Exploring and analysing practices and pathways to improve resource use efficiency of crop-livestock farming systems in North-western Bangladesh

Yifan Wang[1], Jeroen Groot[1], Santiago López-Ridaura[2], Timothy J. Krupnik[3]

Author affiliations

[1] Wageningen University, Wageningen, Netherlands
[2] International Maize and Wheat Improvement Center (CIMMYT), Texcoco, Mexico
[3] CIMMYT, Dhaka, Bangladesh

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The Sustainable Intensification of Mixed Farming Systems Initiative aims to provide equitable, transformative pathways for improved livelihoods of actors in mixed farming systems through sustainable intensification within target agroecologies and socio-economic settings. Through action research and development partnerships, the Initiative will improve smallholder farmers' resilience to weather-induced shocks, provide a more stable income and significant benefits in welfare, and enhance social justice and inclusion for 13 million people by 2030.

Activities will be implemented in six focus countries globally representing diverse mixed farming systems as follows: Ghana (cereal–root crop mixed), Ethiopia (highland mixed), Malawi: (maize mixed), Bangladesh (rice mixed), Nepal (highland mixed), and Lao People's Democratic Republic (upland intensive mixed/ highland extensive mixed).

Transforming Agrifood Systems in South Asia (TAFSSA) is a CGIAR Regional Integrated Initiative that supports actions improving equitable access to sustainable healthy diets, that boosts farmers' livelihoods and resilience, and that conserves land, air, and water resources in a climate crisis.

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Cover Photo: Yifan Wang.

Summary

As the global population continues to grow, the urgency of addressing food sovereignty challenges becomes increasingly apparent. Bangladesh, being a densely populated country, encounters significant hurdles in livestock production sectors the high population density leads to a substantial demand for food, resulting in increased resource requirements. This study aimed to explore and analyse new pathways and practices to improve resource use efficiency of smallholder crop-livestock farms in northwest Bangladesh. Specifically, options to improve manure management and green fodder crop technologies were assessed. The study employed a combination of farming systems characterization, detailed surveys, and model-based methods to assess trade-offs and options for improved livestock management practices. Three study sites were selected based on land size and characteristics with the use of new fodder crops and the production of milk as a key aspect of farming systems. The FarmDESIGN model was utilized for analysis, incorporating a comprehensive database to generate outcomes for each farm.

A total of 32 decision variables were established for the multi-objective optimization of three farms, enabling the visualization and analysis of trade-offs and synergies. Trade-offs between improving soil organic matter balances and reducing soil nitrogen (N) loss, as well as between maximizing operating profit and improving soil OM balance were identified. Synergies were also identified, primarily between increasing operating profit and reducing soil N loss, and between reducing feed costs and mitigating GHG emissions. Also, the model results provided alternatives with maximum operating profit and lower animal feed costs by incorporating more on-farm grown fodder area, and specifically an opportunity to increase the area of Jara-1 hybrid grass by 67%. Furthermore, new pathways and practices were proposed to enhance the use of green fodder crops and improve manure management. The adoption of Jara hybrid-1 grass as a new hybrid green fodder crop, in combination with 60% chopped rice straw, was recommended for feeding cows in the study locations. These results demonstrate that smallholder farmers in northwest Bangladesh have the potential to enhance sustainability and resource use efficiency in their crop-livestock farm systems by focusing on improved manure management methods and cultivation and utilization of green fodder crops.

Materials and Methods

Study area

The study was conducted in Rangpur district, which is in north-west Bangladesh (Figure 1.1). Most farmers in this region are smallholder farmers, with farm sizes between 0.2-1 ha (Anowar et al., 2015). Rangpur has eight Upazilas (an administrative region in Bangladesh, functioning as a sub-unit of a district), including Badarganj, Mithapukur, Gangachara, Kaunia, Rangpur Sadar, Pirgacha, Pirganj, and Taraganj. Three villages were selected within these Upazilas: Badarganj, Mithapukur, and Kaunia (Figure 1).

