Investigation of alternative management practices allowing for sustainable intensification of mixed farming systems with small ruminants in Northern Ghana

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Abstract

Mixed farming systems integrating crops and livestock can promote sustainability and food security, providing benefits such as risk diversification and recycling of natural resources. In this research, several opportunities were investigated to sustainably intensify these systems in Northern Ghana. Using the FarmDESIGN model, alternative diets for small ruminants based on crop residues were formulated. On-site interviews and Focus Group Discussions (FGDs) were conducted with farmers to investigate their current farming practices and gather their perspectives on potentially beneficial practices such as aerobic composting, silaging and reduction of off-farm grazing. The results from the modelling showed that alternative diets can create the chance to either increase flock size without increasing cropland for feed production or maintain the current flock size while reducing the required cropland. The most diversified alternative feeding scenario consisted of 42% cowpea stover, 25% pigeon pea stover, 16% millet straw, and minor percentages of other residues such as rice straw, cowpea pods and pigeon pea pods. The minimum cropland used to produce the necessary crop residues to feed each small ruminant without any feed imports would be 0.075 ha. The interviews and FGDs showed that some farmers performed basic composting practices, but several improvements could reduce nutrient losses. Silaging was not practised due to a lack of knowledge, perceived complexity and a lack of appropriate facilities. Lastly, phenomenons such as land grabbing and the cultural embeddedness of free off-farm grazing were limiting the feasibility of intensifying livestock management. Sustainable intensification could be achieved by promoting the production of crops with high yields of nutrients in residues, such as pigeon pea and cowpea, as well as by investing further resources to correctly implement composting, silaging and on-farm livestock management.

1. INTRODUCTION

1.1 Relevance of mixed farming systems

The widespread adoption of industrial agriculture practices, such as large-scale monocultures and abundant use of synthetic fertilizers and pesticides, have allowed farmers to produce large quantities of food at a relatively low cost. However, there is growing awareness of the numerous problems it has caused on a global scale. These include human health harm, land degradation, air and water pollution, biodiversity loss, and fossil fuel consumption at unsustainable rates (Horrigan *et al.*, 2002). In addition, the increase in food production has failed to eliminate hunger, since approximately one-third of all food produced globally ends up as waste (Quinton, 2019) and the number of people who suffer from hunger has been gradually increasing, reaching 828 million people in 2021 (WHO, 2022). The exploitative approach to food production and uneven distribution of food have underlined the necessity to zoom in on local conditions and empower communities and small-scale farmers to increase food security. With this regard, mixed farming systems with crop-livestock integration play an important role (Danso-Abbeam *et al.*, 2021).

They allow for risk diversification compared to producing a single crop or livestock type, allowing for an increase in the system's resilience in the face of climate change and market-related fluctuations (Cho, 2021). Well-managed mixed systems can also promote the recycling of resources which are already present within the system itself and contribute to the build-up of soil organic matter and fertility (Schiere *et al*., 2002). In turn, they can reduce negative impacts on the environment (e.g. soil nutrients mining) as well as the need for imported fertilizers.

1.2 CGIAR initiative

Research is being done to support mixed systems worldwide, tailored to local conditions. This project is part of a larger CGIAR (Consultative Group for International Agricultural Research) initiative and performed in collaboration with IITA (International Institute of Tropical Agriculture). CGIAR is the largest global partnership working on research in food security. One of their initiatives is the Sustainable Intensification of Mixed Farming Systems (SI-MFS), which provide the majority of food in the developing world. The main challenge is to increase food production without increasing the amount of agricultural land. Priority is given to countries with low per-capita land areas available for agriculture and with large environmental and social challenges, in this case, Northern Ghana. This project is part of Work Package 2 (WP2), namely "developing multi-scale methods and tools for systems analysis", as well as Work Package 3 (WP3), namely the "co-design of SI pathways for different types of MFS in selected agro-ecologies, at the local level and in close partnership with farmers and other local MFS actors" (Hoeschle-Zeledon, 2021).

1.3 Challenges in Northern Ghana

Agricultural production in Northern Ghana is facing large yield gaps, declining soil fertility, and failure to match the increase in food production with the increase in demand due to population growth (Michalscheck *et al*., 2018). Several technological innovations have already been investigated for their application in this area, as part of the AfricaRISING project. It has been shown that they have great potential for sustainable intensification, but they often require a large initial investment.

Michalscheck *et al.* (2018) classified different farm configurations in the Northern Region for three levels of resource endowment (RE): low, medium and high (see *Table 1*). Low RE farms usually have 0.8-1.2 hectares of cropland and own poultry; medium RE farms have 2 hectares of cropland and own small ruminants; while high RE farms have 4-6 hectares of cropland and own cattle in addition to small ruminants. High RE farms are more likely to have the capital to invest in new technologies. Inversely, small and medium RE farms often cannot afford such investments and are more pressured to adopt behavioural changes for sustainable intensification.

This study focused on the investigation of alternative techniques with little or no financial expenditures, as opposed to technologies. It focused mainly on the management of small ruminants, which are a valuable element in sustainable farming systems, converting residues from the land and several by-products of food production into food that humans can eat (Oltjen & Beckett, 1996). Since low-resource-endowed farms often do not own any ruminant animals, this research focuses on alternative practices specifically for medium-resource-endowed farms, which commonly own small ruminant animals such as goats and sheep and not large ones such as cattle.

***Table 1**: Farm size and livestock ownership of farms with different levels of resource endowment (RE) in Northern Ghana.*

RE	Farm size	Main livestock type
Low	0.8-1.2	Poultry
Medium	2	Small ruminants
High	4-6	Cattle and small ruminants

1.3.1 Challenges in small ruminant management

Unsustainable practices in livestock management often undermine the natural resource base. Crop residues are traditionally used as a feed source for small ruminants, usually being left on the field after crop harvest and allowing animals to graze on them. However, this method causes nutrient losses from the residues due to decomposition and exposition to rain and sun (Lukuyu *et al.* 2021) leading to runoff and evaporation. Besides, it limits the awareness that farmers have over the proportions of feed in the animals' diet, creating the likelihood of malnutrition. Therefore, it would be beneficial to gather and store the residues right after crop harvest to reduce nutrient losses. Silaging could be an efficient feeding approach (Jones *et al.* 2017). It is also important to develop and adopt ration formulations which are tailored to the local availability of crop residues and to consider livestock's metabolic requirements.

Furthermore, free off-farm grazing of small ruminants is a common practice in several African countries. Free grazing limits the collection and recycling of manure, a resource which, if managed in beneficial ways, can support the maintenance of soil fertility and reduce the need for external fertilizers (Henao & Baanante, 2006) Free grazing potentially creates other problems, including the following: degradation of communal land and damage to other farmers due to increased soil erosion (as an effect of decreased vegetation cover); degradation of biological conservation practices (e.g. tree plantations); soil compaction, and transmission of several diseases to humans and other animals (Gebremedhin *et al.*, 2001 & Ogri, 1999); increased risk that the animals ingest harmful substances; and increased risk of traffic accidents due to uncontrolled movement of animals. Therefore, challenging aspects of small ruminant management include the need to raise awareness on the mentioned downsides of free grazing, as well as the implementation of more intensive systems which are considered feasible by local farmers.

1.3.2 Challenges in fertilizer use

In 2008 the government of Ghana introduced the Fertilizer Subsidy Program (FSP) targeted at farmers throughout the whole nation, aimed at supporting farmers by facilitating their access to fertilizers. However, access to these subsidies was not uniform and was influenced by farmers' gender - women having limited access to fertilizers - and political aspects - ruling parties misusing fertilizer subsidies to gain support for the elections (Mustapha *et al.*, 2016). In addition, the overall dramatic increase in fertilizer imports caused only a modest increase in crop yields. The low crop response rate to fertilizer application relates to various soil degradation problems (Jayne *et al.*, 2015) and improving soil structure and fertility could increase the crop response rate to fertilizers. However, using fertilizers poses risks to farmers' independence, as it increases reliance on external actors. Fertilizer-producing companies cannot guarantee a long-term steady and affordable supply, especially given the fluctuations and increase in the cost of natural gas, often needed for fertilizer production (EC, 2022). There are also negative environmental impacts associated with fertilizer production, transportation and usage, such as greenhouse gas emissions and groundwater contamination (Viets & Lunin, 1975; Hasler *et al.*, 2015). These aspects underline the importance of interacting with the resource base in a way that minimizes the need for fertilizers in the first place.

