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Integrated analysis of opportunities and trade-offs for mixed crop-livestock farm types in Amhara, Ethiopia

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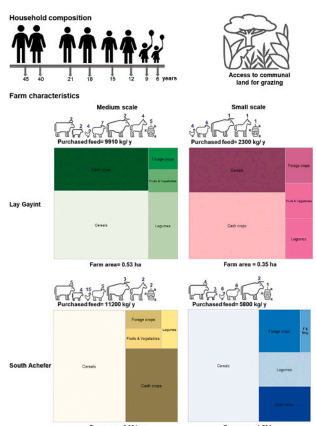
HIGHLIGHTS

- Four contrasting stylized farm types from a low and high potential district in Amhara, Ethiopia were modelled.
- Stakeholders were allowed to prioritize objectives resulting in 15 clusters of the generated farm configurations.
- The results give insight into agricultural options that meet multi-objectives in different pillars of sustainability.
- Poultry was a promising short-term option to meet all set objectives, and cultivation of eucalyptus was highly profitable.
- To meet a living income solely from agricultural activities in this region, farm size should be a minimum of 2.9 ha.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: In Ethiopia, many agricultural interventions have been introduced for mixed farm types in different biophysical and socioeconomic conditions. The contribution of such interventions to multi-objectives at farm level and beyond remains unclear.
OBJECTIVE: To derive insights into interaction of multi-objectives on economic profit-, nutrition security-, and environmental performance that are relevant for improvement of farm household living income in Amhara, Ethiopia.
METHODS: FarmDESIGN model evaluated performance of four stylized medium- and small-scale farm types in a low (Lay Gayint)- and high (South Achefer)- potential district: LG-M, LG-S, SA-M and SA-S. Pareto-based multi-objective optimization was performed to maximize farm profit, livestock density, dietary energy and vitamin A

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yield, and minimize GHG and soil N losses. Further analysis resulted in 3–4 clusters per farm type with varied farm configurations.
RESULTS AND CONCLUSIONS: Higher dietary energy- and vitamin A- yield that meets household and Ethiopian society requirements increased synergistically with profit in three of the four farm type clusters, while LG-S clusters could only increase vitamin A yield substantially with profit. Only LG-M clusters intensified livestock by addition of 4–8 crossbred cows and 1–10 chickens, supported by imported feed and off-farm grazing but face strong environmental trade-offs of increased GHG and soil N losses. Chicken production (eggs and chicken meat) is an option to reduce environmental impact, increase profit and contribute to both human nutrition requirements. In LG-S, SA-M and SA-S farm type clusters, profit was generated mainly from sale of eucalyptus, maize, potato, carrot, finger millet, garlic, beetroot and banana, with eucalyptus accounting at least 35% of the crop profit. Livestock diversification in these clusters also contributed to farm revenue, but always to a smaller extent, due to relatively high management costs. A living income from farming activities was only achieved on SA-M3 as 3.96 USD/capita/day (+0.36 above the threshold). This cluster had a 2.90 ha land area, farm income almost equally generated from crop and livestock production, and successfully met all set objectives except maximizing livestock density.
SIGNIFICANCE: Our study infers the need to increase land area, expand poultry and rear crossbred cows, and cultivate high value crops to realize a living income solely from agricultural activities. For implementation, current land-use policies should support farm area expansion. The suggested agricultural options, which already align with current Ethiopian development plans, must utilize sustainable measures that will not lead to short- or long-term challenges as higher GHG and soil nutrient mining.

1. Introduction

Most food security research in Ethiopia and other low- and middle-income countries focuses on technology that increase crop and livestock productivity or improve management of natural resources (Gebru et al., 2019; Adimassu et al., 2014; Rockström et al., 2009; Varijakshapanicker et al., 2019; Balehegn et al., 2020). This type of research is needed to sustainably increase agricultural production to feed a growing population, but it ignores the complexity of decision-making in farm households concerning consumption, production, investments, and managing natural and labor resources (Singh et al., 1986; Giller et al., 2011). Farm households continuously make decisions on such issues that affect farm performance in the short and long term. In making strategic management decisions, farmers may focus on resilience to production and market shocks by integrating crop-livestock production activities; or on income generation by specializing in production of marketable crop and livestock products (Sumberg, 2003; van der Lee et al., 2018; van der Lee et al., 2020).

Farm households deal with various biophysical and socioeconomic food system drivers that affect farm performance such as prevailing soil and weather conditions, input and product markets, and policies (van Berkum et al., 2018). At the same time, farm performance has an impact on the entire food system via greenhouse gases emission, soil erosion, and nutritious food supply to consumers. Farmers' interests do not always align with objectives at the landscape or food system level, such as national food and nutrition security-, climate change mitigation-, and natural resource management-goals (Fresco and Kroonenberg, 1992; Webster, 1999). A multi-disciplinary and integrated analysis of farming systems is therefore needed to analyze the potential effect of contrasting objectives on farm performance, regional food and nutrition security, and environmental objectives (van Wijk et al., 2009; Giller et al., 2011; Hammond et al., 2021). Methodologically, it is difficult to analyze objectives that are relevant at different spatial scales or levels because of interaction of new variables that are only relevant at specific scales (Dalgaard et al., 2003; Laborte et al., 2007; Ewert et al., 2011). The farming system nevertheless serves as a good entry point because the management and choices of farmers facilitate achievement of objectives at farm level and beyond. Thus, farm level analysis may increase our insights into how different objectives interact, including the identification of trade-offs and synergies among objectives relevant at the farm level; and objectives contributing to local economy, food and nutrition security, and environmental sustainability at the wider food system level.

Lately, the concept of living income has gained traction as a benchmark for poverty, and it is used for developing socioeconomic interventions (van de Ven et al., 2021). Living income is defined as 'the net annual income required for a household in a specific location to afford a decent standard of living for all members of the household' (Living Income, 2022). A 'decent standard of living' consists of elements such as adequate food, water, housing, education, healthcare, transport, clothing, and other essential needs e.g., funds for emergencies. From a socioeconomic perspective, the inability to achieve a living income can be considered as an undesirable food system outcome (Alho et al., 2021).

The aim of our study was to analyze the interactions of economic-, food and nutrition security-, and environmental objectives and their contribution to the performance and configuration of mixed crop-livestock farm types in Amhara National Regional State, Ethiopia. The performance of farm types is typically assessed based on the achievement of relevant objectives in a situation. We applied FarmDESIGN, a static bioeconomic farm model for the design and analysis of mixed crop-livestock farm types (Ditzler et al., 2019; Groot et al., 2012). The model quantifies farm performance by optimization of multiple objectives. Using FarmDESIGN, we explored solution spaces of four farm types and identified potential trade-offs and synergies among economic, nutritional and environmental objectives. We clustered the generated alternative farm configurations based on a participatory prioritization of the objectives by local stakeholders. Performance of the clusters was compared with their corresponding baseline values of the four farm types, and agricultural interventions per farm type meeting multi-objectives were identified. As a post-model analysis, income from farm activities was calculated and used as a benchmark to assess the standard of living in the farm type households.

2. Methodology

2.1. Site description and selection of farm types

The study focused on mixed crop-livestock farm households in two districts of the Amhara National Regional State of Ethiopia, namely Lay Gayint and South Achefer, which differ in biophysical and socioeconomic conditions. South Achefer is labelled by the Government of Ethiopia as a high-potential district (supported by the Agricultural Growth Program). It has a mean annual rainfall of 1485 mm, fertile soils and flat topography, and average annual minimum and maximum temperatures of 12 and 23 °C, respectively (Asfaw, 2016). At 50 km, it is in proximity to Bahir Dar city, the capital of Amhara region, which indicates accessibility to the main markets and administrative center, over tarmac roads (Mureda and Zeleke, 2008; Minten et al., 2020). Lay

Gayint on the other hand, is officially labelled as a low-potential district for agricultural production. It has a lower average rainfall and temperature: about two-thirds (the northern part) receives only 900 mm of rainfall annually while average annual minimum and maximum temperatures are 7 and 22 °C, respectively (Fekadu et al., 2018). Moreover, this district has a less fertile soil and steep topography that are poor conditions for agricultural production. Therefore, many households in Lay Gayint rely on 'food and cash for work' schemes