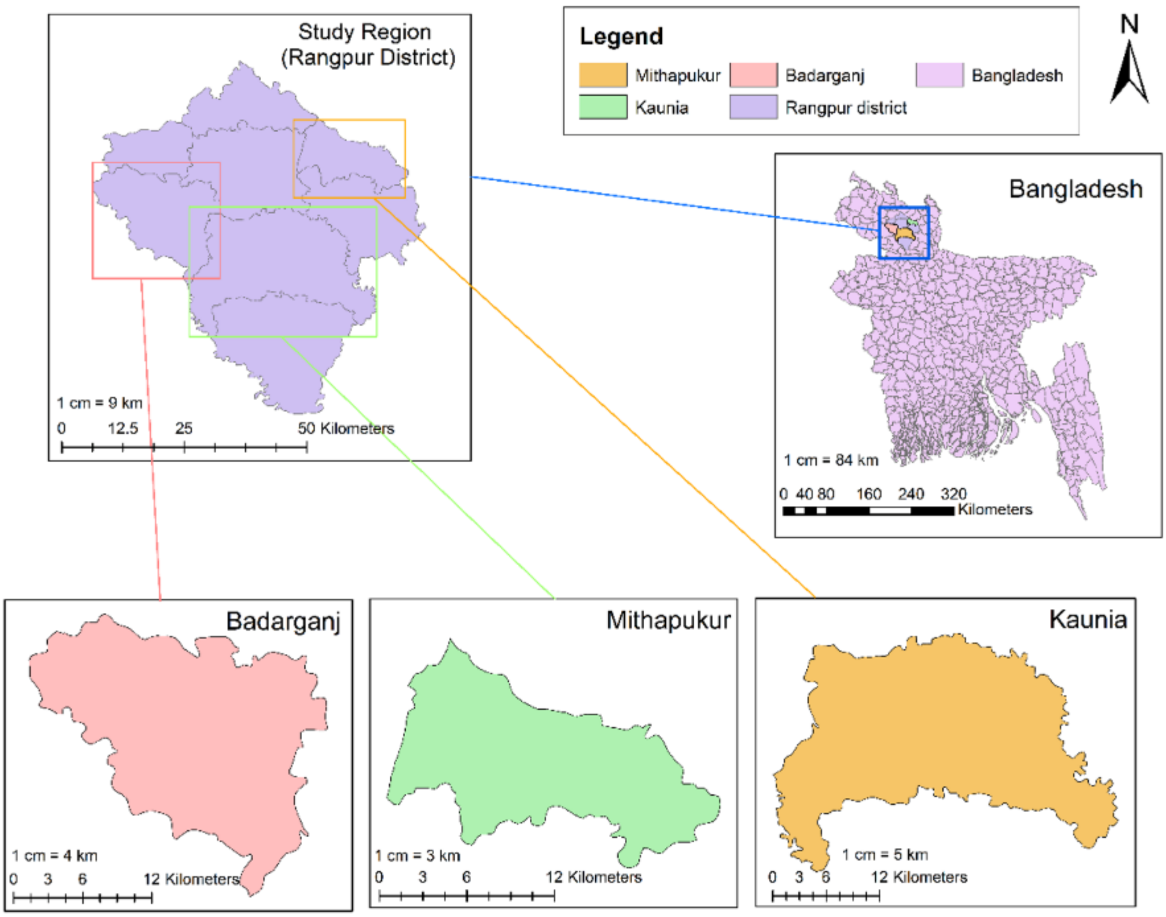


Figure 1. Selected sites in Rangpur district of Bangladesh

Description of selected sites

The main cropping patterns observed this area of Bangladesh are winter *Boro* rice-Fallow-Transplanted (T.) summer rice ('*Aman*'), *Boro*-Fallow-Fallow, and Fallow-Fallow-*T. Aman* (the order of seasons is the main monsoon *Kharif*-2, rabi, and early monsoon *Kharif*-1). *T. Aman* rice is mainly rainfed (Roy et al., 2022), and contributes around 39% of total rice production in Bangladesh. *Boro* rice is the dry season rice crop (BBS, 2019). Some of the additional crops of interest in Rangpur district are *T. Aman*, *Boro*, and also potato, country bean, and a range of species of gourd (Table 1). The most popular cropping pattern in Rangpur district is Boro-Fallow-T. Aman.

Table 1. Generalized calendar of major crops in Rangpur district (light green indicates sowing periods, grey indicates vegetative and reproductive growth, orange represents harvesting periods).

Crop	Month											
	MAR.	APR.	MAY	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.	JAN.	FEB.
	Seasons											
	Kharif-1				*Kharif*-2				*Rabi*			
Boro												
Maize												
White gourd												
Wax gourd												
Spiny gourd												
Bitter gourd												
Bottle gourd												
Wheat												
T. Aman												
Potato												

Bangladesh is confronted with a significant challenge in enhancing its livestock sector. Field observations reveal the prevalence of malnourished cows as a common phenomenon attributed to low-nutrient feedstuff and the economic burden of high feed costs (Figure 2). The widespread practice burning of manure for cooking purposes in Bangladesh (Khanam et al., 2019) contributes to loss of carbon and nutrients and to greenhouse gas (GHG) emissions. Furthermore, a main factor contributing GHG emission in Bangladesh is rice cultivation (Sapkota et al., 2021). While Napier grass serves as the preferred green fodder crop for most households, only a few farmers cultivate it. The majority purchase Napier grass from the local market and mix it with rice straw to feed their livestock (Figure 3). During other seasons without Napier grass, they mainly use rice straw, and some households purchase wheat bran from the local market. . The high cost of purchasing Napier grass renders it unaffordable for many, consequently compromising the nutrient intake of livestock.

Figure 2. Composting site in a farm household compound in Rangpur District, Bangladesh, with a Red Chittagong breed of cattle shown to the left. Photo: Yifan Wang.

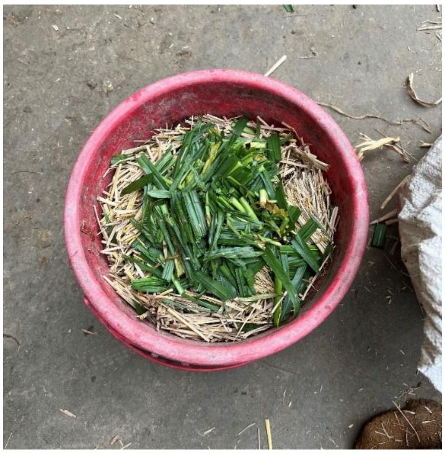


Figure 3. Napier grass mixed with rice straw as a common cattle feed in the study area. Photo: Yifan Wang.

In addition to insufficient manure management and limited utilization of green fodder crops, improper application of synthetic fertilizer by farmers leads to nutrient losses, yielding a scenario of high input and low output, indicative of suboptimal nutrient cycling efficiency (Sapkota et al., 2019).

Methodology

Steps in the methodology

This study employed a four-step methodology. In step 1, an exploratory field visit was conducted in November 2022 to obtain general information for farm characterization in eight Upazilas. Three villages were selected (from three Upazilas) with more diversified cropping systems (shown in Table 1.2). In step 2, 20 farmers were interviewed with a general investigation in each village and categorized them into three land sizes. Then, nine farms from each village were chosen with the feature of having livestock, producing milk and using green fodder crops. In step 3, the selected farms were parameterized in the Farm DESIGN model.