1.4 Research questions

The general aim of this research was to investigate how small ruminants could be managed in alternative ways to promote the low-cost sustainable intensification of medium resource-endowed farms, focusing on two districts near the city of Tamale, Northern Ghana.

This is achieved by answering the following three research questions (RQs), subdivided into several sub-questions (SQs).

RQ1: How can crop residues from commonly cultivated crops be used to provide small ruminants with a complete diet in terms of energy and protein throughout the year?

- **SQ1.1:** How are farms currently managed and what is the use of crop residues?
- **SQ1.2:** What is the nutritional profile of common crop residues?
- **SQ1.3:** What are alternative feeding strategies based on crop residues?

RQ2: What is the perception that farmers have towards the use of silage and compost for sustainable intensification?

- **SQ2.1:** How do farmers perceive the benefits of silage and compost?
- **SQ2.2:** How do farmers perceive the limitations and implications of the production process of silage and compost?

RQ3: What is the perception that farmers have towards intensifying small ruminant management?

- **SQ3.1:** How do farmers perceive the risks and limitations of free off-farm grazing?
- **SQ3.2:** How do farmers perceive the benefits, limitations, and feasibility of intensifying small ruminant management?

2. MATERIALS AND METHODS

2.1 Site description

This research focused on two districts in the Northern Region of Ghana (see *Figure 1*) near the city of Tamale, namely Kumbungu and Savelugu. One community per district was selected: Cheyohi No. 2 and Duko, respectively. Their location is within the Guinea savannah ecological zone, generally characterised by an open canopy of scattered trees and bushes, with a continuous grass understorey during the rainy season (from April until October) and bare soil during the dry season (from November until March). The climate in the Northern region posed several challenges to agricultural production. It was generally a warm climate, with an annual average temperature of 34°C. The rainfall pattern was erratic, with dry periods of more than 10 days in the dry season. The main challenges and threats posed by this climate included severe and prolongated drought, bush fires and windstorms (Husseini *et al.*, 2020).

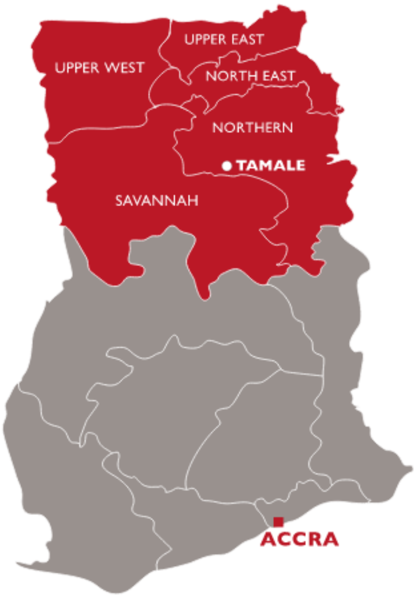

Figure 1. *Map of Ghana displaying the location of Tamale in the Northern Region (USAID, n.d.).*

2.2 Modelling with FarmDESIGN

The static modelling software FarmDESIGN was used to analyse the current feed balance and to explore alternative ones. The model has a multi-objective optimization algorithm based on decision variables set by the user, allowing for an exploration of alternative farm configurations which could perform better than the original one for multiple indicators. The modelling process consisted of 4 parts, based on the 4 steps of FarmDESIGN: Describe, Explain, Evaluate and Explore (Groot *et al.*, 2012). The parameters used for the analysis were specified in the Describe phase, including the values used for the baseline reference farm. In the Explain phase, the feed balance was analysed. The Evaluate phase was then used to set the optimization settings of the model (see *Appendix I*) and lastly, in the Explore phase, new scenarios of small ruminants' diets outperforming the original one were generated.

The exploration was done using an iterative approach starting from the reference farm. After noting the feed balance of the latter, feed sources were adjusted to reach a situation where the "Deviation available/required" values for energy and protein in the feed balance were included between 0% and 5%, optimally. This was the intermediate step before optimization, where imports and fresh biomass sources were removed from the reference farm and dry crop residues were left as the main feed source. The objectives were then set to the minimization of cropland area and the maximization of feed availability. Different decision variables were used depending on the scenarios (see *Paragraph 2.2.3*), but the main indicators were the values of "Deviation available/required" of energy and protein in the feed balance.

For the exploration of each scenario, the model was run for 100-500 iterations, depending on the extent to which a plateau of solutions was approached. Whenever alternative solutions within the constraints could not be found, the "Deviation available/required" of energy and protein were made more flexible and set between 0% and 10-15%. From the multitude of farm configurations generated by the model in this phase, one was selected and described in detail for each scenario, prioritizing the configurations with the lowest cropland area.

2.2.1 *Reference farm approach and data collection*

The reference farm was created in FarmDESIGN as a starting point for the analysis and included information on the current management of crops, crop residues, and small ruminants (see *Appendix IV* and "SI_MFS_Ghana_MNSenesi_2024.xlsx").

The feed balance of the current small ruminants' diet was analysed and deficits or surpluses were identified. Several choices were made to create the reference farm. Firstly, cropland in the reference farm included only the 3 most cultivated crops. Secondly, when calculating the crops' average areas and yields, the farmers who did not grow the crops were excluded from the calculation so that distortion by zero values could be avoided. This way, the averages were more representative of what yields could be obtained whenever the crop was grown. The same was done when calculating the average number of small ruminants owned by farmers. Inversely, the average of imported feeds was calculated using all values from the farmers of the two districts, including zeros. This was done because not all farmers imported all types of feed, and excluding zeros could have resulted in an overestimation of the weight of the imports in the feed balance. Thirdly, the energy and protein requirements of animals as well as the nutritional values of feed were based on the Dutch feed evaluation system, with energy expressed in VEM units and proteins in DVE units (Stichting CVB, 2022). Lastly, the yield of crop residues was calculated using the following equation (Smil, 1999), where yields are expressed in kg DM/ha and HI refers to the crop's harvest index:

$$Residues\ yield = Crop\ yield \times \frac{1 - HI}{HI}$$

The data for the reference farm and further exploration was collected in a combination of ways. A previous study on the investigation of different AfricaRISING technology packages (Michalscheck *et al.*, 2018), was used to collect part of the initial information on farms in Northern Ghana. The FarmDESIGN model was used in this previous study as well, and several inputs have been kept the same as in its baseline medium-resource-endowed farm of the Northern Region. New data has been either added or substituted, when available, through literature research and during interviews with farmers of the two districts of Duko and Cheyohi No. 2. Two important sources of data were Feedipedia and the CVB Booklet (Feedipedia, 2023; Stichting CVB, 2022). Other scientific sources were accessed from Research Gate, Google Scholar and Science Direct.

2.2.2 Metabolism of small ruminants

The metabolism of small ruminants referred to the West African Dwarf (or Djallonké) breed. The average weight of an adult goat or sheep of this breed in Northern Ghana was 25.5 kg (Rahman *et al.* 2022). Goats tend to have slightly higher nutritional requirements for maintenance compared to sheep. *Table 2* lists the metabolic requirements used on FarmDESIGN (Michalscheck *et al.*, 2018; Stichting CVB, 2022).

***Table 2**: Metabolic requirements of small ruminants, including differences between goats and sheep.*

Ruminant	Requirement	Value
Goats	Saturation	4 % of BW
	Structure	1 SW/kg DMI
	Energy	36.6 VEM/kg MW/day
	Protein	22.8 g DVE/day
Sheep	Saturation	3.5 % of BW
	Structure	0.7 SW/kg DMI
	Energy	30 VEM/kg MW/day
	Protein	22.8 g DVE/day

BW = Body Weight. MW = Metabolic weight ($BW^{0.75}$). DMI = Dry Matter Intake. SW = Structure units.

2.2.3 Alternative feeding scenarios

Three alternative diets for small ruminants suitable for sustainable intensification were created. Scenario "STOVER-HAY" was the simplest of the three. It was created using as decision variables the amount of dry grass yearly fed to the animals, as well as the land areas allocated to the 3 most commonly cultivated crops. It was assumed that all the generated crop stover (or straw) was used as feed, and that hay was collected from the grassland surrounding the farm, therefore not interfering with the amount of cropland. The alternative diet generated in the "SIMILAR RESIDUES" scenario, instead, consisted only of bulky crop residues. It was generated using crop areas as the only decision variables and the model was allowed to choose between all the crops included in the research. As in the "STOVER-HAY" scenario, all the generated crop stover (or straw) was assumed to be used as feed. Lastly, the "DIVERSE RESIDUES" scenario was generated using the same approach as in the "SIMILAR RESIDUES" scenario, but with the addition of some finer crop residues (produced on-farm) to the ruminants' diet, namely pods and husks. The relative cropland area needed to feed one small ruminant was then calculated for each scenario. After, it was determined whether any of the alternative feeding strategies could allow to increase in the flock size without exceeding a cropland area of about 2 hectares.