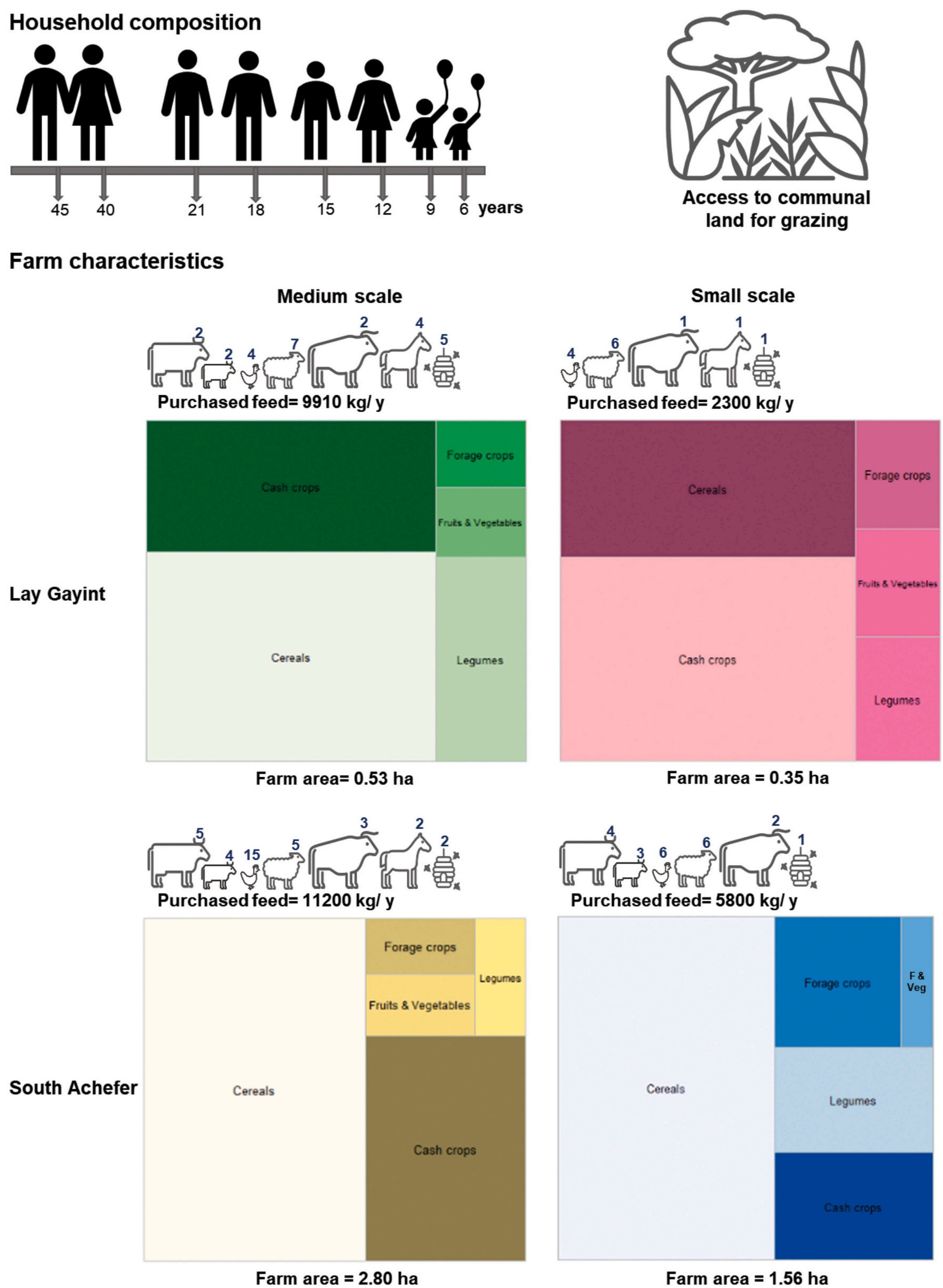

Fig. 1. Pictograms representing the four modelled farm types in Lay Gayint and South Achefer. Depicted are the composition of the household, crop type and livestock density (represented as number of local dairy cow, calf/yearling, chicken, goat/sheep, breeding bull/ox, equine, and beehive). All farm types consisted of an eight-membered household and had access to communal land for grazing. Purchased animal feed (in kg dry matter) is composed of hay, Niger seed (noug) cake and wheat bran. Total farm area per farm type is not to scale. Crop types are depicted relative to their allocated land area on the stylized farm types.

through the Productive Safety Net Program (PSNP) and temporal labor migration is common (de Roo and van der Lee, 2021). At 175 km it is more distant from Bahir Dar city compared to South Achefer and therefore, has less accessibility to main markets.

Four stylized farm types were defined based on the approach described in Section 2.2: one small-scale and one medium-scale farm type in each district (Fig. 1), representing variants of the dominant mixed farming systems in the region. The farm types (Fig. 1) were selected based on scale of production differentiated by (i) land size, with medium-scale about 35–45% bigger than small-scale; and (ii) livestock density (animal type and number), where medium-scale farm types had higher number of large ruminants and total livestock, as well as a higher amount of purchased feed, compared to small-scale. According to the International Farm Comparison Network, 60% of the farms with dairy in Ethiopia have three to nine cows while the remaining 30% have one to two cows (Hemme, 2021). Livestock graze communal land and on-farm with natural pasture *Digitaria abyssinica* and *Pennisetum* spp. Grazing time on communal land was considered as off-farm free resource use (Fig. 1). By this we reduced the time livestock depended on farm produced feed to about half. On-farm natural pasture may be changed to improved forages such as vetch or tree lucerne, and livestock feed demand was also met by on-farm grazing and feeding on crop residues (Ayele et al., 2021; Debela, 2021). Animal feed was further supplemented by purchasing hay, and agro-industrial byproducts, e.g., wheat bran, wheat short, wheat middling and rice bran, edible oil seed cakes (noug, cotton, peanut, linseed, sesame, sunflower), brewery waste, and molasses (Abduku, 2020). The household composition was the same in all farm types since there were no clear differences per farm type.

2.2. Data collection

Data was collected in five steps from July 2020 to April 2021. All data collection steps were performed in the peak of the COVID19 pandemic therefore, travel and contact were limited. (i) Interviews with local experts were conducted to identify relevant objectives in both districts and to collect general information about the farming systems, biophysical data, landholding, crop and livestock productivity, and product prices. The local experts comprised farmers, extension workers from the District Office of Agriculture, District Office of Livestock Promotion and Cooperatives Promotion Agency, staff from the Regional Bureau of Agriculture and Livestock Agency, and researchers from Bahir Dar University. Based on these interviews, two predominant farming systems (small scale and medium scale) were retained for this study. (ii) Two in-depth panel interviews with farmers were conducted to characterize representative farm types per farming system and to compile data per farm type per district. The farmer panelists were selected with support from extension workers, based on their farming experience and representativeness of their farms as typical small and medium-scale farms in the districts. In total, 15 farmers participated from South Achefer (from Ashuda and Abichikeli kebeles) and 24 farmers from Lay Gayint (from Yesero and Ameba Mariyam kebeles). These panels provided data on household composition, biophysical features (soil and climate), farm management costs, crop and livestock distribution, production and product use, facilities (buildings and machines), agricultural input use (manure, fertilizer, and pesticide) and agricultural practices. (iii) For each farm type, complementary farm data was collected through visiting and surveying farmers who are representative for the farm types. Specific data on farm management was recorded for each typical farm type into an excel-based questionnaire (File S1). (iv) Plausibility checks on the collected farm data were carried out by topical specialists from Wageningen University & Research in the areas of crop science, animal science, soil science, and agricultural economics. Any detected inconsistency was triangulated and adjusted with literature data (Soethoudt et al., 2019), unpublished project data and expert opinions to produce plausible values. (v) After the plausibility check, modified data and parameters for optimization were validated by local experts from Bahir Dar University, the Regional Bureau of Agriculture, and the Regional Livestock Promotion Agency. A final representative dataset (Files S2-S5) was defined for each farm type in each district and used for model simulations.

2.3. Farm modelling

The static farm-household model FarmDESIGN (version 5.7.0.0) was used to analyze the annual performance of mixed crop-livestock farm types (Groot et al., 2012; Estrada-Carmona et al., 2020). FarmDESIGN quantifies economic, productive, and environmental objectives of farm households based on the Describe-Explain-Explore-Design (DEED) framework (Giller et al., 2008). The farm types were first described in the model by parameters covering the household composition, biophysical resources, crop and livestock management, economics, facilities, and agrochemical use based on input from stakeholders and literature (Sections 2.1–2.2). Economic, nutritional and environmental indicators were then calculated to explain farm performance. In the exploration step, some of these indicators were set as objectives (to maximize or to minimize) or constraints (with upper and lower boundaries), while others were set as decision variables with upper and lower boundaries (Fig. 2, Table S1). Constraints were set to keep alternative configurations of the farm types within feasible margins, such as lower and upper boundaries on total farm area (ha), and deviations of livestock feed intake capacity and nutritional requirements (%) specified as dry matter, metabolizable energy, and crude protein (Table S1). Pareto-based multi-objective optimization generated sets of alternative farm configurations that constitute feasible solution spaces for each farm type (Fig. 2). Based on participatory prioritization of objectives by local stakeholders, weights were assigned to the objectives enabling identification of farm configurations that support local needs and interests (Section 2.7). Selection of the most desirable solutions as options for redesigning farm types and assessment of the standard of living were performed as last steps.

2.4. Defining objectives in the model

With FarmDESIGN, we studied the effect of simultaneously optimizing six objectives, i.e., (i) maximizing annual farm operating profit (ETB/ha/y), (ii) maximizing livestock density, calculated as annualized tropical livestock units (TLU/ha/y), (iii) maximizing dietary energy yield (capita/ha/y), (iv) maximizing vitamin A yield (capita/ha/y), (v) minimizing greenhouse gas (GHG) emissions (kg CO_2 equivalent/ha/y), and (vi) minimizing soil nitrogen (N) loss (kg/ha/y). These objectives were defined based on interviews with stakeholders (Section 2.2) and are associated with the people-planet-profit concept of sustainable development (Bergmans, 2006): the two economic objectives (i and ii) address the profit component, the two nutritional objectives (iii and iv) the people component, and the two environmental objectives (v and vi) the planet component.

Annual farm operating profit (i) is defined as revenues from crop and livestock sales, after deducting variable costs of farming (agricultural inputs, hired labor) and fixed costs for farm management and assets (depreciation and operational costs). The livestock density objective (ii) relates to the role of livestock as non-monetized household savings (Siegmund-Schultze et al., 2007; Siegmund-Schultze et al., 2011; Behnke, 2010). Both nutritional objectives (iii and iv) express the total number of persons that can be nourished annually by the amount of each nutrient produced per hectare, based on the nutritional requirements of a 30-year-old man (based on Otten et al. (2006)). The energy and vitamin yield include the household requirements for both nutrients. Hence, anything that the farm produces above the dietary requirements for the eight household members is considered as marketable surplus. We converted crop and livestock production into nutritional indicators to allow aggregation of different food types. The nutritional objectives stand for providing healthy diets to reduce undernourishment of the