Decision variables, constraints, and objectives were set up for multi-objective optimization in Farm DESIGN. Focus groups were used to generate and evaluate new farm system configurations. Lastly, in step 4, an analysis was performed to identify trade-offs resulting from the multi-objective optimization based on data collection and variables observed during field work.

Step 1: Farm characterization and village selection

A pre-visit was arranged to characterize the farming systems in eight Upazilas. During this phase, we visited one village in each Upazila for a focus group discussion with 8-10 households to learn about their farm layout and operations. After this pre-visit investigation, we selected Badarganj, Kaunia, and Mithapukur Upazilas as our study sites (Table 2). Farmers in Badarganj Upazila often Jara hybrid-1 grass as their green fodder crop. This crop, as observed in the field and based on farmers' perceptions, tended to produce more biomass than the traditionally used Napier grass (Figure 4). Farmers from Kaunia Upazila conversely rarely cultivated green fodder crops but instead purchased them from the local market. Meanwhile, the cropping patterns in Mithapukur Upazila exhibited significant diversification, presenting various alternative crops for farmers to consider cultivating.

Figure 4. Napier grass (left) versus Jara hybrid-1 grass (both are shown at the same age when cut for this photograph). Photo: Yifan Wang.

Table 2: Special features of selected villages in Rangpur district.

Upazila	Union	Village	Features
Badarganj	Ramnathpur	South Ramnathpur Pathan Pata	Most of farmers cultivate fodder crops and use Jara Hybrid-1 Grass
Kaunia	Shaheedbag	Sabdi	Few farmers cultivate fodder crops. Feed purchased from the market.
Mithapukur	Ranikur	Madarpur Balapara	Diversified crop patterns

Step 2: Farm selection

Basic farm characterization data were collected from 20 farm households in each of the selected villages, comprising both men and women. The survey encompassed various aspects of the household and farming system, including basic information of household members, cropping patterns, feedstuff utilization, livestock status, and general economic details. We sought to include farms based on two key criteria:

1. Level of specialization: specialized systems, focused solely on cultivating major economic crops like rice, and diversified crop-livestock mixed farming systems.
2. Farm size: farms were categorized based on land size into three categories, including small (<0.4 ha), medium (0.4-0.8 ha), and large (>0.8 ha).

For each village, nine households that represented the three size categories were selected from the general survey for a further detailed survey. After collecting detailed information on 27 households on their farming systems based on land size, an overview of their data was summarized in Excel. Based on this overview of data, we calculated each parameter's average value. Then, three crop-livestock mixed farms were selected that represented the three size categories, used fodder crops and produced milk. The three farms were selected to further parameterization of Farm DESIGN and assessment of farm sustainability indicators from the model.

Step 3: Model parameterization and farm evaluation

The Farm DESIGN model can be used to quantify farming system production, nutrient cycles and flows, economic profit, and environmental indicators (Groot et al., 2012; Ditzler et al., 2019). The model requires information about cropping patterns, soil conditions, local factors, costs, profits, labour availability, as well as social and economic aspects. This information was obtained through the detailed survey.

The FarmM3 model is capable of conducting simulations and assessments pertaining to the utilization of animal manure We utilized an interface between the FarmM3 model and the Farm DESIGN model, thereby furnishing a comprehensive portrayal of the manure management practices specific to identified farms. FarmM3 was thus used to parameterize manure use, degradation rates, and manure nutrient flows (Qu et al., 2022; 2023).

Resource use efficiency (RUE) within agricultural systems pertains to the degree to which an agricultural system derives benefits from both internal and external resources. The overarching objective is to enhance the output benefits while simultaneously minimizing the input requirements within the farming system (de Wit, 1992). RUE can be quantified using fertilizer, purchase of input (feedstuff), nitrogen use efficiency, and a range of other parameters (de Wit, 1992, Kansiime et al., 2018). We conducted a comparative analysis between the initial feed cost and enhanced feed cost alternatives, along with a comparison between the original nitrogen use efficiency (NUE, Equation 1) and the improved reconfigured NUE following modeling and nitrogen (N) balance (Equation 2) under conditions aimed at maximizing operating profit. This examination was undertaken to assess the enhancements in RUE in the farming systems of interest. For the formulation of NUE and N balance, we employed the following equations:

$$NUE\ (\%) = \frac{Useful\ outputs\ (nitrogen)^{1}}{Inputs\ (nitrogen)} * 100\% \qquad \text{Equation 1}$$

$$N\ balance = N\ intake - N\ loss \qquad \text{Equation 2}$$

Step 4: Analysis of trade-offs and synergies

The Farm Design model incorporates a multi-objective optimization algorithm, enabling the generation of diverse farm reconfigurations by varying livestock numbers, crop areas, and resource allocation, including livestock feeds. It's important to note that the farm size and the input-output relationships of components mentioned by farmers in surveys remain constant during initial simulations. In accordance with the feed balance within the Farm Design model, various types of feedstuffs were introduced to maintain feed equilibrium as part of the simulation and alternative farm configuration process.