2.3 Fieldwork

The fieldwork lasted 4 weeks. It consisted of quantitative and qualitative data collection on the farming systems in consultation with local researchers from IITA (International Institute of Tropical Agriculture) and local farmers.

2.3.1 Farmers interviews

Semi-structured interviews were conducted to collect data for the scopes of RQ1 and part of RQ2. With the support of a local translator, 5 farmers were interviewed in Duko and 6 in Cheyohi No. 2. About 50% of farmers were male and 50% were female, to maintain gender balance. All of them belonged to medium-resource-endowed farms. They were asked about cultivated crops, allocation of crop residues, amount and management of small ruminants, import of feed, use of manure, and composting processes. The extensive blueprint of the interviews can be found in *Appendix II.*

2.3.2 Focus Group Discussions (FGDs)

The aim of the Focus Group Discussions (FGDs) was to discuss with farmers the practices of composting, silaging, and intensifying livestock management. Their perspectives on these practices were collected during this step and mainly used for the scopes of RQ2 and RQ3. A total of two FGDs were conducted, one for each district. The farmers who participated in the FGDs were the same as in the interviews. The full list of discussion points presented to the farmers during the FGDs can be found in *Appendix III*, while Appendix V shows two illustrations presented to the farmers as examples of simple composting and silaging structures.

3. RESULTS

3.1 Current farm management (SQ1.1)

This section contains relevant findings regarding farm configuration and management at the time of the study. The data collected from each farmer during the interviews can be found in *Appendix IV*.

3.1.1 Crop cultivation

Farmers in Duko only cultivated maize, groundnut, soybean and rice, while some farmers in Cheyohi N. 2 had a higher crop diversity, including crops such as cassava, yam, pearl millet, cowpea, pepper and eggplant. Maize was cultivated by all interviewed farmers and it was the most important staple and cash crop. On average, farmers in Duko had 0.9 ha of cropland dedicated to maize cultivation and generated yields of 2075 kg/ha. In Cheyohi N. 2 numbers were lower, with a maize area of 0.7 ha and yields of 1333 kg/ha. Because of its importance, maize was also the only crop for which fertilizer was used regularly. The second most important crop was groundnut, which was cultivated by about 70% of the interviewed farmers and it was a staple crop considered a precious protein source. Farmers in Duko had, on average, 0.7 ha of groundnut and obtained yields of 720 kg/ha, while in Cheyohi N. 2 the values for area and yield were 0.8 ha and 400 kg/ha. The third most cultivated crop was soybean, which was grown by 55% of the farmers. The average soybean area in Duko was 0.5 ha, while in Cheyohi N. 2 it was 0.4 ha. Yields were 1875 kg/ha in the former district and 875 kg/ha in the latter. Cassava was grown only by two farmers in Cheyohi N. 2, both cultivating it over 0.4 ha of land and achieving similar yields of about 1100 kg/ha. Yam was grown only by one farmer on a field of 0.2 ha, with a yield of 3500 kg/ha. Pearl millet, cowpea and pepper were also grown only by one farmer, on areas of 0.4 ha, 0.2 ha and 0.4 ha, in turn obtaining yields of 1750 kg/ha, 1000 kg/ha, and 1000 kg/ha, respectively. Lastly, peppers were grown by two farmers in Cheyohi N. 2. They both grew peppers over 0.4 ha and obtained an average yield of 438 kg/ha.

3.1.2 Composting practices

In Duko, the interviewed farmers did not make any compost with manure and crop residues. Manure was collected from the stable and gathered in a pile located outdoors on bare soil, where it stayed until its application to the fields at the beginning of the growing season. In Cheyohi No. 2 instead, farmers used manure and certain crop residues to make a basic version of compost. The procedure consisted of digging a pit in the ground and filling it with manure, rice chaff, groundnut shells, maize husks and other residues depending on their availability. The pit was neither sealed at the bottom nor covered at the top. The specific amounts or ratios of each material were not known and the compost was usually not mixed. Materials were added on top and left to decompose. As a result, within the mixture, there were different levels of decomposition. At the bottom of the pile, the decomposition was higher and the compost warmed up, while at the top of the pit, materials did not fully decompose and the temperature was lower.

3.1.3 Small ruminants whereabouts

All the interviewed farmers managed the small ruminants in a very similar way. During the wet season, animals were either kept inside the stable, tethered to a tree close to the stable, or accompanied to the fields tethered to a farm worker to allow for controlled grazing of grasses and avoid damage to the crops. Most of the feed given during the wet season was manually provided to the animals by the farmers. During the dry season, instead, animals were kept in the stable at night and they were allowed to freely graze off-farm from early morning until late afternoon. Free off-farm grazing during the dry season had multiple causes. These included the lack of sufficient feed on-farm; the lack of resources to build larger stables in the farmyard (given that the current stables were often too small to accommodate the animals comfortably); and lastly the fact that it was a common practice for a long time for most farmers in the area, so it was culturally ingrained in the community.

3.1.4 Small ruminants diet

Farmers had, on average, 10 small ruminants (5 sheep and 5 goats). In the dry season, animals were fed with a combination of crop residues, as well as grasses and other feed sources which the animals found during off-farm grazing in surrounding fields and while roaming in the streets. During the wet season, they were fed with the following feed sources: cut and carried grasses from the surrounding grassland or directly grazed by the tethered animals; imported feed (mainly consisting of maize bran, rice chaff, pigeon pea stover and cassava peels); fresh maize leaves collected by leaf stripping; and lastly kitchen scraps, which were partly fed in the dry season too.

3.1.5 Current use of crop residues

Residues were partly used to feed the small ruminants, partly left on the field as mulch, and partly used as firewood. The specific amounts allocated to each use were unknown to the farmers. However, general allocation ratios of the most commonly cultivated crops were mentioned by the farmers during the interviews. Roughly 50% of maize stover was used as firewood, 40% as feed for small ruminants, and 10% was left on the field as mulching material. Maize cobs were all used as firewood. Groundnut stover and soybean straw were, instead, not used as firewood but only used as feed and mulch, in ratios of approximately 70% and 30%, respectively.

3.1.6 Assumptions in the current feeding strategy of small ruminants

The species and amounts of cutgrass and grazed grass were unknown by the farmers. Therefore, a rough estimation of 200 kg of fresh grass per year was made. When taking an average of 26% DM, it resulted in 52 kg DM/year from fresh grass. The amount of fresh maize leaves fed to the animals during the wet season was also unknown, therefore the value of 849 kg FM/ha of fresh maize leaves per household was retrieved from a previous study (Rahman *et al.* 2022) and adapted to the average maize area of 0.8 ha, resulting in 679 kg FM per household. Considering an average of 37% DM, 251 kg DM/year was assumed to be the amount of fresh maize leaves fed to 10 small ruminants. Lastly, kitchen scraps were excluded from the analysis given that they are fed to the animals in neglectable amounts compared to the other feed sources, and given that there can be large variability in their nutritional content, which depends on the specific diet within each household.

3.1.7 Analysis of the current feed balance

The analysis of the current feed balance showed that the feed was sufficient to support the nutrition of 10 small ruminants per farm. The diet consisted of 212 kg DM/animal/year, on average. The ratios of each feed type (in DM) were 27% soybean straw, 23% groundnut stover, 19% maize stover, 12% fresh maize leaves, 9% imports, 8% soybean pods, and 2% fresh grass. Keeping the same feed ratios and the same residue allocation between feed, mulch and firewood, this diet was associated with an average cropland area of 0.21 ha/animal/year, given a total cropland use of 2.1 ha.

3.2 Nutritional profile of common crop residues (SQ1.2)

The analysis of the nutritional profile of common crop residues showed that there can be large differences between the available feed sources. *Figure 2* represents a plot of all the residues included in this study, with a comparison of their energy and protein content per unit of dry matter. On the one hand, it can be seen that pearl millet bran, sorghum bran, cassava stover, yam stover, soybean hulls and maize bran are some examples of highly nutritious residues in both energy and protein. On the other hand, some of the least valuable feed sources per unit of dry matter include groundnut hulls, rice chaff, cassava peels and yam peels.