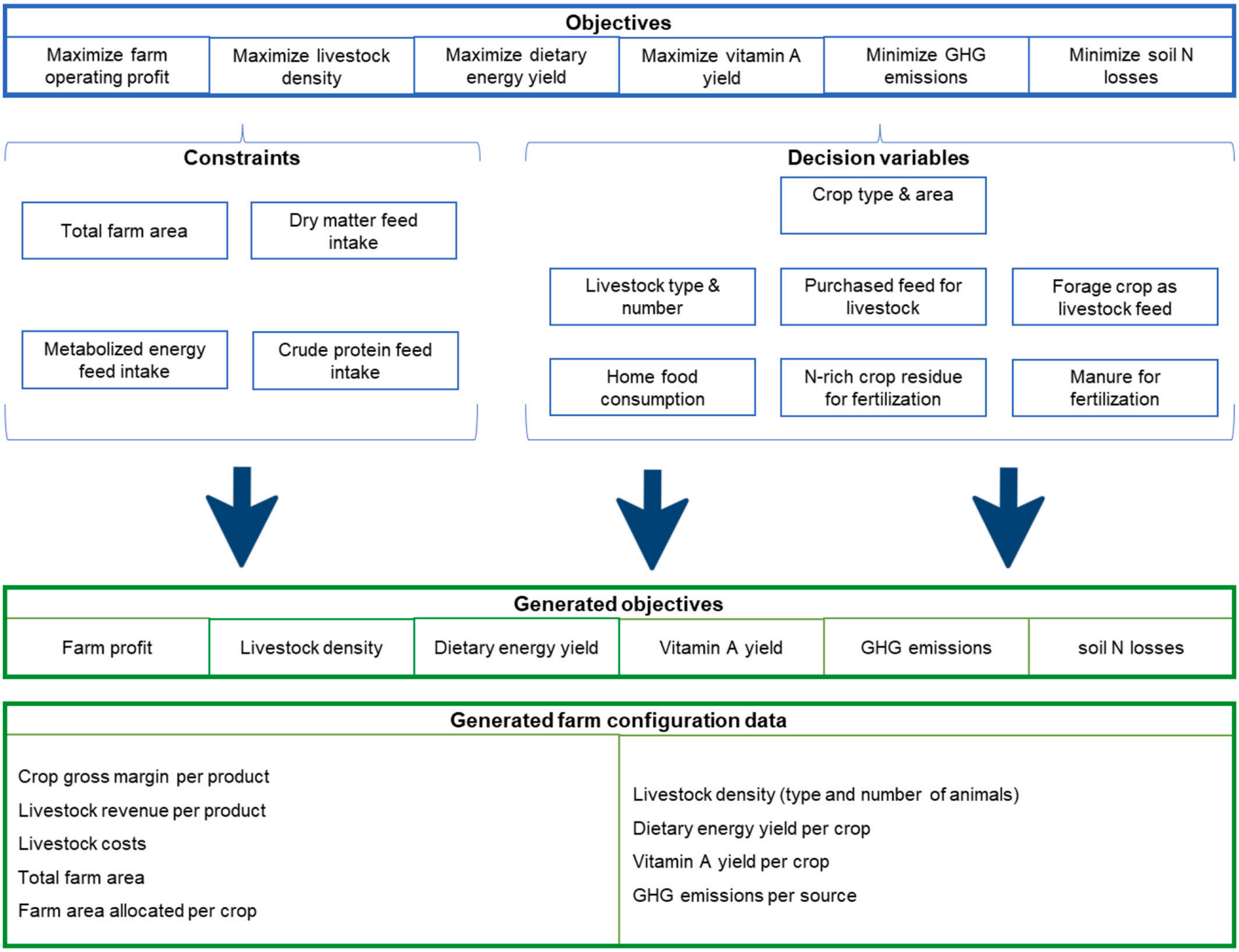

Fig. 2. Methodological framework for the farm-household modelling exercise using FarmDESIGN. Specific objectives, constraints and decision variables (in blue) were defined in the model to generate annual optimization results (in green) of 1000 alternative configurations per farm type.

local population, by diversifying diets and increasing energy and vitamin A intake (Baye et al., 2019; Laillou et al., 2021). The environmental objectives address sustainable use of resources. Objective (v) links to the Paris agreement on reducing national GHG emissions in adapting to climate change, of which Ethiopia is a member (FDRE, 2021; UNFCCC, 2022), while objective (vi) is associated with the widespread soil degradation and nutrient losses occurring in Ethiopia (Hurni, 1988; Abegaz, 2005).

2.5. Decision variables in the model

To generate configurations of the farm types that differ in economic productivity, nutritional yield, and sustainable use of resources, the Pareto-based multi-objective optimization algorithm of FarmDESIGN (Groot et al., 2012) was parameterized with decision variables to adjust land areas of commonly cultivated crops and not widely cultivated crops in both districts (e.g., garlic, chickpea, lentil and pumpkin), type and number of animals and use or sale of on-farm generated crop and livestock products (Fig. 2). Thus, the decision variables indicate ranges of allowed adjustments to achieve the defined objectives. We only included currently existing agricultural practices in the districts and did not include innovations aimed at crop and livestock intensification dependent on external inputs such as fertilizers and pesticides beyond their current use. In recent years, various agricultural innovations or interventions have been adopted by farmers in Lay Gayint and South Achefer, based on fit to farming system, market dynamics, and context factors such as advice by government agencies and ongoing development projects (van der Lee et al., 2018). For livestock, it includes switching from local to crossbred cows; diversification of chicken, goat, and sheep number; and cultivating improved forage crops such as Napier grass, Rhodes grass, tree lucerne and vetch. These interventions were translated into decision variables in FarmDESIGN by setting upper and lower boundaries on livestock density, land area (ha) for forage crops and routing forage crops as livestock feed (Table S1). Crops were selected for their dietary value (dietary energy and vitamin A yield) and market potential. Decision variables for crops were defined by upper and lower boundaries on cropping area (ha) and routing crop products (kg) as food (Table S1). Chickpea, fava bean, finger millet, food barley, grass pea, lentil, maize, potato, sorghum, teff, and wheat were selected for their high dietary energy content. Crops such as apple, banana, beetroot, carrot, Ethiopian kale, and pumpkin were selected for their vitamin A content (although banana is not rich in vitamin A, it represents a locally consumed fruit); while coffee, eucalyptus, garlic, and malt barley were selected as cash crops. Animal products e.g., meat, egg and milk are rich sources of nutrients, and therefore also contribute to nutritional objectives, especially eggs as a vitamin A source. Decision variables were set for the quantities of manure (as a fraction of the total amount produced on farm and recalculated in kg) and N-rich crop residue (kg) used for crop fertilization: both contributing to the environmental objectives by enhancing on-farm nutrient cycling, thus contributing to carbon storage and reducing the need for external fertilizers. Decision variables differed per farm type and were dependent on the feasibility of cultivating specific crops or rearing certain livestock in that farm type (Table S1).

2.6. Baseline performance of farm types

Based on data collected in steps (i) to (iv) of Section 2.2, the current performance of the farm types was calculated with FarmDESIGN (Table 1 for per ha, and for per farm in Table S2). These baseline configurations of the four farm types were used as the starting point for the multi-objective optimization. After objectives, constraints and decision variables were set, the model was configured to yield 1000 alternative solutions for each farm type after 4000 iterations.

2.7. Analysis and validation of the model results

To allow setting priorities on objectives, weights were assigned to the six objectives by stakeholders (Table 2). First, we made model runs using equal weights for the objectives. A workshop in October 2021 with local stakeholders, including farmers and staff from cooperatives, Bahir Dar University and the Regional and District Offices of Agriculture and Livestock, was used to verify model objectives and assumptions, as well as to discuss preliminary results. Workshop participants contributed to refining the assumptions, validating preliminary results and setting weights to the objectives to facilitate identification of optimal farm configurations, based on local needs and interests. The new weights were applied to the objective values after normalization, to facilitate clustering.

The full set of 1001 solutions (i.e., the baseline- and 1000 new farm configuration per farm type) generated by multi-objective optimization was used to analyze the windows of opportunities, trade-offs and synergies among the objectives. Principal component analysis using the “dudi.pca” method in the “ade4” package in R was performed on the alternative solutions. After which, “hclust” and “cutree” methods in the “stats” package of R was used to cluster the generated solutions into 15 groups (Fig. S1, Table S3). The principal component analysis and clustering method were used as data reduction techniques, as it minimizes variability within a cluster while differences among clusters are maximized (Alvarez et al., 2018). Another workshop in October 2022, with a similar group of participants, was used to present and discuss the latest results. Here, the model outcomes were discussed, including the feasibility of agricultural options selected by the model.

The average farm operating profit was used to estimate household incomes of each farm type and to assess the standard of living. It is important to note that off-farm income sources were not quantified and therefore not included in the calculation. The living income of Sidama region in Ethiopia, 3.60 USD/capita/day, was used as benchmark (van de Ven et al., 2021).

Table 1
Calculated current annual economic, nutritional, and environmental objectives and constraints of four farm types, i.e., medium- and small-scale farm types in Lay Gayint (LG-M and LG-S) and South Achefer (SA-M and SA-S).

	LG-M	LG-S	SA-M	SA-S
Objectives:				
Operating profit (ETB/ha) [a]	19,611	132,996	150,146	76,811
Livestock density (TLU/ha) [a]	19.9	7.7	4.6	5.2
Dietary energy yield (capita/ha)	7.1	3.6	15.7	14.1
Vitamin A yield (capita/ha)	0.9	0.4	7.1	0.6
Greenhouse gas emissions (kg CO_2 equivalent/ha)	16.8	7.3	5.4	7.2
Soil nitrogen losses (kg/ha)	96.3	53.0	43.9	14.8
Constraints:				
Total farm area (ha)	0.53	0.35	2.80	1.56
Deviation feed dry matter intake capacity (%) [b]	−4.3	−2.8	−3.0	−4.9
Deviation in ME content of feed (%) [c]	−4.9	−6.9	−2.0	−4.3
Deviation in CP content of feed (%) [c]	41.0	50.8	0.3	5.2

[a] ETB stands for Ethiopian Birr (1 ETB = 0.0176 Euro and 0.0249 US Dollar, 01/03/2021). TLU stands for Tropical Livestock Unit which represents an animal of 250 kg liveweight (TLU; 250 kg = 1 TLU) calculated by summing factors for dairy cow (1), calf (0.4), yearling (0.6), chicken (0.005), goat/sheep (0.1), breeding bull/ox (1), donkey/mule (1), horse (1.4), and beehive (0.1) (adapted from: (Vall et al., 2021; Gryseels, 1988; Musau, 2022).

