moving target' as farmers coped and adapted quickly to the fast-changing local and regional environment (Valbuena, Groot, Mukalama, Gérard, & Tittonell, 2015; Fraval et al., 2018). Such rapid changes on farms limit the strength of structural farming system typologies, and pose challenges the selection of representative farms for modelling and targeting of interventions.

An alternative approach to modelling of representative farming system types is modelling of entire farm populations (see for example Frelat et al., 2015; Paul et al., 2018; Shikuku et al., 2017). While this enables to analyze the variability and spread of intervention responses, tends to be more rapid, and avoids pitfalls of constructing and selecting representative farms, it only allows for calculation of relatively simple indicators that can only deliver a first picture or snapshot of a situation. Moreover, quality of outputs entirely depends on the quality of household survey data, which has often been questioned. Key data including land and plot sizes and yields are often over- or under-estimated by farmers themselves (Carletto, Zezza, & Banerjee, 2013; Fraval et al., 2019). Modelling few farming systems, and participatory validation and triangulation of input data using mixed-methods including actual on-farm measurements, such as performed in this study, enables more in-depth understanding of complexities, underlying dynamics and relationships between farming systems components. Working with real farms allows for feedback loops and participatory modelling that can improve modelling quality and outputs, and allows mutual learning processes. However, mixed methods data collection and modelling can also be more time and resource-intensive, and less replicable across time and contexts (Thornton et al., 2018). It is a balancing act to obtain a sufficiently accurate picture without being overly simplifying, using the least resource-intensive approach available.

4.2 Improved dairy breeds and feeds as sustainable livestock intensification options in Tanzania

This study confirms that livestock is the main contributor to agricultural greenhouse gas emissions in Tanzania (CIAT & World Bank, 2017) and other countries in East Africa (Ortiz-Gonzalo et al., 2017; Paul et al., 2018; Seebauer, 2014). As enteric fermentation and manure management are the main contributors to whole-farm GHG emissions, livestock is a key entry point for climate change mitigation in East Africa. On-farm farm emissions in Babati were higher than in other sites in the region due to the relatively large livestock herds, ranging from 2.9 t CO_2e (SMALLEST) to 16.2 t CO_2e (LARGE LIVESTOCK). In Rwanda for example, average annual GHG emissions per household only lay between 0.4 and 1.5 t CO_2e (Paul et al., 2018). In Central Kenya, whole farm GHG emissions amounted to an average of 1.05 kg CO_2e kg milk^{-1} (Ortiz-Gonzalo et al., 2017), while in this study they ranged from 2.1 to 15.3 kg CO_2e kg milk^{-1} reflecting the lower milk production levels. However overall, Tanzania has negligible total and per capita GHG emissions (0.2 t CO_2e per capita) and taking into account the 48.1 Mio. ha forests, the country is a net carbon sink (United Republic of Tanzania, 2015). In contrast to industrialized countries that need to reduce absolute emissions, the focus in East Africa should be on reducing emission intensities through efficiency gains (Salmon et al., 2018). Reducing ruminant numbers, replacing local cattle with improved dairy breeds, and improving feeding through on-farm Napier grass cultivation were synergetic options, decreasing GHG emission intensities without compromising income and food security. Fewer animals of improved dairy breeds, which are better managed and fed, has often been presented as promising climate-smart livestock intensification options (Bryan et al., 2013; CIAT & World Bank, 2017; Herrero et al., 2016; Paul et al., 2018; Shikuku et al., 2017). Smallholder dairy systems, when compared to more extensive livestock keeping, have lower GHG emission intensities per kg milk produced, but also lowest trade-offs with other farm performance dimensions. External drivers like increasing land pressure and policy reform might further favour transition towards dairy systems.

This study also demonstrated that with diminishing off-farm grazing, and remaining large livestock and crop sales, nutrient mining is of potential concern. Unless cattle feed is imported from outside the farm, fodder and crop residue feeding are not sufficient nutrient replenishment. In low population pressure areas, potential trade-offs can be managed through temporal or spatial arrangements while in areas with high land pressures, these traditional nutrient transfer systems collapse (Vanlauwe et al., 2017). Babati illustrates this shift in systems, with Hallu (LARGE LIVESTOCK) representing the vanishing nutrient import systems. The village lies in an area that only recently received land from the Tarangire National Park, and farm areas are large and communal grazing areas still available. Long (SMALLEST) and Sabilo (DAIRY, SHOAT) represent the increasing reliance on on-farm resources, reducing farm sizes and zero-grazing systems. Already now, at least 52% of the fields in Babati had negative nutrient balances (Kihara et al., 2015). However, planted forages can also have other environmental benefits that were beyond this study. A study from Long in the 2014 rainy season demonstrated that although 75% of rainfall water was lost by evapotranspiration, runoff levels were significantly lower under forage grass-legume intercrop, resulting in 30% higher soil moisture (Kizito et al., 2016).