Figure 3 represents crop residues plotted based on the amount of energy and protein produced per unit of land area. Pigeon pea stover was the most remarkable crop residue in terms of high yield of energy and proteins, followed by cowpea stover, millet straw and soybean straw. Most other residues were relatively similar to each other in energy and protein productivity per unit of land area, but considerably lower than those mentioned above.

3.3 Analysis of alternative feeding strategies (SQ1.3)

Out of the three alternative feeding scenarios generated during modelling (see *Table 3* for the extensive list of the specific quantities of feed sources for each scenario, and *Figure 4* for the relative amounts of feed sources expressed as percentages in the animal's diet), the "STOVER-HAY" scenario proposed the simplest diet: 53% groundnut stover, 29% soybean straw and 18% grass hay, with approximately 212 kg of biomass dry matter fed to each small ruminant per year. 0.17 ha of cropland would be sufficient to produce the necessary residues to feed one animal. In other words, for each hectare of cropland, 6 animals could be fed, representing a slight increase when compared to the baseline situation of about 5 animals/ha. A more diversified diet with greater intensification opportunities was seen in the "SIMILAR RESIDUES" scenario, based on the most prevalent bulky crop residues such as stover and straw, and where the prevalent feed source was cowpea stover (47%). The latter was used in combination with millet straw (22%), rice straw (11%), groundnut stover (8%), pigeon pea stover (6%) and cassava stover (5%). In this scenario the cropland needed to feed one animal further decreased to 0.12 ha, allowing to feed 8-9 animals with each hectare of cropland.

In the "DIVERSE RESIDUES" scenario, where finer crop residues such as pods and husks were included too, the lowest amount of cropland needed to feed each animal was achieved (0.075 ha), out of the three scenarios. Therefore, the flock size could be intensified by up to 13 small ruminants for each hectare of cropland necessary for feed production, when following this diet. In this scenario, cowpea stover was still the prevalent feed source (42%), this time followed, in terms of descending quantities of dry matter, by pigeon pea stover (25%), pearl millet straw (16%), cowpea pods (7%), rice straw (5%), pigeon pea pods (3%), pearl millet husks (1%) and soybean straw (1%). Regarding the total feed biomass, the three scenarios ranged from 198 to 226 kg of dry matter per animal per year.

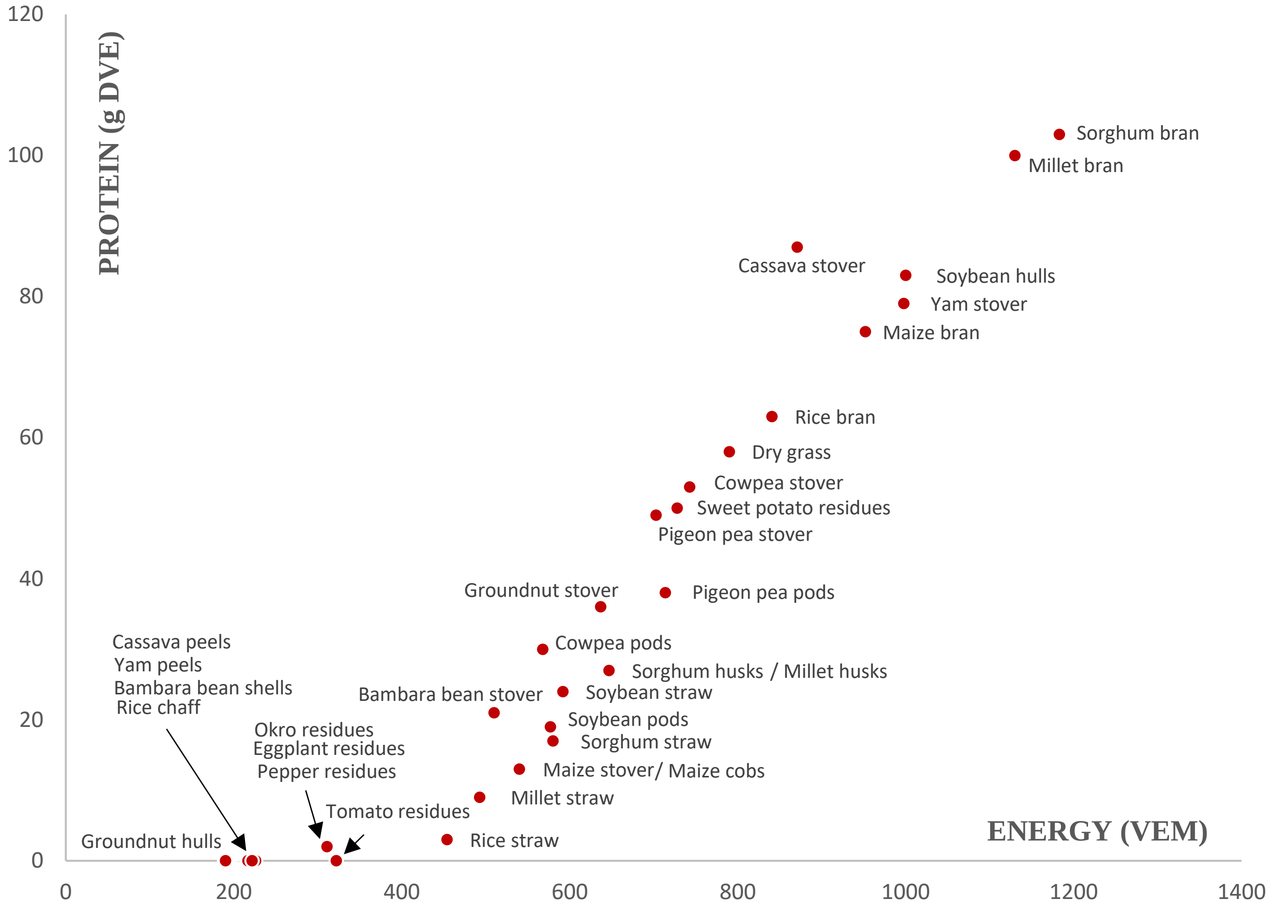

Figure 2: *Energy and protein content of crop residues per unit of dry matter.*

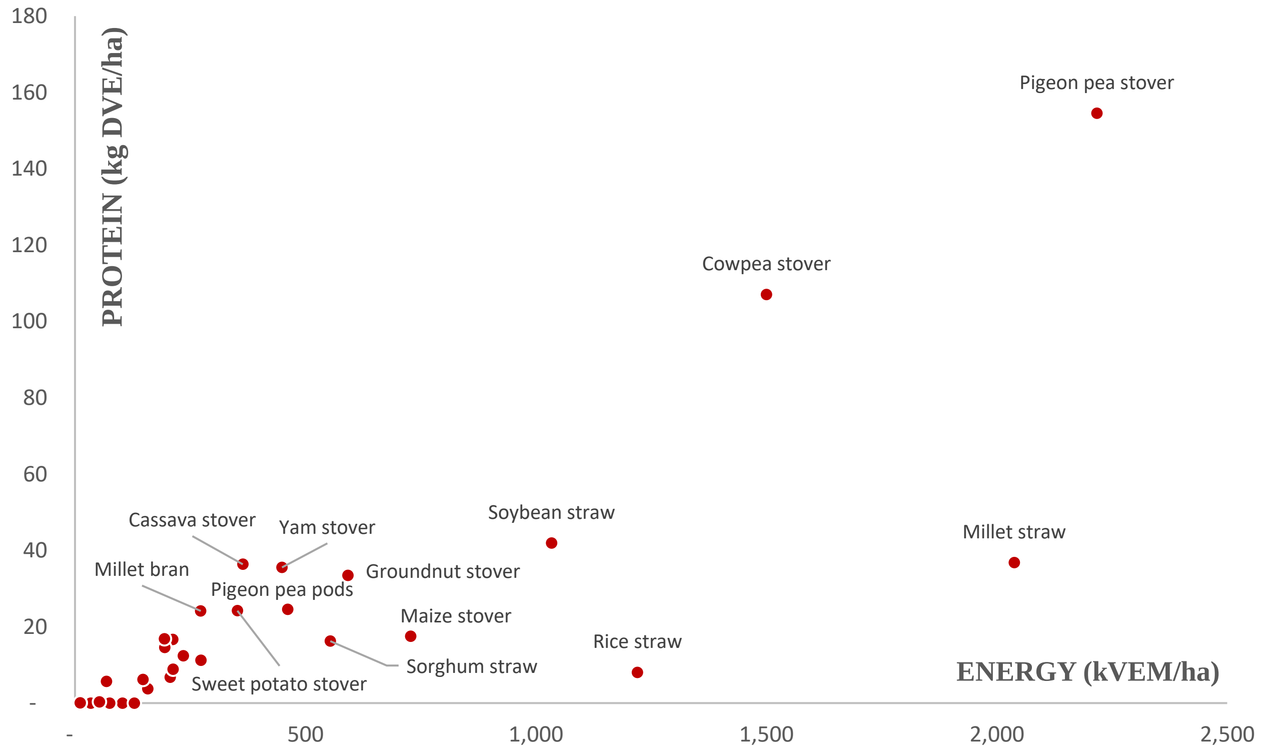

Figure 3: *Energy and protein yield of crop residues per unit of land area.*

Table 3*: Feed sources and cropland allocation in the current and alternative feeding scenarios for small ruminants (expressed in units of measurement).*