The multi-objective optimization algorithm in the Farm DESIGN model is based on the Differential Evolution (DE) evolutionary algorithm (Storn and Price, 1997, Groot et al., 2012), combined with Pareto-based selection across multiple objectives. To parameterize the optimization algorithm, decision variables, constraints, and objectives were specified in the user interface of Farm DESIGN. Regarding the decision variables, a total of 32 variables were established for the three chosen farms, and these variables are associated with the cultivated land area, output production, and the quantity of feedstuff employed by the farmers. Constraints were imposed on factors such as land size, feed balance, and feed quantity. We also defined specific objectives, which include maximizing operating profit,

[1] Useful outputs for nitrogen refer to the production of crops and livestock

maintaining soil organic matter (OM) balance, achieving feed self-sufficiency, and optimizing dietary energy yield. Furthermore, the objectives encompassed minimizing feed costs, soil N losses, and GHG emissions. (Table 3). With the DE algorithm, we generated 1,000 solutions from the optimization, with parameters amplitude of F=0.15 and CR=0.85 cross-over probability. The number of iterations was 500 to stabilize outcomes from the Farm Design model.

Table 3. Objectives quantified as indicators in Farm DESIGN that were used in the multi-objective optimization.

Indicators	Units	Objective description
Profit	USD ha^{-1} yr^{-1}	Maximize operating profit originating from crop and livestock production gross margins minus fixed costs
Feed costs	USD yr^{-1}	Minimize feed costs but maximize production and profits
Soil N loss	kg ha^{-1} yr^{-1}	Minimize soil N loss due to leaching and denitrification
GHG emission	Mg CO2 ha^{-1} yr^{-1}	Minimize emissions of greenhouse gases from crops, animals, manures and soils
Soil OM balance	kg ha^{-1} yr^{-1}	Maximize soil organic matter balance
Feed self-reliance	%	Maximize farm livestock feed self-reliance
Dietary energy yield	persons ha^{-1} yr^{-1}	Maximize the number of farm house hold members and others that can be satisfied dietary energy requirement from the products produced by the farm

After the Farm DESIGN model ran, we used the output file of objectives by using Excel to adjust data into the version fit to R, and then to visualize data by using the RStudio program. The visualization of data shows multi-objective optimization, Trade-offs between different objectives are discussed to identify alternative pathways.

Preliminary results

Livestock population and manure use

The Large farm type demonstrated a greater utilization of manure in comparison to the other two types studied. Interestingly, despite the Medium-sized farm having a cow distribution similar to that of the large farm, has relatively lower manure use (Figure 5). It is worth noting that the majority of farmers opted for a composting practice that spanned approximately six months, with the notable absence of stirring treatment that would likely aerate and increase the processing time of compost. However, a minority of farmers did integrate stirring treatment for a period of roughly one month prior to the manure harvest. We also observed that it is a common practice among households to utilize cattle manure as a fuel source for cooking purposes.

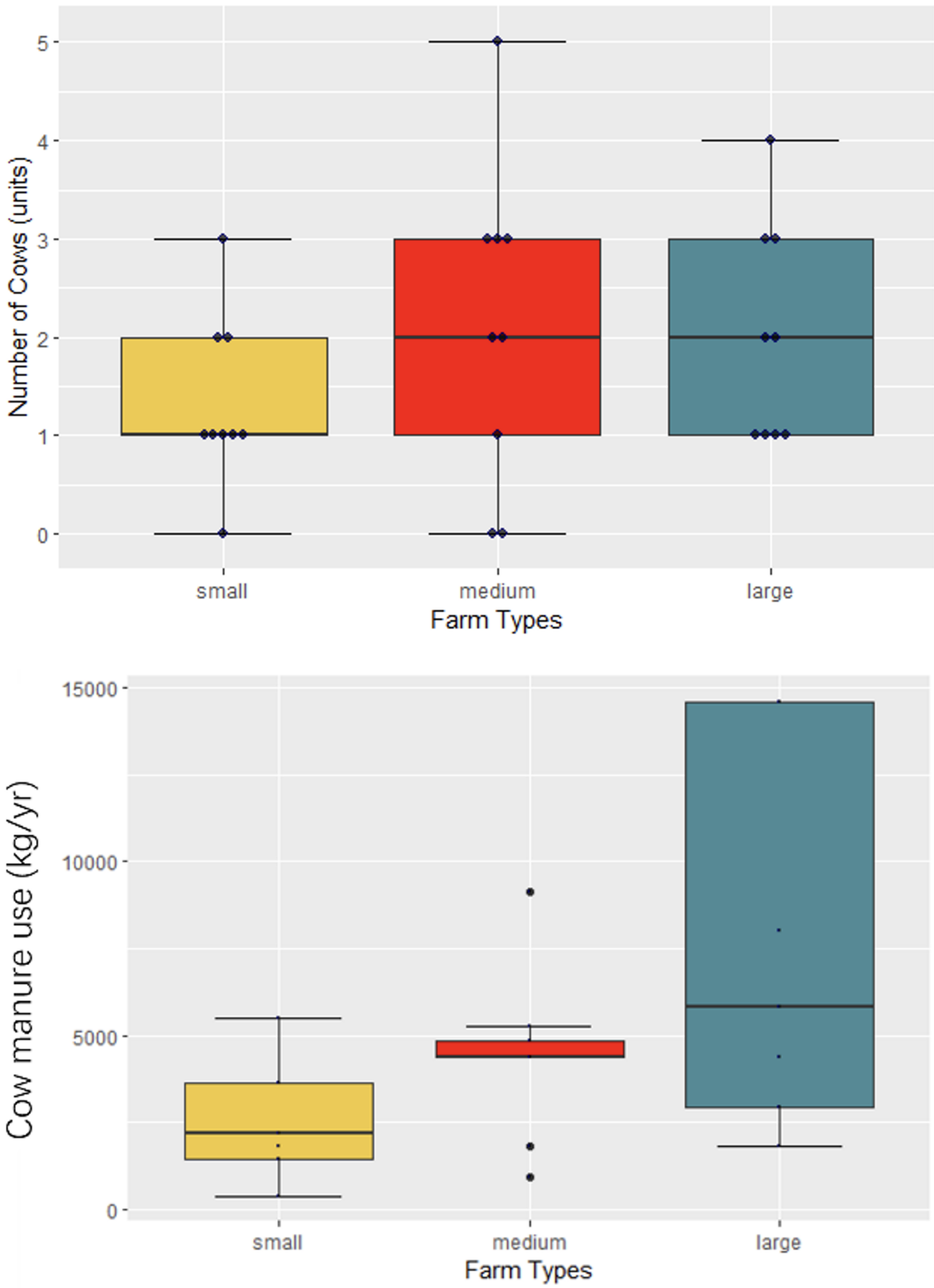
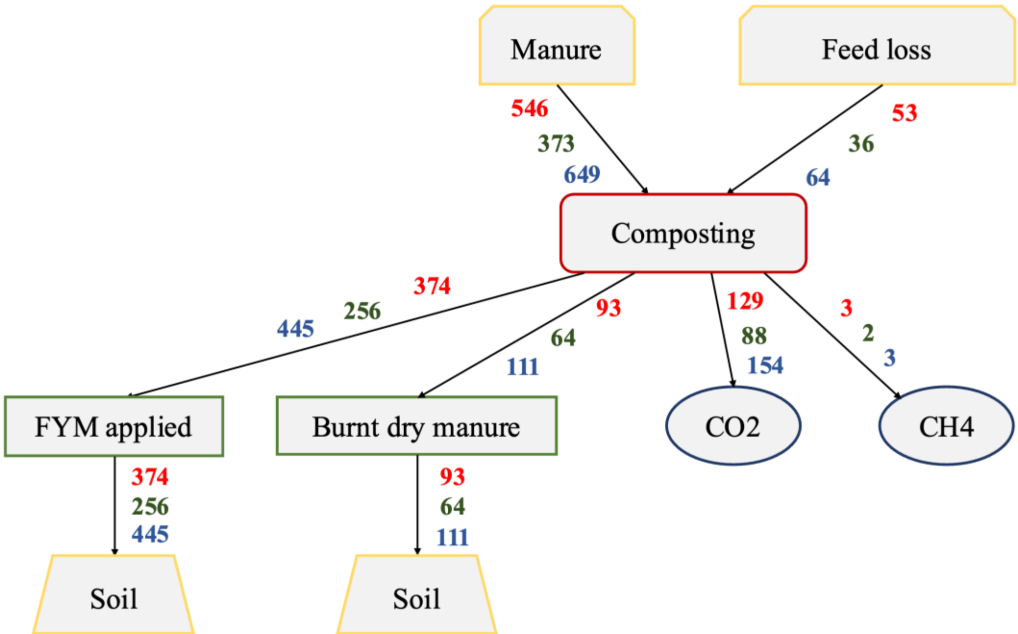