[b] The deviation represents the percentual difference between intake capacity and actual supply of feed dry matter; a negative value indicates DM shortage.

[c] The deviations in metabolizable energy (ME) and crude protein (CP) represent the percentage difference between animal requirement for maintenance and production, and the supply from the feed. Values should be between −5 and + 5% for ME, to ensure selected production level are achievable, and between 0 and + 30% for CP, to avoid negative environmental impact due to inorganic N losses in excreta (values >30% occur for low-productive livestock).

3. Results

In this section, we first give an overview of the cluster analysis of the optimization results from FarmDESIGN (Section 3.1). We then analyze relationships between the economic, nutritional, and environmental objectives to illustrate trade-offs and synergies between objectives (Section 3.2). The potential changes in configurations of the farm type clusters using the weighted objectives are described in Section 3.3. Results are presented per hectare, not per farm. Therefore, absolute optimization values for Lay Gayint farm types are lower than shown in the figures since their farm areas are <1 ha, while absolute values for South Achefer farm types are higher because their farm areas are >1 ha (Table 1, Table S2). In Section 3.4, we calculate the living income of households derived from the simulated farm operating profit of the farm type clusters.

3.1. Cluster analysis of annual optimization results

The cluster analysis based on weighted objectives resulted in three (LG-S) or four (LG-M, SA-M, SA-S) clusters of similar opportunity spaces per farm type, which differed in their performance and farm configurations (Fig. 3). In general, Lay Gayint clusters showed bigger variation within a farm type compared to the South Achefer clusters. The best performing clusters for the farm types were LG-M1, LG-S2, SA-M3 and SA-S1, respectively.

The best performing clusters of each farm type scored well on most objectives (Fig. S2). Lay Gayint clusters LG-M1 and LG-S2 performed well in meeting the economic and nutrition objectives but scored low in meeting environmental objectives. South Achefer clusters SA-M3 and SA-S1 performed well in maximizing operating profit and dietary energy yield while minimizing GHG emissions and soil N loss, at the cost of reduced livestock density for SA-M3 and lower vitamin A yield for SA-S1. All four best performing clusters scored similarly on profit only (Fig. S2a). The main difference between Lay Gayint and South Achefer is in meeting their nutritional objective: the former farm types boosted their vitamin A production while for the latter, this was done for dietary energy yield (Fig. S2c, d). LG-M1 showed the biggest differences among the best performing farm types scoring much higher on livestock density, GHG emissions and soil N losses (Fig. S2b, e, f).

3.2. Synergies and trade-offs among objectives in farm type clusters

At least one of the identified clusters per farm type generated operating profits of >100 K Birr/ha (equivalent to ~2500 USD; exchange rate March 2021) but there were trade-offs to reach these high profits (Fig. 4a, S2a). For all farm types except LG-M, livestock density remained relatively stable with increasing farm profit (Fig. 4a). For LG-M clusters, both operating profit and livestock density could be

Table 2
Selected objectives and their corresponding weights.

Objective	Maximize operating profit	Maximize livestock density	Maximize dietary energy yield	Maximize vitamin A yield	Minimize greenhouse gas emissions	Minimize soil nitrogen losses
Weight	0.30	0.26	0.06	0.20	0.14	0.04

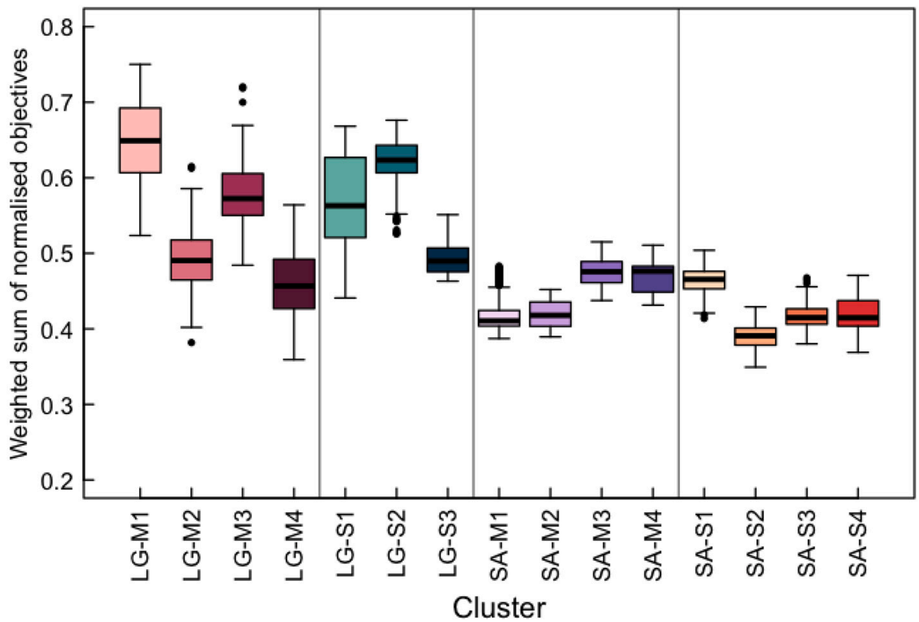

Fig. 3. Weighted sums of the normalized objective values for the four farm types. Box plots of the clusters are based on 1000 alternative farm configurations per farm type. The clusters were generated from weighed objectives from stakeholders' input, for medium- and small-scale farm types in Lay Gayint (LG-M and LG-S) and South Achefer (SA-M and SA-S).

simultaneously increased, but only to a small extent: the highest operating profit ~208 K Birr/ha was achieved with a livestock density of 24 TLU/ha (+4 TLU/ha compared to its modelled baseline). However, further increasing livestock density in LG-M clusters resulted in negative operating profits (with capital being fixed in animals at the expense of cash flow), indicating a tipping point when simultaneously maximizing both economic indicators.

Few opportunities exist for all farm type clusters to increase annual dietary energy yield and profit per hectare simultaneously, relative to their baseline (Fig. 4b). For LG-S, increasing profit occurred at the expense of dietary energy yield. For LG-S, SA-M and SA-S clusters, livestock density remained stable while either increasing or more often, reducing dietary energy yield (Fig. 4c). There were more opportunities to increase both livestock density and dietary energy yield at the same time in LG-M.

The overall opportunity space to synergically increase profit and vitamin A yield was relatively large for LG-M farm type clusters (Fig. 4d). LG-S clusters had large scope to similarly increase vitamin A yield with profit between 130 and 190 K Birr/ha. SA-M already cultivated vitamin A-rich crops in the baseline and showed little room to further increase vitamin A yield with increasing profit. SA-S clusters had similar response as LG-M but with smaller vitamin A yield and operating profit brackets. Similar trends as in Fig. 4c were observed for vitamin A yield vs. livestock density on the four farm types (Fig. 4e). All LG-S clusters can increase their vitamin A yield, while the potential increase of dietary energy yield is much lower (Fig. 4f, S2c). This was in contrast with South Achefer, where their farm type clusters had more opportunities to increase dietary energy yield but less opportunities to increase vitamin A yield (Fig. 4f, S2d).

LG-S, and to some extent SA-M and SA-S, had opportunities to further improve profit without much impact on GHG emissions, compared to their baseline configurations (Fig. 4g). On the other hand, GHG emissions soared with increasing economic profits in LG-M. Increasing livestock density in the four farm type clusters was linked to an increase in GHG emissions, with the biggest surge observed in LG-M3 (Fig. 4h). All farm types had opportunities to increase either dietary energy or vitamin A production with minor impact on GHG emissions (Fig. 4i, j). Yet, for LG-M, most solutions that generated an increase in dietary energy or vitamin A yield caused a significant increase in GHG emissions.

An increase in profit resulted in an increase in soil N loss in Lay Gayint farm types but a reduction in South Achefer farm type clusters (Fig. 4k), indicating that there are opportunities to simultaneously optimize both operating profit and N loss in the latter farm types. Livestock density in SA-M and LG-S remained stable regardless of increasing N loss (Fig. 4l). For SA-S, there were equal opportunities to increase livestock density while either increasing- or reducing- N loss. On the other hand, an increase in livestock density showed a concurrent increase in N losses for LG-M (Fig. 4l), like observations in Fig. 4h. Similar trends across the farm types as in Fig. 4i, j was observed for soil N loss vs. dietary energy yield (Fig. 4m), and soil N loss vs. vitamin A yield (Fig. 4n). GHG emissions vs. soil N losses showed strong interaction between these two objectives (Fig. 4o). Increases in N losses and GHG emissions occurred simultaneously in all four farm types, especially in LG-M, associated with the largest livestock density.

3.3. *Potential changes in configurations by farm type clusters*

In most cases, crop cultivation (specifically sales of crop products) contributed the biggest proportion to the profit generated in the baseline and optimized farm type clusters, except in the best performing Lay Gayint cluster LG-M1, where most of the profit was attributed to livestock rearing (Fig. 5a). Some of the farm type clusters, i.e., modelled