	Current scenario		Scenario “STOVER-HAY”		Scenario “SIMILAR RESIDUES”		Scenario “DIVERSE RESIDUES”	
Feed sources (kg DM/year)*	Soybean stover	580 kg	Groundnut stover	1125 kg	Cowpea stover	940 kg	Cowpea stover	945 kg
	Groundnut stover	495 kg	Soybean straw	615 kg	Millet straw	435 kg	Pigeon pea stover	555 kg
	Maize stover	410 kg	Hay grass	380 kg	Rice straw	225 kg	Pearl millet straw	370 kg
	Maize fresh leaves	250 kg			Groundnut stover	160 kg	Cowpea pods	160 kg
	Imports	200 kg			Pigeon pea stover	120 kg	Rice straw	120 kg
	Soybean pods	170 kg			Cassava stover	100 kg	Pigeon pea pods	60 kg
	Fresh grass	50 kg					Pearl millet husks	30 kg
							Soybean straw	20 kg
TOTAL Feed		2120 kg		2120 kg		1980 kg		2260 kg
Cropland	Maize	~0.8 ha	Groundnut	~1.3 ha	Cowpea	~0.5 ha	Cowpea	~0.5 ha
	Groundnut	~0.8 ha	Soybean	~0.4 ha	Pearl millet	~0.1 ha	Pigeon pea	~0.1 ha
	Soybean	~0.5 ha			Rice	~0.1 ha	Pearl millet	~0.1 ha
					Groundnut	~0.2 ha	Rice	~0.04 ha
					Pigeon pea	~0.04 ha	Soybean	~0.01 ha
					Cassava	~0.3 ha		
TOTAL Cropland		2.1 ha		1.7 ha		1.2 ha		0.75 ha
Intensification	-		0.17 ha/animal 6 animals/ha ~12 animals with 2 ha		0.12 ha/animal 8 animals/ha ~16 animals with 2 ha		0.075 ha/animal 13 animals/ha ~26 animals with 2 ha	

* Values have been rounded up to multiples of 5 for simplification purposes

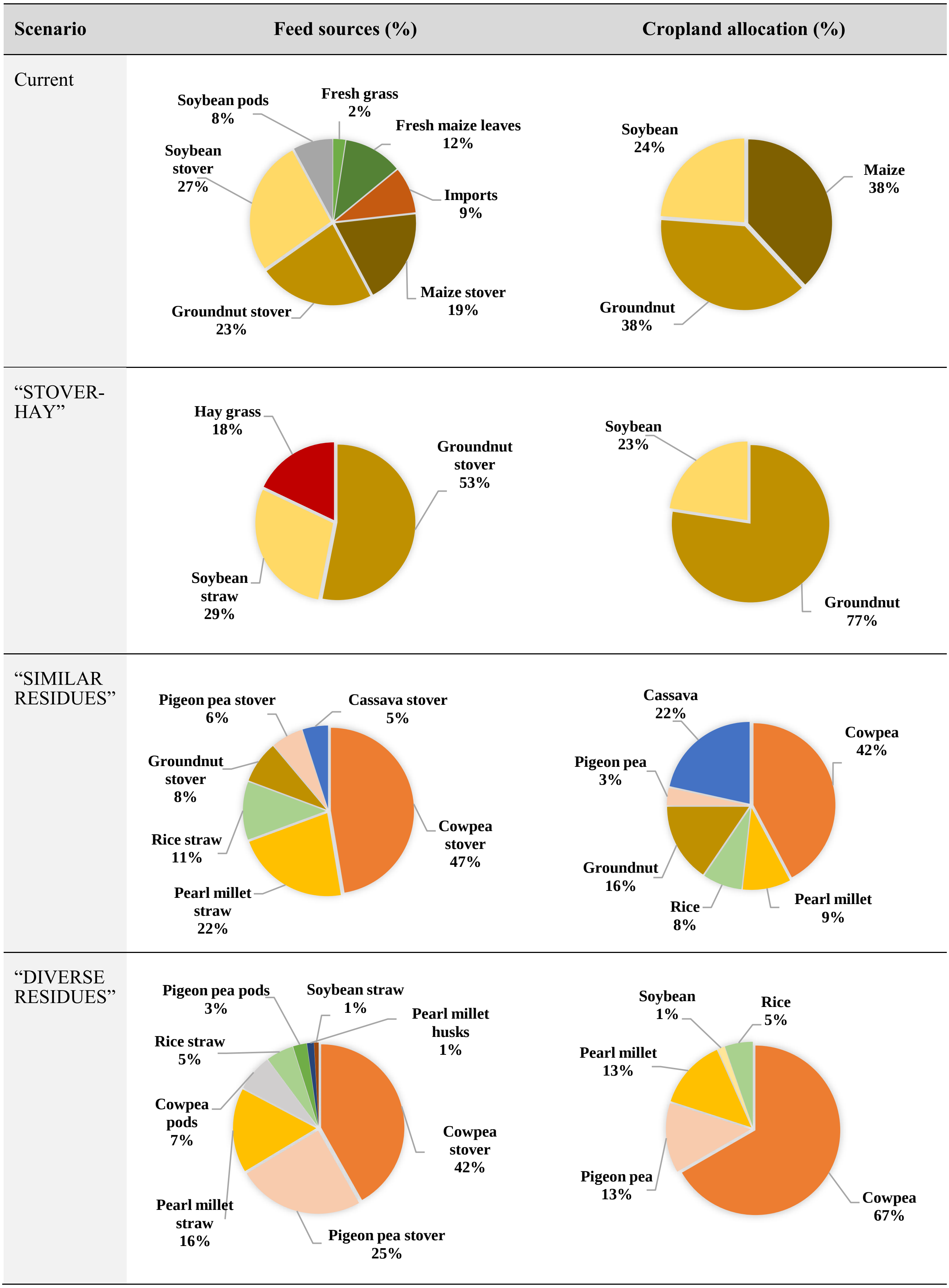

Figure 4: *Feed sources and cropland allocation in the current and alternative feeding scenarios for small ruminants (expressed in percentages).*

3.4 Farmers' perceptions of silage (RQ2)

Silage was not used as a feed for small ruminants in the study area. During the FGDs, it became clear that most farmers do not know what silage consists of. After listening to the advice, the farmers perceived the silage-making process as too complex for their level of knowledge. They have not directly observed any farmer in the surrounding area making use of this type of feed and would therefore appreciate support for the implementation of the silage-making process to avoid the negative consequences of an incorrectly managed process. In addition, to avoid the necessity to make large investments in the silage-making structures, farmers expressed favour towards the idea of a common facility used by multiple farms in the area which could facilitate the initialization of this process, so that the financial pressure on each farm is reduced. Financial aid from the government was also sought by the farmers since it could be beneficial for this purpose. Comparably, at the time of the study, a public facility for chopping biomass material (e.g. straw) was available to the farmers by the Ministry of Food and Agriculture. Farmers could bring their crop residues to this facility to chop them into finer pieces and create feed mixtures for the livestock by adding salts and/or ammonia. If silos were made available to the farmers in addition to the chopping machinery, silaging was seen by the farmers as a more realistic opportunity. For the moment, they preferred to rely mainly on fresh residues and hay as a source of feed for their livestock as it was perceived to be simpler, cheaper and less risky.

3.5 Farmers' perceptions of compost (RQ2)

Farmers perceived the idea of building dedicated aerobic composting structures as too expensive, given the unavailability of free wood or concrete suitable for construction. What they perceived as feasible was, instead, the use of plastic liners to seal the bottom of the pits where they normally make compost, as well as liners to cover the top of the piles, since these could be obtained more easily and for a cheaper price. They were not aware of the large nutrient losses that can take place through leaching and volatilisation. Also, they were pleased to discover the potential benefits of turning the compost pile periodically and they showed a positive attitude towards adding this practice to their regular farm activities.