Figure 5. The number of cows (top) and the quantity of manure (bottom) used by farms in this study.

In Figure 6, the flows of carbon (C) and organic nitrogen (Norg) in Small, Medium, and Large farms are depicted. The amount of manure was collected from the survey, and other values were simulated by FarmM3 model. After the composting process, model explorations suggested a large amount of carbon lost in the form of CO_2 due to manure burning . On the other hand, Norg was predominantly applied to soil, partly distributed to cooking fuel, and some was lost in the form of inorganic nitrogen.



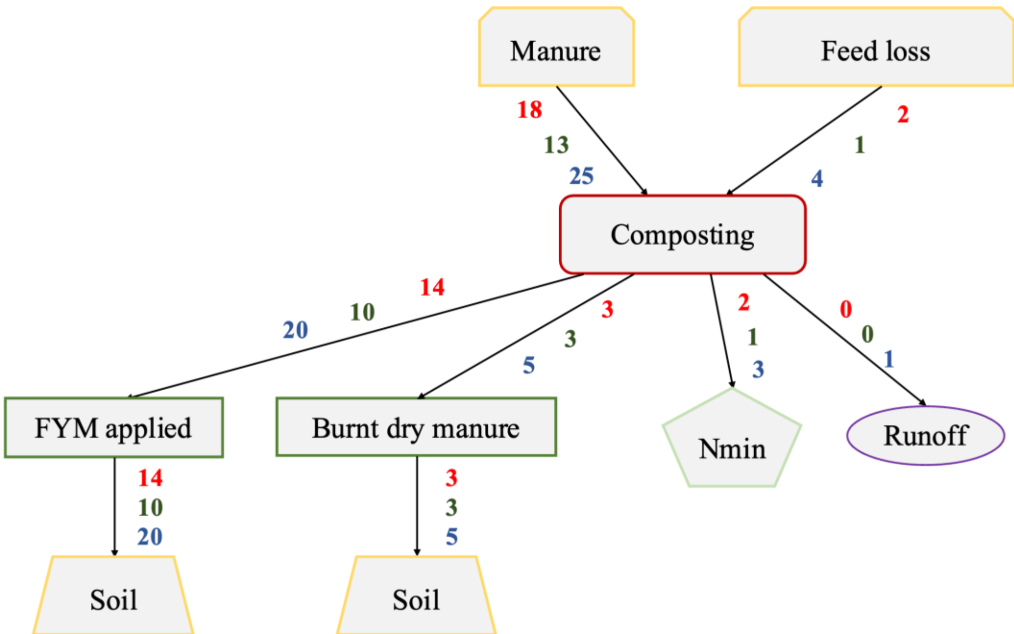


Figure 6. (Top) The simulated flow of carbon (C) (a) and organic nitrogen (Norg) (bottom) in the farming systems described in this study. The units are kg/ha. Yellow bastion shapes represent inputs, dark red rectangular shapes mean pools, and the green rectangular indicate Applications. Nmin means inorganic nitrogen, FYM indicates farmyard manure. The red, dark green, and blue numbers represent the small, medium, and large farm respectively.

