Exploring socio-ecological niches for forages in climate-smart dairy systems in Rwanda

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Abstract

Land scarcity and seasonal feed deficit are the main constraints to increase milk productivity in crop-livestock systems in Rwanda. Improved forage technologies can not only narrow the feed gap during the dry season, but also contribute to the reduction of enteric methane emissions. There are various forage technologies on hand but the adoption often remains low because they might not fit into the respective contexts. In this study, we used farming systems characterization and the agro-ecological and socio-economic characteristics of the forage technologies to quantitatively evaluate their suitability in socio-ecological niches in three agroecological zones in Rwanda. Impacts on milk yield and enteric methane emission for scenarios of grass and legume integration in banana fields were simulated through the Ruminant model. Forage-niche matching results show that the variation in socio-ecological suitability is largely determined by the household's labour and land availability, income, and the yield of the forage. In comparison to other plants, *Pennisetum purpureum* had a fairly consistent high score across all niches. *Desmodium intortum* had high average scores in the three sites, while *Brachiaria brizantha* had the lowest scores. The Ruminant model results further confirmed the impacs of matching forages to a socio-ecological niche. Integrating forages in the socio-ecological niches had raised average milk production from 2.8 l/day to 3.9 l/day when matching with grass, and to 4.2 l/day with legume. At the same time, enteric methane emission intensity reduced from 83.7 l CH_4/l milk to 44.8 l CH_4/l milk and 40.3 l CH_4/l milk respectively. The study has provided a method for operationalizing the socio-ecological niche concept on matching forages to the niches. It further showed that improving livestock diets through matching forages to the socio-ecological niches can increase milk yield while reducing enteric methane produced per liter of milk.

Keywords: Climate-smart dairy systems, smallholders, forage intensification, socio-ecological niche, intercropping, agro-forestry

1. Introduction

1.1. Opportunities and challenges in livestock farming systems

Progress towards higher agricultural productivity has been made in the past few decades. Agricultural development has created benefits in multiple aspects. It provides job opportunities, with around 24.5% of the world employment are in agricultural sector in 2020 (World Bank, 2020). It feeds the increasing food demand from the growing population. Agricultural research and development draws attention to opening market access and constructing infrastructures in rural areas (Cunguara & Darhofer, 2011). Nonetheless, the industrialized agricultural system evolves at a cost to social and environmental conditions such as unequal spatial and temporal distribution of food, low women welfare, water pollution, biodiversity loss (FAO, 2018). In the year 2010, non-CO_2 greenhouse gases (GHG) emitted from agricultural, forestry and other land use sector took up 24% of the total emission (IPCC, 2014), ranking the second largest contributor. Within the agricultural sector, enteric fermentation and manure management from livestock represented over a quarter of the methane (CH_4) emission (EPA, 2018).

Even though livestock rearing is a major source of GHG emission, it is important in the agricultural sector in Sub-Saharan Africa, contributing to nutrition security and rural livelihoods (Otte & Chilonda, 2002). In Rwanda, around 80% of the smallholder farmers keep livestock, especially cattle, for various purposes. Farmers deem cattle not only as a source of protein and of income, but also as an attribute to social status. It is also used as a capital asset and for draught power. In addition, livestock as part of the agroecosystem, accelerates nutrient cycling (Herrero et al., 2013). In Rwanda, many policies and reforms have been implemented to get the most out of livestock rearing, such as Girinka (also known as "one cow per poor family") and improved feeding, both of which have proven to be very effective. However, current livestock production is still lower than the attainable yield (Umunezero et al., 2016). Deficits in feed quantity caused by land scarcity have been identified as the largest constraint to animal production improvement (Klapwijk et al., 2014; Shapiro et al., 2017). Feed deficits occur especially during the dry season (June to September), where almost no rainfall occurs. However, crop-based food and feed production is excessive in the long rain season. Strong seasonality in feed production was also reported in other studies (Umunezero et al., 2016; Paul et al., 2020). To compensate the limited production, some farmers make use of crop residues from home-grown crops as well as purchases from industrial by-products, which are expensive and with low nutrient values. Furthermore, low productivity and environmental degradation have been reported by farmers (Paul et al., 2018). Therefore, finding solutions to close yield gaps with improved land use efficiency and mitigated environmental impacts is crucial.

1.2. Attempts to sustainable livestock production systems

Climate-smart agriculture (CSA) is one of the approaches to address sustainability issues in livestock production systems A CSA baseline study in Rwanda has been conducted by the International Center for Tropical Agriculture (CIAT) and the World Bank to show the potential of CSA as an agricultural transition approach (World Bank & CIAT, 2015). The approaches to combat temporal variation in feed supply and lack of high-quality feed has been widely researched (Romney et al., 2003; Hassen et al., 2017; Paul et al., 2020). There are two broad forage-based strategies to fill the seasonal feed gap: conserving excessive rainy season feeds for the dry season and increasing forage production in the dry season. Forage conservation techniques were conveyed to farmers by trainings and a manual (Lukuyu et al., 2012). However, low use of conserved feed was still reported in Nyagatare district (Mazimpaka et al., 2017), possibly owing to their limited feed production at the first place (Mutimura et al., 2013). For the second strategy, research on high-yield tropical forage species has been conducted extensively on different types of forages: grasses (such as *Pennisetum purpureum* and *Brachiaria* hybrid cv. Mulato II), herbaceous legumes (Baudron et al., 2014), and tree legumes (such as *Leucaena leucocephala*, Shelton & Brewbaker, 1994). Most of them have been proven to have multiple benefits for household economics, forage productivity and quality, soil quality, food crop productivity, and livestock productivity depending on types of technologies (Paul et al., 2020).