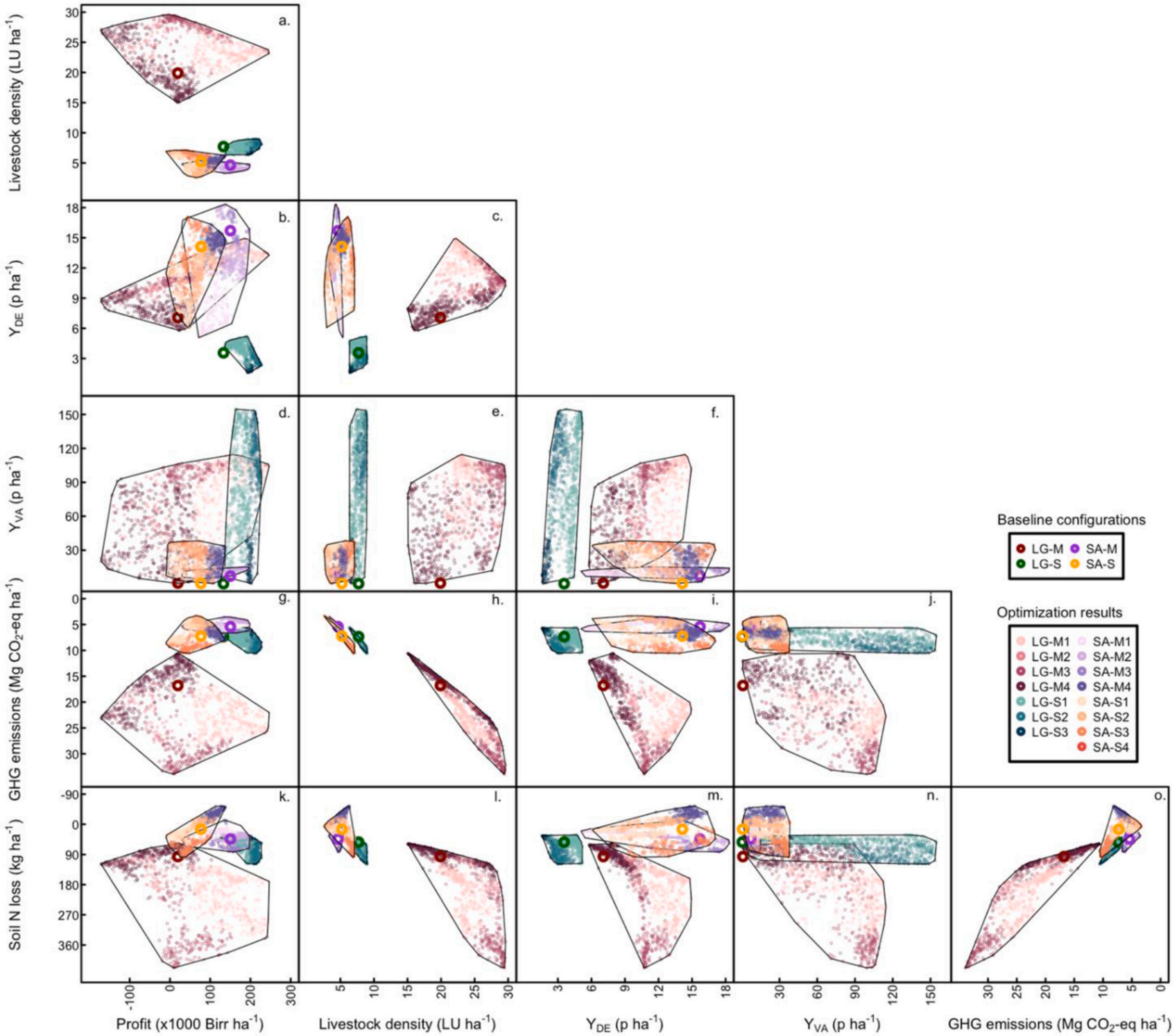

Fig. 4. Opportunity spaces for the four farm types using six objectives of maximizing profit, livestock density, dietary energy yield (Y_{DE}), vitamin A yield (Y_{VA}), minimizing GHG emissions, and soil N loss. In all of the graphs (clockwise direction for y-x axis), loss-loss situations are in the bottom left, followed by win-loss, then win-win, and ending with loss-win situations represented in the bottom right section. Each dot stand for one of the 1000 alternative configurations per farm type and the larger open circles indicate the modelled baseline farm type. The clusters were generated from weighed objectives from stakeholders' input, for medium- and small-scale farm types in Lay Gayint (LG-M and LG-S) and South Achefer (SA-M and SA-S).

baseline LG-M, clusters LG-M2 to LG-M4, SA-S2 and SA-S4, showed negative margins from livestock rearing. This correlated with lower overall farm profits on the baseline or optimized farm type clusters (Table 1, Fig. S2a). Eucalyptus sales accounted for at least 27% of crop profit in the clusters, especially in LG-S where it reached up to 95% (Fig. 5b). Teff, grass pea (LG-M only), potato, carrot, garlic, and beetroot, in descending order, contributed to crop gross margin of Lay Gayint clusters. Maize, finger millet, potato, grass pea, lentil, chickpea, banana (SA-S only) and food barley (SA-S only) were profitable crops in the South Achefer clusters. Total farm area of all clusters was slightly higher on average (+0.01 to +0.1 ha) than their corresponding baseline (Fig. 5c, Table 1) indicating that an overall increase in farm area was suggested by the model. Profit generated from most crops positively correlated with land area allocated to the crop (Fig. S3a-e, g) but this was not the case for others. Indicating that certain (high-value) crops- such as potato, beetroot, carrot, garlic, and banana- were able to generate high profits even on small land areas (Fig. S4 a, d, e, g, l). Therefore, increasing farm profit is not only dependent on farm area but also on selection of high-value crops for cultivation.

Mutton sales generated most of the revenue for the LG farm types: between 21 and 77% (Fig. 6a). As expected, LG-M clusters with the highest livestock density also had high revenue from animal products. Apart from mutton, chicken meat, eggs, chevon and milk from crossbred cow also contributed significantly to livestock revenue while beef, honey and milk from local cows filled out the rest. LG-S clusters on the other hand had additional revenue from chevon, chicken meat and egg only. SA-M clusters had most (76 to 92%) of their livestock revenue from chicken meat, egg and beef while butter and milk from local cow accounted for the other much lower percentage. For SA-S clusters, mutton, beef, milk from crossbred cow, butter, and eggs (in descending order) contributed to livestock revenue. Animal husbandry costs remained similar across the farm type clusters except for LG-M clusters,

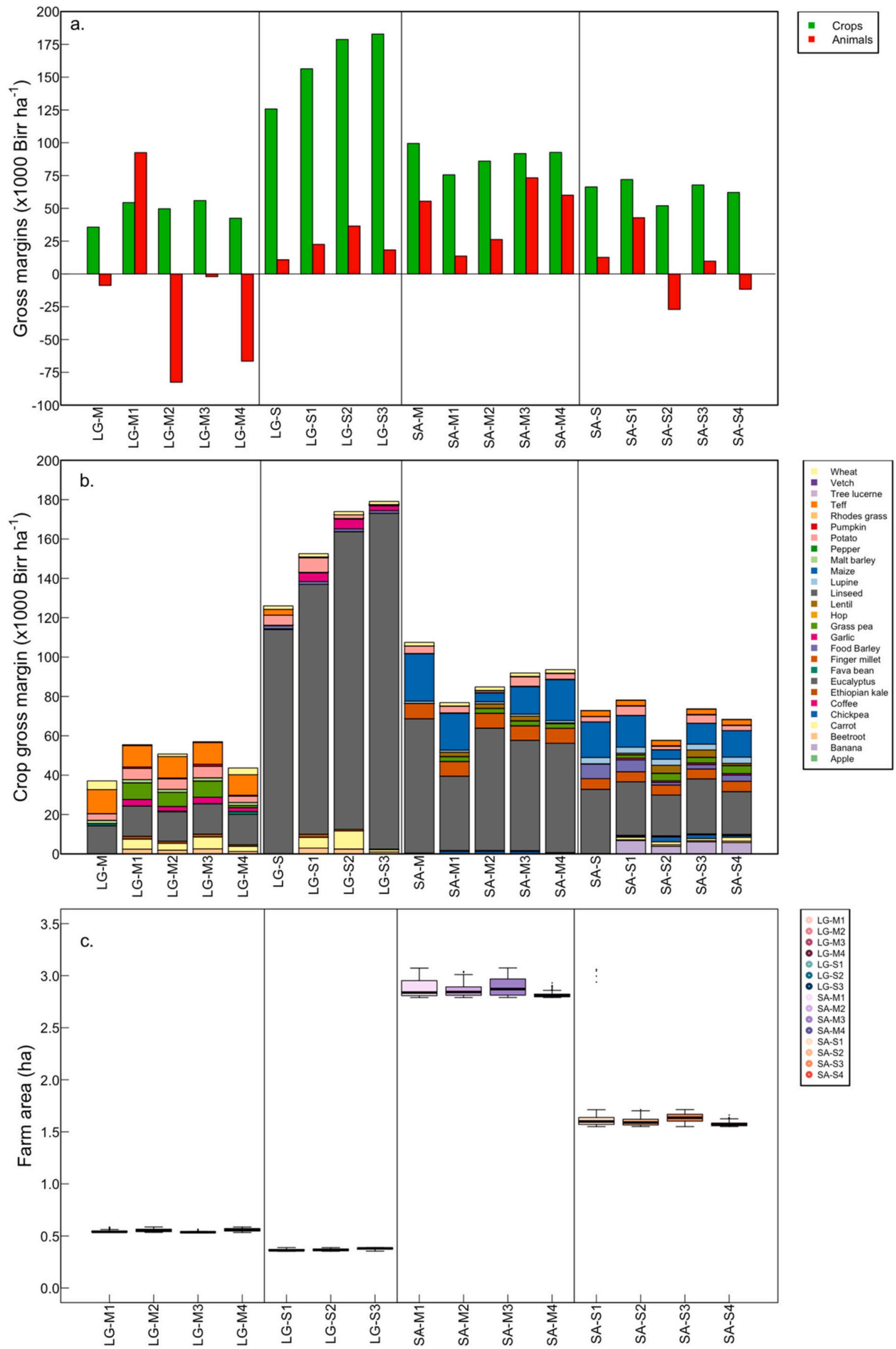

Fig. 5. Crop and animal gross margin (a), gross margin per crop (b) and total farm area (c) for baseline farm types and/or each cluster in the opportunity space. The clusters were generated from weighed objectives from stakeholders' input, for medium- and small-scale farm types in Lay Gayint (LG-M and LG-S) and South Achefer (SA-M and SA-S).