Current indicator performance of the studied farms

Two farms were chosen from the South Ramnathpur Pathan Pata village, representing small and large household sizes, as outlined in Table 4. The Small farm had a smaller land area, yet these farmers dedicated a substantial portion of land to the cultivation of green fodder. Conversely, despite a larger expanse being allocated to green fodder, this farm type exhibited elevated feed costs for a single cow. Moreover, this farm experienced notably high soil nitrogen (N) losses and a diminished organic matter (OM) balance within its farming system.

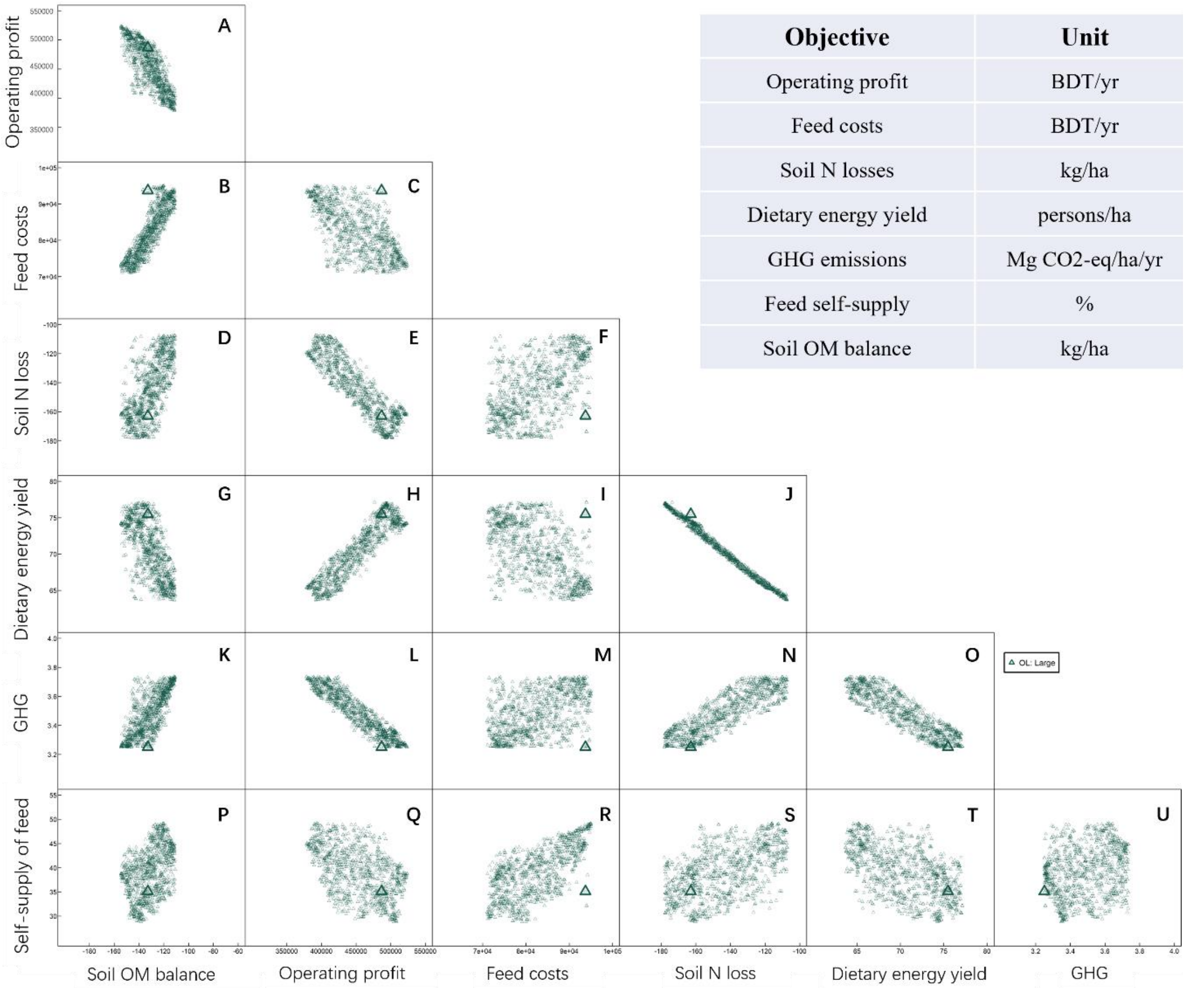
Table 4. Current performance of selected farms (1 USD = 108 BDT)

Variables considered	South Ramnathpur, Pathan Pata		Madarpur Balapara
	Small	Large	Medium
Cropped area (ha)	0.36	1.44	0.656
Household size (unit)	5	4	5
Green fodder crop area (ha)	0.12	0.12	0.016
Number of cows (unit)	1	4	2
Self-reliance (%)	94.0	35.1	27.8
OM balance (kg ha^{-1} yr^{-1})	-40	-133	21.7
Manure applied (kg yr^{-1})	878	1611	598
Soil N losses (kg ha^{-1} yr^{-1})	423	-163	396
Operating profit (USD yr^{-1})	193.2	4506.6	343.6
Feed cost (USD yr^{-1})	689.9	867.8	478.3
GHG emissions (Mg CO_2 ha^{-1} yr^{-1})	4.49	3.25	3.67
Dietary energy yield (persons/ha)	9.6	75.5	9.7