Concerning the benefits, the farmers were not aware of some of the benefits that compost can bring. For example, they did not perceive it as a way to increase the water-holding capacity of the soil and they wondered if the application of compost to each plant could be more efficient than applying it to the whole cropland area. Lastly, farmers perceived the transportation of manure and crop residues to the compost pile as a limiting factor. Often the fields were located away from the farm and farmers would require a transportation method (such as motorized tricycles) to move crop residues from the field to the compost pile in the farmyard, which can result in a large economic investment.

3.6 Farmers' perceptions of semi-intensive systems (RQ3)

Farmers perceived the option of fencing the cropped fields to prevent the goats and sheep from leaving the farm, as well as keeping other animals outside of their fields, as a non-feasible option. The reason for this was that they usually did not own the fields they cultivated. The owner of the fields was an external party who was often unknown to the farmers and who could claim the fields at any time. Also, they would need the owner's permission to build any additional structures to the fields. If they would build structures without permission, the risk would be that the owner subsequently asked for removal, or would directly remove them without communicating it to the farmers. For this reason, the farmers perceived it as a potential loss of time, labour and materials. Since the farmers had more control over the farmyard in the close vicinity of the household, they perceived the construction of a fence around the farmyard as a more feasible option, rather than around the cropped fields. This practice was also perceived to reduce the risk of theft of the materials used to build the fences, since some household members ware present in the farmyard for the majority of the day, as opposed to the cropped fields away from the household, which were often left unattended.

4. DISCUSSION

Several combinations of residues from common crops in Northern Ghana could represent a valuable choice to meet the dietary requirements of small ruminants (see *Table 3* and *Figure 4*). Choosing to switch to alternative diets can open up various opportunities for sustainable intensification. A simple but effective feeding strategy could consist of groundnut stover for the major part, together with soybean straw and dry grass (see scenario "STOVER-HAY"). Feeding strategies with a higher degree of diversification, instead, could include other nutritious crop residues such as pigeon pea stover and pods, cowpea stover and pods, pearl millet straw and husks, and cassava stover (see scenarios "SIMILAR RESIDUES" and "DIVERSE RESIDUES"). Sustainably intensifying small ruminant production could involve choosing to cultivate crops that produce residues with larger amounts of energy and protein per unit of land (see *Figure 3*). This approach has the potential to considerably reduce the amount of cropland necessary to generate the residues used as feed while meeting the animals' nutrient demand. In turn, this creates space for increasing flock size without the need to rely on additional feeds from outside of the farm. With this regard, pigeon pea and cowpea are two of the most important crops in terms of energy and protein content of the residues, as well as biomass productivity per unit area. In addition, the cultivation of these crops can promote natural soil fertility due to their nitrogen fixation, reducing the need for chemical fertilizers and their associated negative impacts on the soil, as opposed to maize cultivation.

The excellent nutritional quality of pigeon pea forage was previously underlined by Phatak *et al.* (1993), who also mentioned the remarkable hardiness of this crop to harsh environmental conditions. According to Tenakwa *et al.* (2021), pigeon pea stover could be added to the ruminants' diet in relatively large amounts without risks. However, the forage potential of this crop has not yet been fully harnessed by smallholder farmers in Ghana. Cowpea stover also has a great feed potential which has been explored in other studies involving small ruminants (Grings *et al.* 2020; Garba Bala & Rabiu Hassan, 2023). Notably, even the inclusion of small amounts (about 10%) of cowpea residues in the livestock's diet can support the needs of rumen microbes in a way that increases overall feed palatability and the digestibility of lower-quality forage (such as cereal stover).

A commonly used cereal stover in the small ruminants' diet at the time of this study was maize stover, despite its relatively poor nutritional value seen in *Figures 2* and *3* and further discussed by Dejene *et al.* (2021). Its use could perhaps be more suitable as mulching material or as fuel, whenever more nutritious feed sources are available. Rice chaff also has a low nutritional content but is often used as feed. Besides, it has low digestibility and low palatability for small ruminants (Roba *et al.* 2022). A common practice to increase the digestibility of lower-quality forages involved mixtures of these materials with salts or residues from milling processes. However, further research is necessary to estimate the nutritional content of these mixtures and compare it with crop residues alone.

An arguable consideration, which was the reason why pods and husks were eventually preferred over bran for the formulation of alternative feeding strategies despite being often less nutritious, regards the fact that bran can be either seen as a crop residue or as food for human consumption. Bran is the residue of food processing steps such as milling, starch production and ethanol production (FAO, 2012), but it can also be digested by humans and can provide important nutrients such as fibres, vitamins, minerals and antioxidants (Harvard, 2019). Subsequent studies could therefore investigate the intensification potential of adding bran to the livestock's diet, whether or not used in combination with stover, straw, pods and husks. However, this could be done while reflecting on the priorities and comparing of benefits and downsides of using bran as food or feed.

The adoption of beneficial farming practices such as silaging and aerobic composting requires a higher investment of time and resources into farmers' education. Farmers could greatly benefit from increased opportunities to learn and share scientific knowledge on sustainable farming practices. Smallholder farmers utilize their indigenous knowledge for most of their agricultural activities, which is often not sufficient to adequately support the system's fertility. As explained in detail in a study by File & Nhamo (2023), factors such as limited access to extension services, scarce reliability of farming practices, and socio-cultural beliefs pose a threat to food security in Northern Ghana. Farmers' access to scientific information is also limited by their lack of knowledge of the English language, as well as the lack of technological items useful for education purposes, such as smartphones and computers, besides paper-based information. Improving the collaboration between farmers of nearby villages and districts could also open up interesting possibilities. Not only it could promote useful discussions on farming knowledge, but it could also allow for sharing valuable resources on a landscape level. For example, compost fertility could be increased by using various manure types from farmers that own different types of livestock, as well as with residues from a larger multitude of crops. Further research is needed to understand what actions could be taken to support this type of development from a social perspective.

Concerning land ownership, the fact that farmers often do not own the land they cultivate is a serious concern. They could be deprived of land at any time to the benefit of foreigners, with very limited prior consultation. This can have significant negative impacts on the livelihood of local households, especially smallholder farmers (Alhassan *et al.* 2021). Land grabbing is one of the reasons why several farmers in this study seem more interested in investing energy and resources into animal farming rather than crop farming since they have a greater sense of ownership over their livestock. However, soil and livestock should be greatly connected in terms of nutrient cycling and availability of feed sources (Powell & Valentin, 1997). Therefore, farmers need to be further informed about improved practices that strengthen this connection.

Land grabbing also seems to be one of the main reasons why farmers refuse to fence the cropped fields, but prefer the idea of fencing the area around their homestead. In this regard, to considerably reduce the economic investment needed to build such fences and its related risk and fear of theft, materials obtained from crop residues could be used as an alternative to, for example, purchased wood. Pigeon pea stalks are well suited as fencing material, and even living fences using tall and perennial pigeon pea cultivars have been observed in Africa and the Caribbean (Phatak *et al.* 1993).

This research, however, had several limitations. Firstly, the feed balance created to analyse the current situation excluded the feed that small ruminants ate during off-farm grazing, given its unpredictability. Secondly, the main focus was on dry residues collected at the end of the harvesting season, but other feed sources such as fresh biomass at different stages of crop development, as well as residues of the processing industry (such as cereal brans and soybean hulls), would be interesting to include in the development of further feeding scenarios. The same goes for residues of different crop cultivars and grass species, which can have large differences in terms of nutritional aspects. Thirdly, the collected nutritional values of the crop residues were obtained from sources based on data from multiple countries, which may differ widely from those in Northern Ghana. Analysing the average nutrient content of residues specific to the study area before the adoption of alternative diets for small ruminants could be crucial. Fourthly, the creation of new scenarios for feeding strategies assumed that almost all residues produced by crops are used as feed. It would be beneficial to investigate the effects of different allocation ratios between feed and mulching (or composting) materials on both livestock diets and the improvement of soil fertility. Lastly, the participants of the FGDs did not contribute equally to the discussions. This was due to reasons including gender inequality, with women being generally less involved in the discussions. Separate FGDs for men and women could have allowed to collect opinions more equally between genders.