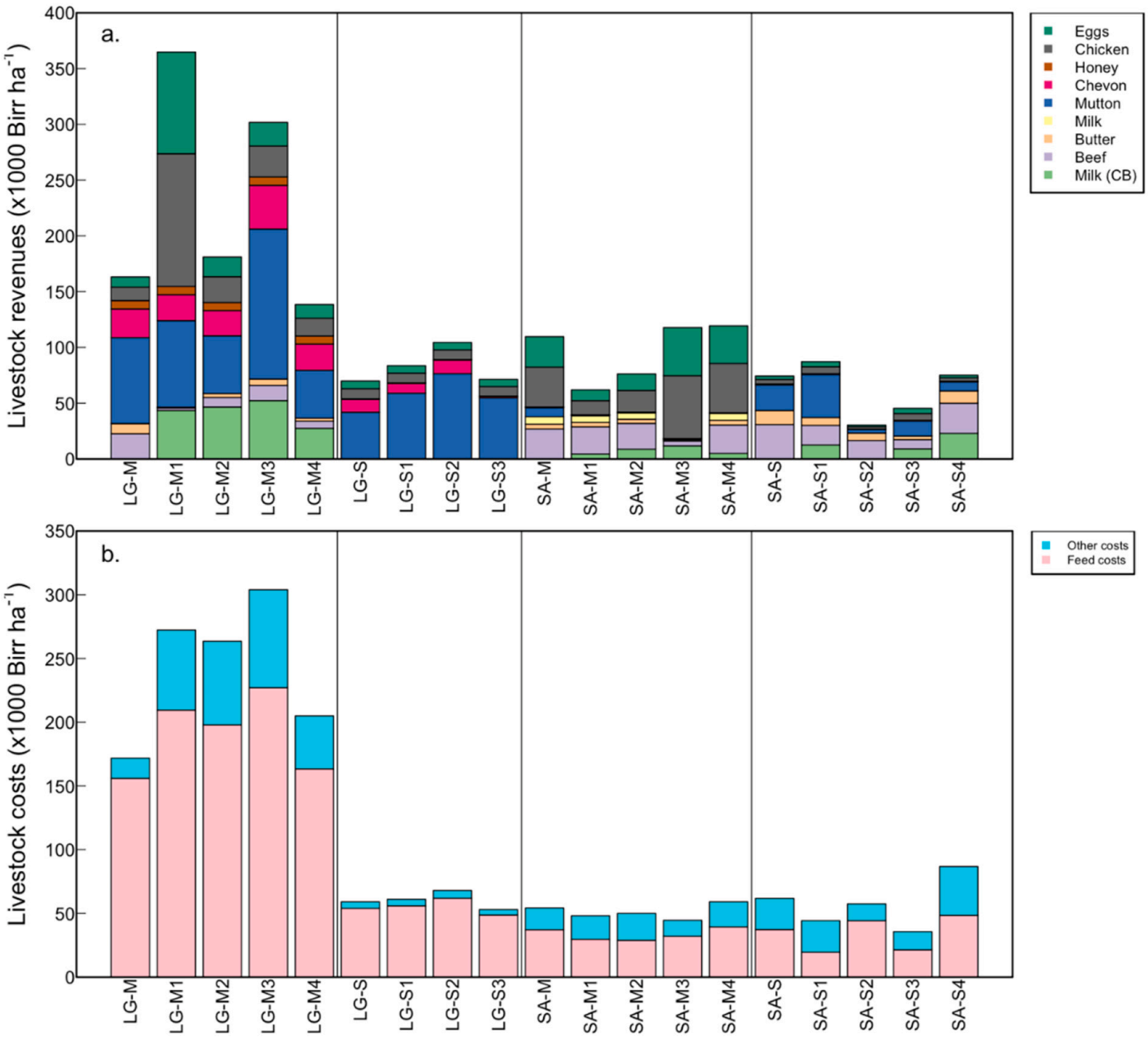

Fig. 6. Animal product revenues (a) and costs (b) for baseline farm types and each cluster in the opportunity space. The clusters were generated from weighed objectives from stakeholders' input, for medium- and small-scale farm types in Lay Gayint (LG-M and LG-S) and South Achefer (SA-M and SA-S). Milk and Milk (CB) refer to milk from local- and crossbred cows respectively. Other livestock costs relate to animal management e.g., costs for drinking water, insemination, vaccination, and medicine.

which was much higher (Fig. 6b). Feed accounted for most of the animal husbandry costs, especially evident in LG-M clusters due to their higher livestock density (Fig. S2b). Low-income generation from livestock rearing in most of the farm type clusters (Fig. 5a) was due to the trade-off between livestock revenue and high husbandry costs (Fig. 6).

Most farm type clusters increased or decreased their dietary energy yield relative to their baseline but were still able to meet nutritional demands for the household and wider Ethiopian society (Fig. 7a). Exceptions were for LG-S clusters and SA-M2 that were unable to meet the dietary energy requirements of even the eight-membered household. All farm type clusters were able to increase the availability of vitamin A-rich food products beyond their baseline, which was sufficient to meet requirements for the household and that of the wider society in Ethiopia (Fig. 7b). Both crop and animal products were sources of important nutrients for more diverse diets and reduced malnutrition in Ethiopia. Human dietary energy requirements were met from a combination of cereals, legumes, potato, meat (e.g., beef, chicken), milk, egg, and buttermilk (Fig. 7a). Vitamin A-rich foods supplied by the farm types include carrot, beetroot, Ethiopian kale, egg, milk, and pumpkin (Fig. 7b).

The introduction of crossbred cows (+1 to +8) with a reduction of one local cow, and increasing chicken numbers (+1 to +10) increased livestock density (LU/ha) for LG-M clusters, while all other animal numbers remained like their baseline LG-M (Fig. 8a). In the LG-S clusters, shifts in sheep (+1 to +2) and goat (−1 or + 1) number occurred. The South Achefer clusters varied with changes in proportions of livestock density including addition of one or two crossbred cows, although total animal number remained mostly unchanged. It should be noted that the livestock density of chicken is much smaller i.e., 0.005 TLU, compared to 1 TLU for dairy cow (Table 1 footnote), so increases in chicken number have little impact on total livestock density in the farm type clusters, even though these changes are easily reflected in revenue generated from livestock (Fig. 6a, Fig. 8a). As expected, GHG emissions were largest for LG-M clusters, and most of the emissions were associated with animal feed and enteric emissions (Fig. 8b). CO_2 emissions from livestock manure applied to crops also contributed to GHG emissions, as did fertilizer use in South Achefer.

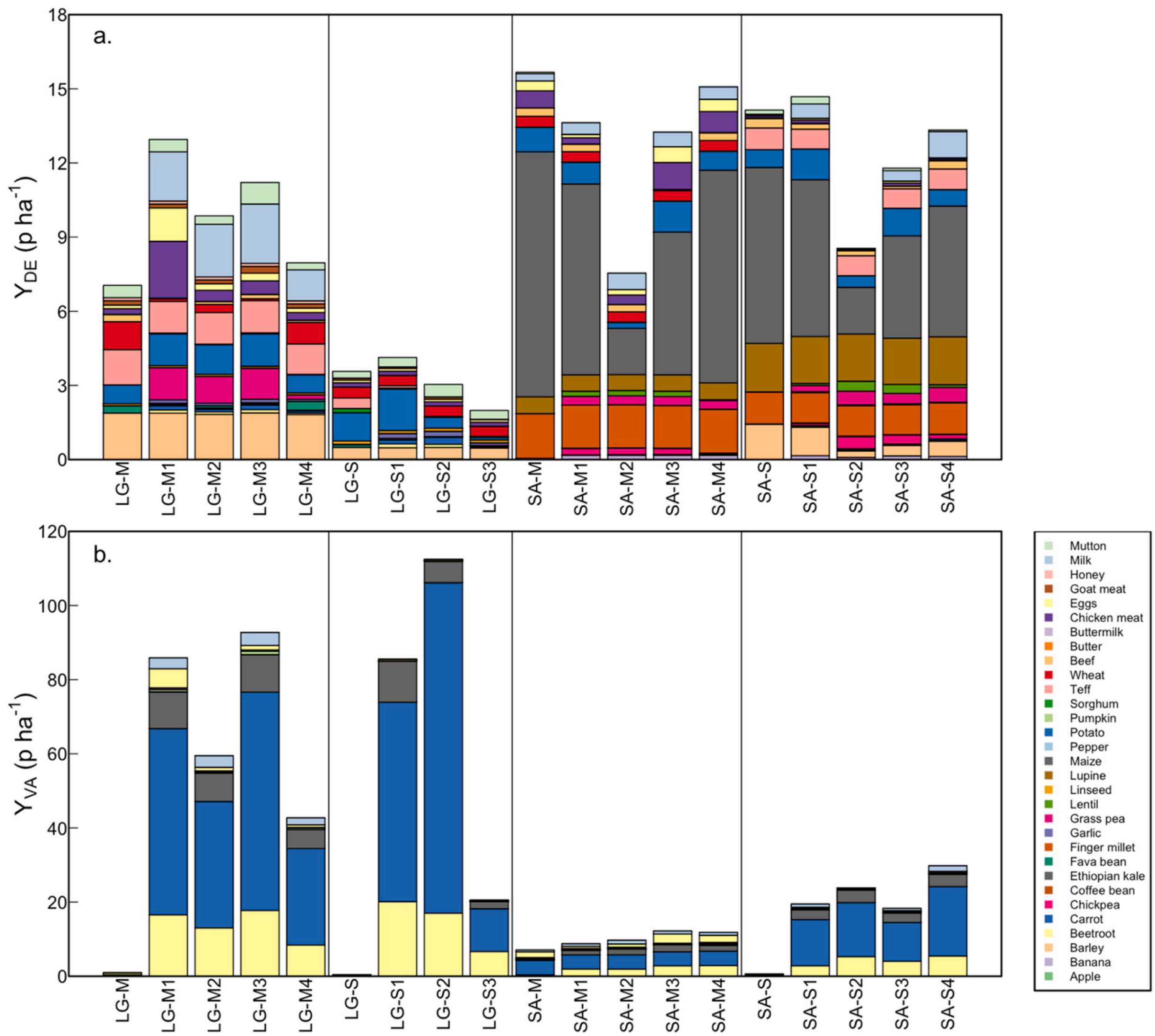

Fig. 7. Dietary energy yield (Y_{DE}) (a) and vitamin A yield (Y_{VA}) (b) originating from different crop and animal products for baseline farm types and each cluster in the opportunity space. The clusters were generated from weighed objectives from stakeholders' input, for medium- and small-scale farm types in Lay Gayint (LG-M and LG-S) and South Achefer (SA-M and SA-S).