The additional large farm in this village possessed a greater expanse of land, yet it allocated only a small percentage of it to the cultivation of green fodder crops. Furthermore, the farm engaged in the cultivation of Jara hybrid-1 grass. Despite its larger landholding, the large farm type exhibited a lower capacity for self-reliance when compared to the small farm. Notably, farmers applied a higher quantity of animal manure for cultivation purposes, but paradoxically, the model suggested that this resulted in a lower modelled organic matter balance within its farming system. This clearly requires additional analysis and exploration to confirm and identify why lower OM balances are generated in the model. On the other hand, the Medium-sized farm located in the village of Madarpur Balapara featured a larger land size but cultivated fewer green fodder crops compared to the small farm type. This farm type recorded very low operating profits and a diminished dietary energy yield in our modelling outputs. Furthermore, model explorations suggested that it experienced high soil N losses, although it did maintain a high OM balance within its farming system.

Trade-offs and synergies among indicators

The exploration of alternative farm reconfigurations for the large farm was a key focus of our analysis. In this report, we present the results obtained from the large farm's evaluation. The selection of alternative optimal options was based on the principles of Pareto ranking theory, where ideal options were chosen from among all the alternative solutions generated through multi-objective optimization in the FarmDESIGN model. An overview of the relationships between various objectives specific to the large farm is depicted in Figure 7. Within this framework, we observed both trade-offs and synergies, underscoring the complex interplay of factors affecting the large farm's performance and sustainability.



Objective	Unit
Operating profit	BDT/yr
Feed costs	BDT/yr
Soil N losses	kg/ha
Dietary energy yield	persons/ha
GHG emissions	Mg CO2-eq/ha/yr
Feed self-supply	%
Soil OM balance	kg/ha

Figure 7. Relationships between objectives for large farm in Rangpur District, explored by FarmDESIGN model (Dark green scatters represent options for large farm. OL means the original farm configurations of the large farm studied).

Compared to the original configuration of the large farm, evident linear relationships were observed, indicating potential synergies between (1) enhancing operating profit and reducing soil N loss, mitigating feed costs, and increasing dietary energy yield (Figure 7 E&C&H), (2) reducing feed costs and mitigating GHG emissions and soil N loss (Figure 7 M&F), (3) minimizing soil N loss and improving dietary energy yield (Figure 7 J). Out model outputs also showed that there were distinct trade-offs between (4) improving soil OM balance and increasing both operating profit and dietary energy yield (Figure 7 A&G), (5) enhancing soil OM balance and reducing both GHG emissions and soil N loss (Figure 7 K&D), (6) decreasing feed costs and improving both self-supply and dietary energy yield (Figure 7 R&I).

The configuration and performance of the improved Large farm involved selecting and analysing the top 10 solutions generated through multi-objective optimization in the modelling environment, which exhibited the best results in terms of operating profit and feed self-reliance, as detailed in Table 2.2.Among these top-performing solutions, those optimized for operating profit (which recorded a 7% increase compared to the original) also demonstrated enhanced feed self-reliance, with an improvement of 9%. These solutions notably featured a larger area allocated to the *T. aman*-chili-potato cropping pattern, while reducing area under the *T. aman*-fallow-boro rotation and decreasing the country bean area in the home garden by 0.05 hectares. However, it's important to note that for achieving further improvements in feed self-reliance, with potential gains of up to 40% in the top 10 solutions (Table 5), the operating profit on this farm could experience a decline of 15%.

Table 5. Original indicators performance (objectives) and crop areas and feed quantities (decision variables) for the original configuration of the large farm and top-10 generated solutions with highest operating profit or feed self-reliance after multi-objective optimization.

Variables	Original	Highest profit	Highest self-reliance
Indicators			
Organic matter balance (kg/ha)	-133	-154	-123
Operating profit (BDT)	486,717	522,015	411,525
Feed costs (BDT)	93,727	73,510	94,665
Soil N losses (kg/ha)	-163	-162	-121
Dietary energy yield (persons)	75.5	74.2	66.3
Total GHG emission (Mg CO_2-eq)	3.3	3.3	3.6
Feed self-reliance (%)	35.1	38.3	49.0
Cropped area (ha)			
Aman-fallow-boro	1.20	1.17	1.05
Aman-potato-chili	0.12	0.15	0.11
Zara-1 hybrid grass	0.06	0.10	0.10
Napier grass	0.06	0.07	0.10
Country bean	0.10	0.05	0.05
Amounts of feed (kg)			
Rice bran 1	150	103	206
Rice straw 1	200	14	317
Rice bran	100	8	4
Rice straw	350	351	346
Fava bean	250	590	231
Napier grass	800	443	798
Jara hybrid-1	1,825	1,655	1,850

This shift would involve a transition from cash crops to feed crops, and requires additional analysis to confirm the utility of this suggestion among farmers of this typology in Rangpur. Moreover, the utilization of Jara hybrid-1 grass was found to be significantly higher in this optimization analysis, with a 65% increase compared to the original, in both sets of the top 10 solutions, as indicated in Table 5.

Discussion

During the farmer interviews and focus groups conducted in this preliminary study, it became evident that most farmers prioritized the reduction of their feed costs as a key objective. The redesign exploration conducted using the Farm DESIGN model has provisionally opened up numerous possibilities for farmers to achieve significant reductions in feed costs, with potential savings of up to 22%, while simultaneously increasing their profit by 7%. In the context of the Large farm, the multi-objective optimization yielded options that allowed for an increase in the area allocated to Jara hybrid-1 grass and the home garden. These modifications resulted in reduced feed costs and an enhanced ability to self-supply feed resources. However, it is noteworthy that the Large farm did not exhibit any significant change in NUE as a result of these reconfigurations.