From a broader perspective, this research supported the intensification of mixed farming systems by providing ideas on how to increase feeding efficiency and illustrating potentially beneficial management strategies to local farmers. When approached locally by taking into account specific challenges and availability of resources, mixed systems can be an extremely valuable sustainable farming practice and source of a multitude of food and economic benefits for smallholder farmers and communities as a whole.

5. CONCLUSION

Developing livestock diets based on the most nutritious crop residues could help farmers move towards sustainable intensification, provided that these diets are well-balanced to fulfil the ruminants' metabolism. Pigeon pea and cowpea could be two of the most important crops to move in this direction. These crops produce large amounts of residues which are highly nutritional for ruminants (see *Table 3* and *Figure 4*) and promote soil fertility. Tackling unsustainable traditional farming practices, developing effective feeding strategies such as those explored in this research, and investing further resources into farmers' education could lead to a future of increased food security with minimal economic investment.

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APPENDIX I – OBJECTIVES / CONSTRAINTS OF THE EXPLORATION

Objectives

Description	Direction
Farm Area (main objective)	Minimize
GrazingPeriod.Deviation TDN (“dummy” objective)	Maximize

General Constraints

Description	Minimum	Maximum
Farm Area	0	2.1
NonGrazingPeriod.Deviation STR	0	999
GrazingPeriod.Deviation STR	0	999
NonGrazingPeriod. Deviation DM	-999	0
GrazingPeriod.Deviation DM	-999	0
NonGrazingPeriod.Deviation CP	0	5
GrazingPeriod.Deviation CP	0	5
NonGrazingPeriod.Deviation TDN	0	5
GrazingPeriod.Deviation TDN	0	5
(Crop Residues) FractionNonGrazPeriod	0	1.1

STR = Feed structure; DM = Dry matter intake; CP = Protein intake; TDN = Energy intake.

Additional Constraints in Scenario “STOVER-HAY”

Crop areas of maize, groundnut and soybean were constrained to a minimum of 0 to a maximum of 2.1 ha. All generated stover and straw were used on-farm and given to the animals as feed.

Additional Constraints in Scenario “SIMILAR RESIDUES”

Crop areas of all crops were constrained to a minimum of 0 to a maximum of 2.1 ha. All stover and straw were used on-farm and given to the animals as feed. All other residues such as pods and husks were used as mulching material.

Additional Constraints in Scenario “DIVERSIFIED RESIDUES”

Description	Minimum	Maximum
(Pods/Husks) ToAnimals	0	100
(Pods/Husks) ToSoil	0	100
Crop areas of all crops	0	2.1

All crop residues were assumed to be used on-farm. Stover and straw residues were only used as animal feed, while pods and husks were used partly as animal feed (as necessary to complete the fulfilment of animal nutritional requirements) and partly as mulching material.

APPENDIX II – FARMER INTERVIEW GUIDE

Introduction

- Aim of the interview: collect data to analyse current farm performance and alternatives
- Duration: approx. 20-30 minutes
- Introduction of the interviewer: Margherita Senesi, a student from Wageningen University
- Information on the interviewee: Name and gender

Questions

Topic: Land availability and use

- What is the total farm area?
- What are the total areas of cropland and grassland?

Topic 2: Crops cultivated

- What crops do you grow?
- How much land is dedicated to each crop?
- Do you use any fertilizers or pesticides? If yes, how much?
- How many times are the crops harvested?
- What are the annual yields you get from these crops?

Topic 3: Crop residues

- How many times are the crop residues harvested?
- What are the yields of the crop residues per year?
- How do you currently manage the crop residues? (feed, mulch, compost, firewood, etc.)
- What are the allocation ratios of the crop residues for different purposes?
- What are your preferred crop residues for ruminants feeding and why?
- What grasses do you feed to ruminants and in what amounts?

Topic 4: Small ruminants management

- What is the main purpose of having small ruminants?
- What type of grass is fed to ruminants?
- How do you feed the small ruminants?
- How much time do the animals spend on-farm, in the stable and off-farm?
- What are the differences in management between the dry and the wet season?
- How much manure do you manage to collect and how do you use it afterwards?
- What breeds of goats and/or sheep do you own?
- What is the average weight of the animals?

APPENDIX III – DISCUSSION POINTS WITH FARMERS

Silage

- Silage is the product of anaerobic fermentation of forages containing high levels of moisture (40-80 %).
- Lactic acid bacteria are the main actors of the fermentation process, since they ferment plant sugars (namely water-soluble carbs) present in the biomass into lactic acid, and to a lesser extent into acetic acid.
- The pH of the forage is reduced during the process (pH often lower than 5.0), in turn reducing the activity of spoilage microorganisms.
- A common type of structure used for the silage process is a called “silo”.

Some benefits:

- The bacteria responsible for the anaerobic fermentation allow to preserve the quality of feed. The nutritional quality of silage is similar to crop residues in their fresh state.
- Silage allows the harvesting of more nutrients from the same land area compared to hay, which is associated with nutrient losses during the drying phase.
- It can be stored for approximately 6 months without compromising the nutritional values.
- It is highly palatable for livestock.
- It promotes digestion and absorption of nutrients from forage.
- The fermentation process can be controlled by adding preservatives and additives, such as molasses. However, if the process is correctly performed, no additives are needed.

Some downsides:

- Specific equipment is necessary, such as a chopping machine and a silo. This can require a substantial initial investment.
- It is not as easy as hay to transport.
- Nutrient losses can occur if the process is not done correctly (e.g. if materials are not quickly transported from the field to the silo).
- It can take a few years of trial and error before performing the process correctly.
- It can be challenging to keep oxygen out of the silo to avoid the growth of moulds and yeasts.
- If the moisture content drops below 40% it can result in a fire.
- Improper management can result in the development of toxic substances and endanger livestock health.

(Jones *et al.* 2017; Huhnke, 2017)

Compost

- Make use of a sealed surface such as a plastic liner, concrete, or a stone floor to reduce leaching.
- Place it under a roof to keep the moisture content more easily controlled.
- Mix it every few days to introduce oxygen and allow for an even decomposition.
- Keep the temperature controlled by adding water to avoid fire.
- Keep moisture content at approximately 50%.
- Consider the C:N ratio of the materials added to the pile, adding about 2:1 of browns to greens.
- Once the temperature has decreased and the materials are largely decomposed the pile can be covered to avoid nutrient losses by volatilization.
- The 3-step composting approach could be useful to promote even decomposition.

Some benefits:

- Compost can improve soil fertility and structure, increase soil water retention and pest/weed suppression, sequester carbon and reduce erosion and greenhouse gas emissions.
- Compost can increase yields while reducing the need for fertilizers.
- Compost relies on biomass that can freely be obtained from the farmland and livestock, allowing farmers to save money on external fertilization sources.
- It can support long-term income generation due to long-term soil health improvement.

Some downsides:

- It can produce unpleasant odours and attract rodents and other wildlife if not managed correctly.
- Regular management is required, which can result in more labour.
- If a composting structure is built, it can require an initial investment.
- It requires some knowledge of C:N ratios of compostable materials, as well as the capability to make calculations to obtain the correct ratio to start the process.
- If not managed correctly, pathogens can develop in the compost pile and could later have negative impacts on the soil and the cultivated crops.
-

The contact of a local NGO called “CEAL Ghana” (Centre for Ecological Agriculture and Livelihoods) located in Walewale was shared with the farmers to promote future collaboration and more detailed and participatory support for compost making (CEAL, 2024).

(Martínez-Blanco, 2013; Krans, 2016; Hu, 2020)

Intensification of small ruminants management

- Reducing grazing and roaming off-farm to a minimum could be beneficial to minimize the downsides of free grazing mentioned in *Paragraph 1.3.1* and increase control on livestock’s diet.
- Fencing the crop fields or the farmyard could help in achieving a more efficient grazing system.
- Manure dispersal could be reduced by reducing free grazing, facilitating manure collection.
- A more intensified system could require more labour and materials for fencing and feeding.