3.4. Comparing farm operating income with living income benchmark

In the baseline, none of the farm types were able to realize a living income from only agricultural activities since the calculated farm operating profit in all cases was below the threshold of 3.60 USD/capita/day (Fig. 9). Only SA-M came close, with farm operating profit of 3.58 USD/capita/day. Even when there was an increase in land area and farm operating profit relative to the baseline, most of the clusters could not realize a living income demonstrating that profit generated from their farm activities was insufficient to achieve a decent standard of living. Only SA-M3, the best performing farm type cluster of SA-M, could realize a living income observed as farm operating profit above the threshold at 3.96 USD/capita/day. Generally, smaller farm area generated lower total farm profit, indicating the limitations imposed by farm size on the realization of a living income.

4. Discussion

4.1. Economic, nutritional, and environmental performance of potential farm type configurations

Some farm household models applied in Ethiopia focus on household economics (Tesfaw et al., 2022), while others address both the household economics and nutritional aspects (Bizimana et al., 2020) or require combination with other models for an integrated system analysis (Clarke et al., 2017). FarmDESIGN allowed an integrated analysis of economic, nutrition, as well as environmental aspects of farm households in Amhara. We discuss the windows of opportunity for the different farm types, the trade-offs, and synergies between the objectives, and resulting agricultural options.

The results show that there is significant space to improve the performance of farm types in Lay Gayint and South Achefer districts for most of the six objectives. Remarkably although the farm area of LG farm types is smaller than those of SA, the windows of opportunity are larger in LG, especially for LG-M (Fig. 4). This may be due to bigger differences in the LG baseline: LG-M specialised in livestock production with high animal densities and cereal cultivation while LG-S had less livestock and oriented towards cash crop production (Fig. 1). Firstly, LG-M shows the largest window of opportunity related to the already high livestock density of this farm type in the baseline situation (Fig. 8a). Secondly, the large scope of LG-S to increase vitamin A production stands out in Fig. 4 due to higher vitamin yield from carrot, beetroot and kale (Fig. 7b). In hindsight, both SA farm types were similar except for farm size, and their response to the objective optimization was not

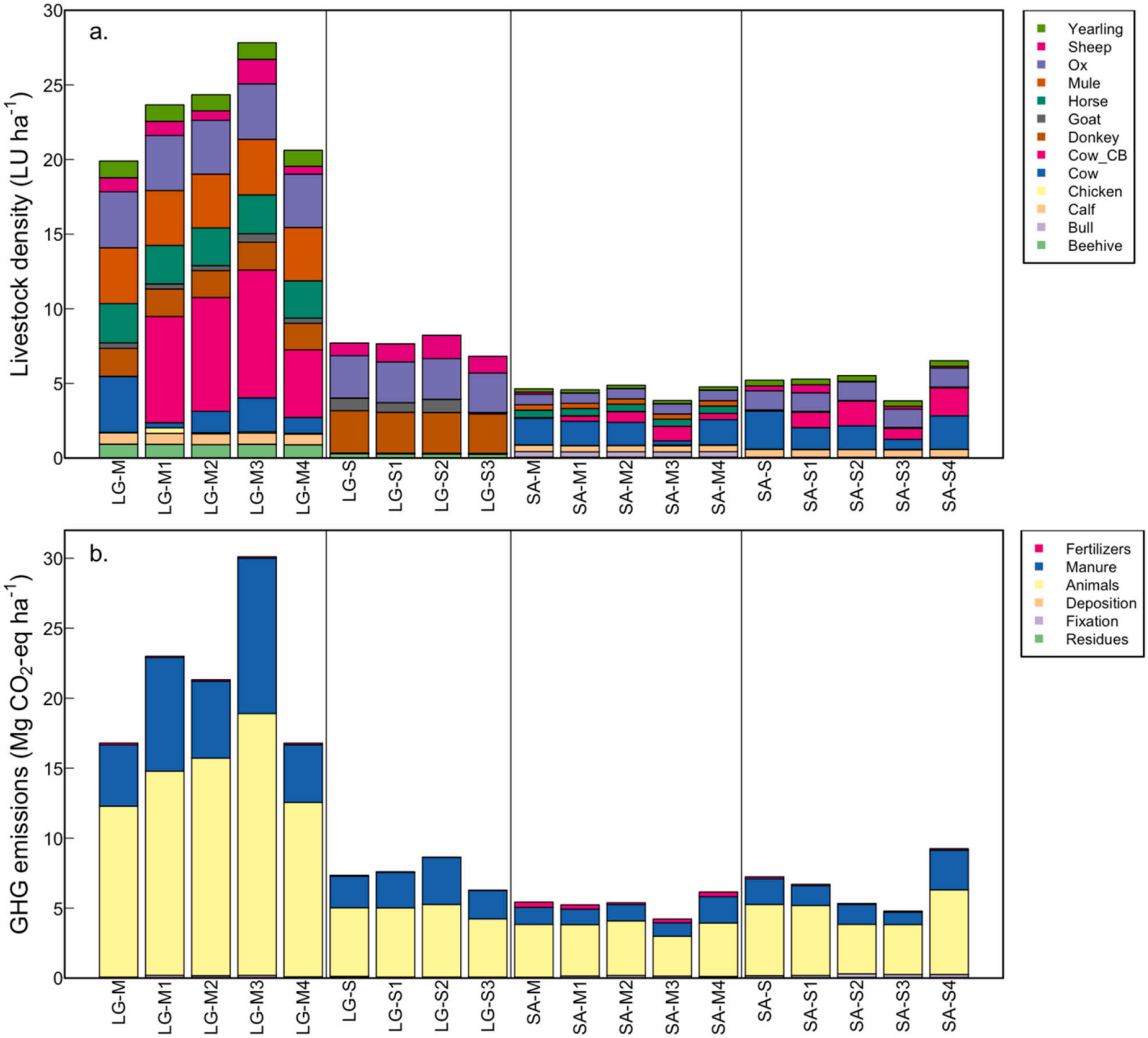

Fig. 8. Livestock density (a) and greenhouse gas emissions originating from various sources (b) for baseline farm types and each cluster in the opportunity space. The clusters were generated from weighed objectives from stakeholders' input, for medium- and small-scale farm types in Lay Gayint (LG-M and LG-S) and South Achefer (SA-M and SA-S). Cow and Cow_CB refer to local and crossbred cows, respectively. GHG emissions were derived from crop *residues*, symbiotic N *fixation*, atmospheric N *deposition*, feed and enteric emissions from *animals* especially ruminants, *manure* from livestock, and crop *fertilizers* (NPSZnB and urea).

different. The results suggest that the model outcomes are robust for a range of similar small and medium farm types present in South Achefer. All clusters in SA farm types show sufficient space to meet household vitamin A needs, significantly surplus dietary energy, and increased production of marketable products indicating the potential for increased market integration without negatively affecting household nutrition security.

Some trade-offs were expected and are clearly visualized in Fig. 4. An increase in animal densities positively correlates with an increase in both GHG emissions and soil N loss, while an increase in soil N loss is associated with an increase of GHG emissions (Fig. 4h, j, o). However, different from findings of Brosseau et al. (2021), the environmental objectives show heterogenous interactions with economic and food and nutrition security objectives across the different farm types, indicating that trade-offs are context-specific, which is particularly relevant in the diverse agroecological and socioeconomic environments of Sub-Saharan Africa (Paul et al., 2020). In general, increasing profit of farms does not always result in higher livestock densities as low-productive cattle are replaced by high-productive crossbreds or with chickens, which barely change livestock density (Fig. 8a). LG-M1 responds differently by improving both profit and livestock density (Fig. 4a, S2a,b). Additionally, improvements on vitamin A yield are difficult to combine with improvements in dietary energy yield for LG-S only (Fig. 4f). Here, production of vitamin A dense crops is at the expense of energy dense crops.

We have used FarmDESIGN to assess the contribution of current and innovative production activities to various sustainability objectives. The selected innovative production activities, beside those already present in the baseline farm types included the introduction of crossbred cows and milk sales, cultivating improved forage crops such as Napier grass, tree lucerne and vetch for feed, cultivating vitamin A dense vegetables (such as carrot, beetroot, and kale), garlic, pulses (lentil, chickpea) and banana for cash and/or food. These innovations link to various policy and development plans that have been published over the past decade to ensure food and nutrition security and to speed up the economic growth and transformation of Ethiopia's society (Shapiro et al., 2015; FDRE,

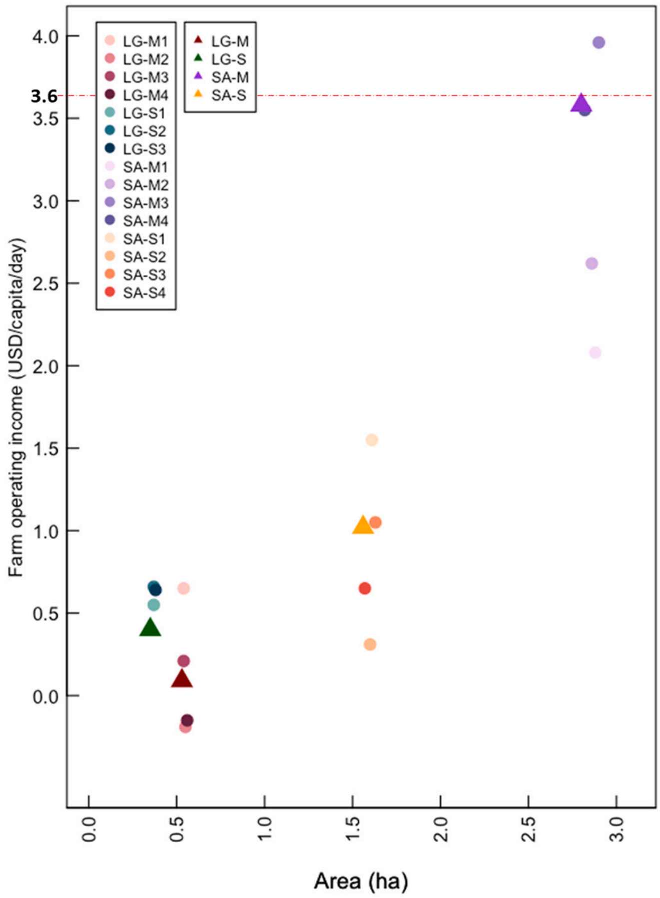

Fig. 9. Provision of living income from farm activities showing the interaction between farm operating profit and the total farm area of the baseline and farm type clusters. The clusters were generated from weighed objectives from stakeholders' input, for medium- and small-scale farm types in Lay Gayint (LG-M and LG-S) and South Achefer (SA-M and SA-S). The operating profit was calculated as $[(OP_f/ HH_\#)/Y_\#] * Ex_{USD}$ where OP_f is the farm operating profit (ETB/year) realized by the farm types (f), $HH_\#$ is the household number which was eight persons in each farm type, $Y_\#$ is the number of days in a year denoted as 365 days, and Ex_{USD} is the exchange rate in US Dollar set at 1 ETB = 0.0249 USD (on 01/03/2021). The living income benchmark of 3.60 USD/capita/day is indicated as a dotted red line in the figure.