Why are these results relevant? Firstly, they have economic implications. The reduction in feed costs and the concurrent increase in profits can improve the financial sustainability of farmers, ultimately enhancing livelihoods. Furthermore, the findings are particularly pertinent to milk production. Improved feed quality can directly enhance the health and productivity of dairy animals, leading to increased milk production and overall improved animal well-being. The choice of Jara-1 hybrid grass over Napier grass is a noteworthy aspect. Jara-1 hybrid is associated with substantial greater biomass production, making it a good feed resource for livestock, especially dairy cows. This implies that farmers could potentially benefit from selecting and cultivating this and other superior forage varieties. In the regional context of northwest Bangladesh, where Napier grass is commonly used for livestock feed, the introduction and expansion of Jara-1 hybrid offers an alternative and potentially more beneficial option.

According to the modeled farm reconfigurations, there is potential for an increase in the cultivation of green fodder crops, particularly for the Large farm observed in our study. In options emphasizing profitability, the total area allocated to green fodder crops could expand by 37%, and for those prioritizing feed self-reliance, this expansion could be as much as 66%. Additionally, a promising strategy involves integrating legumes with green fodder crops to enhance nitrogen input through symbiotic fixation, as proposed by Orodho (2006). In selecting a suitable legume, local species like country beans could be considered, and these legumes could be effectively cultivated as alley crops, a practice involving planting them in narrow rows between other tall trees or crops, as documented in studies by Wolz and DeLucia (2018) and Garrett et al. (2021).

In addition, while rice straw is commonly used as a feed in Bangladesh, it is not ideal from an animal health standpoint. It boasts a high biomass content, a substantial silica content, and an adequate C/N ratio, although it does have a relatively low crude protein content, typically around 3% to 4% (Devendra, 1997; Drake et al., 2002). Elevated crude protein levels can enhance the bacterial digestive process during forage utilization. However, excessively high crude protein levels may result in increased emissions of waste N (Kalscheur et al., 1999). Consequently, a blend consisting of approximately 60% chopped rice straw combined with 40% chopped Jara-1 hybrid grass may be a promising feedstuff combination (Gummert et al., 2020). This composite has the potential to mitigate animal feed costs while concurrently improving milk production (Figure 8).

Figure 8. A farmer in Rangpur, Bangladesh feeding green fodder to her cattle. Photo: Abdul Momin.

Manure management presents an inherent challenge in dairy farming systems (Chadwick et al., 2011), including in Bangladesh. The prevailing method of manure management in northwest Bangladesh is associated with elevated greenhouse gas emissions, nutrient loss, and adverse effects on human health (Bruce et al., 2015). An alternative approach to using animal manure as cooking fuel is to utilize it as a soil amendment (Snijders et al., 2009). Previous research on manure management has shown that vermicomposting offers advantages over traditional composting techniques for manure. Vermicompost typically exhibits a lower C/N ratio, resulting in a more stable and mature fertilizer (with a C/N ratio <15) and a higher nitrogen content (Font-Palma, 2019). Moreover, research by Duan et al. (2020) suggests that the addition of 0.5% *Bacillus subtilis* can expedite compost maturation and enhance the quality of compost fertilizer. While previous recommendations have included employing a single deep pit with appropriate coverage and infrequent stirring treatment for six months to effectively implement vermicomposting (Eghball and Lesoing, 2000; Parkinson et al., 2004; Getahun et al., 2012), it is important, however, to consider the labor costs associated with this approach, which can and should be explored in additional modeling simulations. We also explored the use of Farm DESIGN model to quantify human nutrition using the dietary energy yield indicator, which measures the energy content in fresh food. The model's outputs revealed that the original household diets are predominantly composed of cereals, with limited inclusion of fruits and vegetables. Livestock products also constitute a significant portion of their food intake. Notably, the optimized dietary energy yield for the Large farm is sufficient to meet the household's energy needs. However, despite meeting their energy requirements, diet diversity remains unbalanced. In-person observations however indicate that the households under investigation in this study face challenges in accessing a diverse range of foods, as food access is linked to household economic and also cultural circumstances, as discussed by Jia et al. (2023).

Preliminary conclusions

This study underscores the potential of implementing novel manure management approaches and integrating green fodder crops to enhance resource use efficiency within smallholder crop-livestock mixed farming systems in northwest Bangladesh. Farmers in our study expressed substantial concerns regarding the costs associated with animal feed. The Farm DESIGN model provided a means to explore alternative strategies aimed at reducing feed expenses and concurrently increasing profitability for farmers. Notably, the utilization of Jara hybrid-1 grass, characterized by higher nutrient content, suggests that a 3:2 combination of Napier grass and Jara hybrid-1 grass is a potential approach. However, further research should be conducted to compare various species of green fodder crops with Napier grass and explore the incorporation of leguminous fodder crops. Despite their challenges, this study indicates that smallholder farmers within crop-livestock mixed farming systems still have untapped options to enhance resource use efficiency, improve manure management, and expand the utilization of green fodder crops. The Farm DESIGN model can serve as a valuable tool for researchers, farmers, and policymakers, offering optimization strategies to promote sustainable intensification within crop-livestock mixed farming systems.

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Left: A farmer in Rangpur, Bangladesh cutting rice straw to feed cattle. Photo: Abdul Momin.

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