(Lemus & Parish, 2008)

APPENDIX IV – DATA FROM THE FARMERS’ INTERVIEW ANSWERS

Table 4: *Current farmland use and crop yields*

	Land use			*Crops*																			
	Total	Crops	Grass	Maize		Groundnut		Soybean		Rice		Cassava		Yam		Millet		Cowpea		Pepper		Eggplant	
Farmer ID	(ha)	(ha)	(ha)	A	Y	A	Y	A	Y	A	Y	A	Y	A	Y	A	Y	A	Y	A	Y	A	Y
1 (m) - D	4	2.4	1.6	0.8	2500	0.8	600	0.8	2000	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2 (m) - D	4	2.4	1.6	0.8	1875	0.8	600	0.4	1750	0.4	3570	-	-	-	-	-	-	-	-	-	-	-	-
3 (m) - D	3.2	2.4	0.8	1.2	2000	0.8	800	0.4	1500	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4 (f) - D	2.8	2.0	0.8	0.8	2000	0.8	700	0.4	2250	-	-	-	-	-	-	-	-	-	-	-	-	-	-
5 (f) - D	3.6	2.0	1.6	0.8	2000	0.4	900	-	-	0.8	2520	-	-	-	-	-	-	-	-	-	-	-	-
6 (m) - C	4	2.4	1.6	0.8	1500	1.2	400	-	-	-	-	0.4	1200	-	-	-	-	-	-	-	-	-	-
7 (m) - C	2.8	2.8	0	0.8	1250	-	-	-	-	-	-	0.4	1000	0.2	3500	0.4	1750	0.2	1000	0.4	500	0.4	1000
8 (m) - C	1.6	1.2	0.4	0.8	1000	-	-	-	-	0.4	2100	-	-	-	-	-	-	-	-	-	-	-	-
9 (f) - C	3.2	2.4	0.8	0.8	1500	0.8	500	0.4	1000	-	-	-	-	-	-	-	-	-	-	0.4	350	-	-
10 (f) - C	3.2	1.6	1.6	0.8	1750	0.4	300	-	-	0.4	2100	-	-	-	-	-	-	-	-	-	-	-	-
11 (f) - C	1.2	0.8	0.4	0.4	1000	-	-	0.4	750	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Average D*	3.5	2.2	1.3	0.9	2075	0.7	720	0.5	1875	0.6	3045	-	-	-	-	-	-	-	-	-	-	-	-
Average C*	2.7	1.9	1.0	0.7	1333	0.8	400	0.4	875	0.4	2100	0.4	1100	0.2	3500	0.4	1750	0.2	1000	0.4	425	0.4	1000
Average DC*	3.1	2.1	1.1	0.8	1670	0.8	600	0.5	1542	0.5	2573	0.4	1100	0.2	3500	0.4	1750	0.2	1000	0.4	425	0.4	1000

A = Area (ha); Y = Yield (kg FM/ha); (m) = male; (f) = female; D = Duko; C = Cheyohi N.2; DC = Duko & Cheyohi N. 2; * = average calculated excluding zeros

***Table 5**: Amount of small ruminants per farm and quantities of imported feed.*

	Small ruminants (n)		*Imported feed (kg/year)*			
Farmer ID	***Goats***	***Sheep***	***Cassava peels***	***Rice chaff***	***Maize bran***	***Pigeon pea stover***
1 (m) - D	5	-	90	-	90	-
2 (m) - D	3	2	60	-	-	60
3 (m) - D	4	6	180	30	30	180
4 (f) - D	3	2	90	-	90	60
5 (f) - D	3	-	90	30	60	90
6 (m) - C	7	5	-	90	120	90
7 (m) - C	10	6	120	-	60	-
8 (m) - C	5	7	-	-	30	150
9 (f) - C	4	5	-	-	150	-
10 (f) - C	8	4	120	90	60	-
11 (f) - C	5	4	90	30	30	-
Average D	4	3*	102	12	54	78
Average C	7	5	55	35	75	40
Average DC	5	5*	76	25	65	57

A = Area (ha); Y = Yield (kg/ha); (m) = male; (f) = female; D = Duko; C = Cheyohi N.2; DC = Duko & Cheyohi N. 2; * = average calculated excluding zeros

Table 6: *Crop and crop residue yields, percentage of dry matter in yield and harvest indexes.*

Crop	Crop yields			Harvest Index	Crop residues yield (kg DM/ha)**
	kg FM/ha	% DM*	kg DM/ha		
Maize	1670[a]	87	1453	0.47[g]	1638
Groundnut	600[a]	95	570	0.38[g]	930
Soybean	1542[a]	91	1403	0.40[g]	2105
Rice	2573[a]	89	2290	0.42[g]	3162
Pearl millet	1750[a]	85	1488	0.25[g]	4463
Cowpea	1000[a]	90	900	0.27[g]	2433
Sorghum	1213[b]	90	1092	0.48[g]	1183
Bambara bean	753[b]	95	715	0.50[g]	715
Pigeon pea	1500[c]	89	1335	0.26[g]	3800
Cassava	1100[a]	38	418	0.50[g]	418
Yam	3500[a]	30	1050	0.70[b]	450
Sweet potato	1600[d]	37	1480	0.55[g]	1211
Tomato	7500[e]	6	450	0.53[g]	399
Eggplant	1000[a]	8	80	0.32[h]	170
Pepper	425[a]	16	68	0.65[b]	37
Okro	425[f]	10	42.5	0.54[b]	36

* % of dry matter in the crop product and crop residues at the moment of harvest. Crops such as grains are harvested when the crop has already lost most of its moisture content, as opposed to tubers and vegetables, in which the biomass is still relatively fresh at the moment of harvest.

** Calculated using the formula: Residues yield (DM) = Crop yield (DM) * [(1-HI)/HI]

Sources:

a) Data obtained from farmers' interviews during fieldwork (average calculated without zeros).
b) Data previously filled in on FarmDESIGN in the baseline medium resource endowed farm (Michalscheck *et al*., 2018).
c) Average from the three varieties for which yield was available (1.1 + 1.6 + 1.8)/3 = 1.5 tons/ha (Adjei-Nsiah, 2012).
d) Average of 1.6 tons/ha in the Upper-West region, where fertilizer is not applied (Bidzakin, J.K. et al. 2014).
e) Average yield of 7.5 tons, a combination of irrigated and rainfed cultivation (MoFA-IFPRI, 2020).
f) The yield of okro was assumed the same as the yield of pepper obtained from farmers' interviews during fieldwork.
g) Average HI retrieved from average values in the Harvest Index Excel file provided by WUR (see sheet "Harvest_Index_fromWUR" in the Excel file "SI_MFS_Ghana_MNSenesi_2024.xlsx").
h) Mean HI of eggplant of 0.32 (Díaz-Perez & Eaton, 2015).

Find further detailed data on the nutritional aspects of crop residues in the Excel file "SI_MFS_Ghana_MNSenesi_2024.xlsx". These values were used for the creation of the reference farm on FarmDESIGN.

APPENDIX V – ILLUSTRATIONS FOR FOCUS GROUP DISCUSSIONS

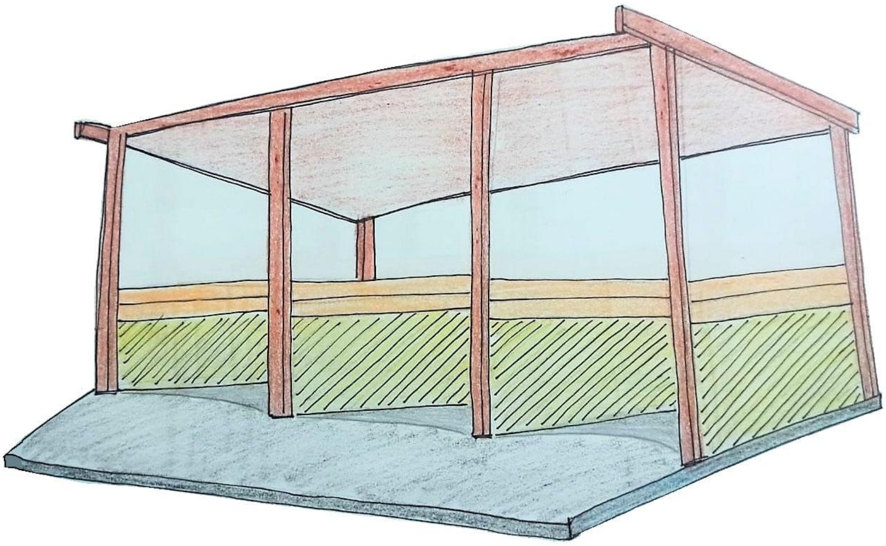

Figure 4: *Example of an aerobic composting structure (3-steps). Built with wood and concrete. Drawing based on a figure from Kurtz (2023).*

Figure 5: *Example of a simple cellar silo for making silage, built with metal and concrete. Drawing inspired by a figure from the Treccani (n.d.) definition of silo, as well as other online figures of silos and storing facilities.*