Ex-ante impact assessment and prioritization studies are increasingly important to target scarce research and development resources, and support decisions for improved adaptation and mitigation of mixed crop-livestock systems in SSA (Descheemaeker et al., 2016). Studies like this aim to generate results that can inform policy makers, project designers, investors, donors and other decision-makers on prioritizing options towards low emission livestock, despite the complexity of potential impacts and trade-offs. However, the uncertainty of simulation and optimization modelling is often unknown, and if known it might be large (Thornton et al., 2018). Future research in simulation and optimization modelling needs to take into account and communicate such uncertainty, and output from simulation modelling should be seen rather as discussion and not necessarily decision support (Kanter et al., 2018).

4.3. Social and institutional settings affecting adoption of improved breeds and feeds

Despite its bio-economic potential as a climate-smart livestock intensification pathway, adoption of improved dairy breed, feed and husbandry is affected by social and institutional settings. Smallholder dairying has been presented as fast-tracking development, and an advanced, 'modern' technology but Green (2017) argues that livestock modelling neglects the social context of smallholder dairying. Three main adoption obstacles can be distinguished: Firstly, the introduction of improved dairy breeds or feeds is not as simple as inserting a singular technological object, but a change or re-organization of the entire production system. For example, improved feeding needs to go hand in hand with a range of other technological changes including improved animal breeds, appropriate animal shed, provision of drinking water and availability of veterinary services in order to reap satisfactory production responses (Ndah, Schuler, Nkwain, Nzogela, & Paul, 2017). This re-organization in time and space requires capacities, investment and experience that might not be present among resource-constrained smallholders. This argumentation is reflected in the perceptions of farmers in Babati. If improved breeds were introduced in farming systems, they were kept as a completely separate and re-organized enterprise, and not integrated with the local cattle herds: different feeds and feeding system (zero grazing), different and high labour demands for fetching water and fodder. Farmers were reluctant to venture in improved dairy cows due to lack of training and experience. There is a lack of awareness and knowledge, support and investment from national and local authorities, and market linkages for inputs and outputs (Ndah et al., 2017).

The second obstacle to adopting improved dairy breeds and feeds is the partial loss of the multi-functionality of livestock (Descheemaeker et al., 2016). Sumberg and Lankoandé (2013) showed in their study from Tanzania that income and nutritious food is only one function of livestock. Livestock intensification may not be the main priority for farmers that primarily keep livestock for providing drought power, as assets and risk management strategy, or for cultural reasons such as identity or status (Sumberg & Lankoandé, 2013; Thomas & Sumberg, 1995). Moving towards improved dairy for income and food, some farmers would be reluctant to accept the trade-offs of losing the savings, cultural and draught functions (Sumberg & Lankoandé, 2013). These functions provide incentives for keeping large livestock herds at low productivity levels, instead of reducing stocking rates and investing in increased productivity (Descheemaeker et al., 2016). This is reflected in farmers' quotes in Babati, mentioning the role of local cattle in social status, as well as draught power and asset and insurance function. The last major obstacle to adoption would be increased risk (Green, 2017; Sumberg & Lankoandé, 2013). Farmers reported high mortality, low fertility, sensitivity to heat, sun and tropical diseases, and high costs for disease prevention and veterinary care.

5. Conclusions

This mixed-methods study from Northern Tanzania illustrates how sustainable livestock intensification options can be a key entry point to reduce agro-environmental trade-offs across four diverse smallholder farming systems. Livestock was the main contributor to whole-farm GHG emissions, but GHG emission intensity was lowest for DAIRY (2.1 kg CO_2-e kg^{-1} milk) when compared to the other livestock systems types (3.8–15.3 kg CO_2e kg^{-1}). Reducing ruminant numbers, replacing local cattle with improved dairy breeds, improve feeding through on-farm Napier grass (*Pennisetum purpureum*) cultivation to reach higher milk production levels, and reduce crop residue feeding to leave them on the field increased household incomes and N balances while decreasing GHG emissions. However, semi-structured interviews with farmers revealed three main obstacles to adoption: they require a skilful re-organization of the entire production system, result in loss of some multi-functionality of livestock, and incur higher production risks.

These findings have implications for climate-smart agriculture in Tanzania. As enteric fermentation and manure management are the main contributors to whole-farm GHG emissions, livestock is a key entry point for climate change mitigation. However, mitigation cannot be a primary objective in East Africa but only a co-benefit of much-needed productivity increases as overall emission levels are low. Sustainable livestock intensification provides one of the few synergetic opportunities, increasing productivity and incomes while decreasing emission intensity as co-benefit. A better understanding of the wider institutional settings and incentives is needed to inform and accompany the sustainable transformation of the livestock sector. One of the priorities should be an investment in capacities and supporting infrastructure, and coordination between various actors including policy, private sector, extension and farmer associations.

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