2016b; FDRE, 2016c; FDRE, 2016a). Results indicate opportunities to increase both farm profit and vitamin A output through the production of vegetables, by area expansion and limited substitution of staple crops (Fig. S3, S4). In line with these findings, recent production growth of fruits and vegetables in Ethiopia is based on area expansion (FAO, 2023). Yet it is uncertain whether consumers can benefit from increased supply because most fruit and vegetable production is rainfed and off-season market prices tend to be high thereby limiting accessibility to low-income earners, that require a more nutritious food intake (Hengsdijk et al., 2021). A first step to lower consumer prices and improving the accessibility of fruits and vegetables is to reduce the cost price through input intensification including irrigated production, allowing farmers to produce the crops year-round.

Next to fruit and vegetable production, livestock options are needed to increase meat, milk, and egg production. Replacement of low-yielding local cattle with high-yielding crossbred cows showed opportunities for only a limited number of farm type clusters. This may be due to high feed (hay, wheat bran and noug cake) costs since only a few farm types produced their own high-quality feed such as tree lucerne, Napier grass and vetch but in general, farm types are too small to secure their own feed supply. Another option is poultry, whose products are a source of vitamin A (eggs) and income (eggs and meat). In addition, poultry has a much lower environmental footprint than other livestock (Gerber et al., 2013). Whether such livestock options transcend acceptable boundaries requires additional comparison with spatial alternatives and on a per-kg product basis (Herrero et al., 2015; Gerber et al., 2013; Paul et al., 2020). The introduction of crossbred cattle addresses income generation and serves as an asset for farmers, while rearing chicken increases the chances of farm households to consume animal-based protein and vitamin A more frequently.

Authors such as Brosseau et al. (2021) have stressed that government programs and farmers' organizations strongly influence farmers' decision making. Successful adoption of new crops and changing livestock breeds require farmer knowledge and skill, an enabling environment, e.g., service providers for technology and inputs, as well as policies to stimulate technology and knowledge development and dissemination (van Berkum et al., 2018). Traditional keeping of free ranging chickens is common in Ethiopia but comes with several challenges (Abera and Geta, 2014; Leta and Bekana, 2010; Reta, 2009). Small or large-scale poultry intensification using modern methods, such as battery or deep litter systems, or breeding and gene selection may be a suitable alternative for farmers to meet local needs in the short term. Knowledge and skill development should be prioritized on increasing productivity with local/exotic breeds and feed resources, prevention and treatment of common diseases, and overall management (Abera and Geta, 2014; Leta and Bekana, 2010; Reta, 2009). Moreover, increasing the production of energy- and vitamin A-rich food potentially contributes to diet diversification and reducing malnutrition in Ethiopia but still requires consumer market development, e.g., raising awareness on the health benefits of nutritious food (Melesse and van den Berg, 2021).

The best clusters show space for significant operating profit per hectare, but the small farm sizes result in household operating profits below living wage level for all but SA-M3 (Fig. 9). This corroborates with previous studies highlighting the limitations imposed by farm size on realization of a living income (Giller, 2020). Farm acreage presented in our study is in the same range as the thresholds found by Marinus et al. (2022), i.e., 2.1 ha and 2.7 ha for study sites in Tanzania and Uganda, respetively. These farmers may need to increase the farming area by renting land and/or have other sources of income from off-farm activities to secure a minimum standard of living (Giller, 2020). Farm types in the SA-M3 cluster have an average land area of 2.9 ha. Income in farm types of this cluster is generated from sales of eucalyptus, maize, finger millet, potato, grass pea, lentil, chickpea, and wheat; and livestock products such as eggs, chicken meat, and milk from crossbred cows (Fig. 5b, Fig. 6a). Labor was completely excluded from our analysis since this information was not consistently collected during the surveying stage (conflicting and incomplete data). As income from off-farm labor was not included in this study, although migrant labor is significant in Lay Gayint (de Roo and van der Lee, 2021), returns from labor and costs of additional hired labor required for adoption of farm innovations was not considered. The inability of most farm types to meet a living income with the current technology-, crop- and livestock options, indicates the need to broaden additional agricultural options through concurrent changes in technology, market, and policy (van der Lee et al., 2018).

4.2. Limitations of this study

The approach used in this study has some limitations that need to be considered when interpreting the results. Firstly, the farm model used. FarmDESIGN is a static model with an annual timestep, which has consequences on how perennials such as eucalyptus, coffee and fruit trees are modelled because the start-up phase (first unproductive years) is not considered. Hence the profitability of perennials may be overestimated in our study, even though eucalyptus was already a major cash crop for all four baseline farm types and sustained this role in all farm type clusters (Fig. 5b). Several other studies have shown the economic profitability of eucalyptus in Ethiopia (Tesfaw et al., 2022; Jagger and Pender, 2003). The profitability of eucalyptus was locally discussed as positive for rural development in Lay Gayint. Its production was criticized in South Achefer due to soil water and nutrient mining, using land for other than food production, and promoting air pollution through the connected firewood use (next to its use in construction). Such local evaluations may also change over time. The timestep of the model could also explain the lack of synergy between the economic objectives, i.e., maximizing operating profit and livestock density. Investments in cattle take multiple years to yield economic returns as beef (two to three years after conception) or milk (three to four years after conception). This may also explain why selection of crossbred cattle is not the most profitable option in the model, in contrast with other studies (van der Lee et al., 2018; Hawkins et al., 2022; Paul et al., 2020). Also related to the time step of the model, temporal variability in crop productivity is difficult to account for in FarmDESIGN while weather variability has a major impact on the performance of Ethiopian agriculture (Demeke et al., 2011; Bewket, 2007). Related to the static nature of FarmDESIGN, the model contains a detailed description of annual nutrient (N) flows among farm components. However, the model does not consider feedback loops, i.e., nutrient flows do not affect the state variables such as crop biomass production or feed intake of animals.

Secondly, some limitations relate to data collection. In the absence of standardized surveys, two contrasting stylized farm types were defined through participatory identification in both a low potential- and a high potential district, for which local data was collected to parametrize FarmDESIGN. The consequences of the differences between the farm types in Lay Gayint and the similarities between farm types in South Achefer have been described above. Additionally, we limited our decision variables to crops, livestock and technology that are currently within reach of most farmers in Lay Gayint and South Achefer. We defined ranges for change, considering this as a more realistic approach than allowing complete farm redesigning by removing limits. The study did not consider new crops, livestock and technology that require and depend on increased use of additional external inputs (e.g., improved crop varieties, fertilizers, and pesticides) and associated capital to intensify the current farming systems. However, such options would broaden the solution spaces but require favorable market and context conditions, and a prolonged pathway for development, implementation and adoption.

Thirdly, discussions on the model outputs were held with a forum consisting of various stakeholders. Although these stakeholders included representatives of farmer organizations, a fuller discussion with farmers may yield additional insights into the drivers and barriers for adoption of the suggested changes in farm configuration. Policies on communal land use should be integrated in such discussions. Any decision to expand herd or flock sizes may affect those areas, if at least part of livestock feed will come from communal areas. Risk management is not included in FarmDESIGN even though risks are a key factor for adoption of innovations by farmers (Yesuf and Bluffstone, 2009; Cavatassi et al., 2011; Alemayehu et al., 2018). Next to production risks discussed before, uncertain market and regulatory conditions, and high cost of finance make it unattractive for farmers to invest in innovations such as replacing local cattle with crossbreds and growing improved forages (Paul et al., 2020). These are outside farmers' scope of influence and should be the focal point for policy development. The solution spaces provided by this study can be further used to inform both farmer discussions and development of policy instruments (Timler et al., 2020).

5. Conclusion

To meet multiple farmer and societal objectives, our farm modelling approach applied to four farm types in two districts of Amhara, suggested several agricultural options. Although the model has several limitations, FarmDESIGN improves insights in the options needed to meet multiple farmers' objectives concurrently and to identify tradeoffs. The advantage of the model is that it produces the outcomes of such options in a coordinated and systematic manner. Livestock diversification options were rearing chicken for their products, increasing sheep, switching to crossbred cows, and cultivating improved forages. The model suggested crop diversification of high value crops, including those that also meet human dietary energy and vitamin A needs. Some of these agricultural options suggested by the model have been proposed in Ethiopia as strategies to meet current food and nutrition security (Shapiro et al., 2015; FDRE, 2016b; FDRE, 2016c; FDRE, 2016a). The associated costs for implementing and upscaling these interventions remain beyond the scope of this paper, and require further analysis, discussion and testing with stakeholders. In this way, FarmDESIGN can be used as a bridge between science and practice to build trust, improve data requirements of the model, and enable cooperation in experimenting and testing promising farm configurations based on the model results.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

I have shared additional data as attached supplementary files

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2023.103665.

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