1.3. Tailoring forage technologies to the diverse farming systems

Not every technology is perfect for all sites and farming systems. As an example, the yields of climbing beans differed among farms' resource endowment types because of their limitation in choosing stacking materials (Descheemaeker et al., 2019). To help select proper forage species for a specific agro-ecological condition, tools have been developed for screening the abundant tropical forage species (https://www.tropicalforages.info/text/intro/index.html). In addition to the biophysical environment, the socio-economic and cultural environment such as labour availability and household's financial condition also determine whether a forage technology is suitable for on-farm integration. Misplacing forage technologies into the wrong socio-economic context is one of the reasons why improved forages are still not widely adopted by farmers. Forage technology adaptation research is abundant but joint analyses of biophysical and socio-economic aspects of farms are scarce. The socio-ecological niche concept proposed by Ojiem et al. (2006) for pairing legume technologies with suitable smallholder farming systems in western Kenya has provided a good example to match technology with specific niche considering agro-ecological and socio-economic environment collectively. It is an extension of the ecological niche that uses socio-economic factors as one of its boundaries. The concept was further practiced by Descheemaeker et al. (2019), who proved tailored options selected through the socio-ecological niche approach performed better than the non-tailored ones. Paul et al. (2016) assessed agro-ecological adaptation of improved forages as well as a participatory research to understand farmers' decision on which forage and how it was integrated into their own production systems. Bucagu et al. (2013) used the concept to study farmers' interest in agroforestry in terms of tree species, management practices, and on-farm location for implementation. Despite all the efforts in operationalization, the approaches and criteria boundaries were vaguely set.

2. Objectives

Preliminary niches were identified and characterized for potential forage production nationwide by Umunezero (2016), including marshy areas, woodlots, intercropping, farm boundaries, soil erosion control structures, cropped land, and lowland and drier areas. However, a localized characterization and assessment of the practicality of utilizing these niches has not been researched. Therefore, the aim of this research is to further characterize the socio-ecological niches for forage integration in the study sites and match them with the best-bet forage species to determine whether it can narrow the feed gap of dairy cows during the dry season. It is achieved by addressing the following subsidiary objectives:

1) Identifying and characterizing socio-ecological niches for forage integration to supplement the existing feed basket.
2) Matching forage species to the socio-ecological niches for filling the feed gap of dairy cows;
3) Quantifying the impacts of filling the forage niches on milk productivity and enteric methane emission intensity at farm level across the three agro-ecological zones.

Since socio-ecological niches are shaped by a broader context (i.e. market, institution and policy) where social interactions play a substantial role, mixed methods (socio-economic household survey and quantitative modelling) will be used to address the research question. Niches and their contexts were described and explained through the socio-ecological niches approach, while the ex-ante impact assessment of the forage interventions at farm level was conducted using a quantitative modelling approach. The results of this research may provide a scope for 1) farmers to decide whether the forage integration could achieve their own production objectives, 2) extension services to give more accurate advice on adopting forage technologies.

3. Materials and methods

3.1. Study sites and farming system selection

The study was conducted in three districts in Rwanda: Burera, Nyagatare, and Nyanza. They are located in the three agro-ecological zones (AEZs) in Rwanda, Eastern Africa: Buberuka Highland (AEZ 1), Eastern Savanna (AEZ 2), and Central Plateau (AEZ 3), respectively (Figure 1). The three AEZs show a gradient in temperature, annual precipitation and elevation within Rwanda (Table 1). Buberuka Highland is more prone to soil erosion than the other two because of its higher average precipitation and steeper slopes. Soil in the Central Plateau is generally more suitable for a wide range of crops than the Eastern Savanna which is characterized by scattered indigenous acacia trees on farm (Iiyama et al., 2018). Though annual precipitation varies among AEZs, they generally have four seasons: short dry season (January to February), short rain season (March to May), long dry season (June to August), and long rain season (September to December).

The majority of Rwanda is covered by rain-fed sub-humid/humid or temperate/highland areas (Paul, 2020). The main crop production for home consumption includes maize, bean, plantain banana, cassava, sweet potato, and Irish potato. In addition to food crops, Napier grass is commonly grown though with limited land allocation. Ruminants such as local and cross/improved cow, sheep, and goat are more popular in the districts than non-ruminants. Natural grass and Napier grass are both basal feeds in the three districts, though pastures in Nyagatare were found to have more diverse forage species (CIAT, 2018). Burera and Nyanza were practicing zero-grazing system due to the Zero Grazing Program encouraged by The Government of Rwanda, while Nyagatare was under extensive to semi-intensive grazing system. Demographically, Burera was more densely populated, with a population density of 522 inhabitants per km^2 (NISR, 2012), than Nyanza (482 inhabitants per km^2) and Nyagatare (242 inhabitants per km^2). Economically, they were both regarded as the city center of its province. However, Nyanza has a lower percentage of population identified as poor (38.0%), while this number is 50.4% in Burera and 44.1% in Nyagatare (NISR, 2015).

A socio-economic baseline survey of 36 households (12 from each district and from 2 villages in each district) has been conducted before this study by the CIAT project 'Climate-smart dairy systems in East Africa through improved forages and feeding strategies'. It is a detailed household survey covering multiple dimensions for characterizing a farm (i.e., farm size, land use, agricultural products and activities, farm assets, nutrition security, and group memberships etc. in the year 2018). The households were selected within Innovation Platforms, which are farmer groups or primary societies in the AEZs who are willing to participate in the project. Small to medium size smallholder farms with similar age distribution in the households were selected (Nyangaga, 2019). For this study, four farms were excluded because there was no milking cow on-farm at the time of the household survey was done. Eight farms were excluded because there were no crossbred female cow on farm. For identifying and charactering on-farm forage niches and assessing potential impacts, six farms (two from each district) were selected as representatives for the district with average farm size, household size, and number of ruminants in their districts.

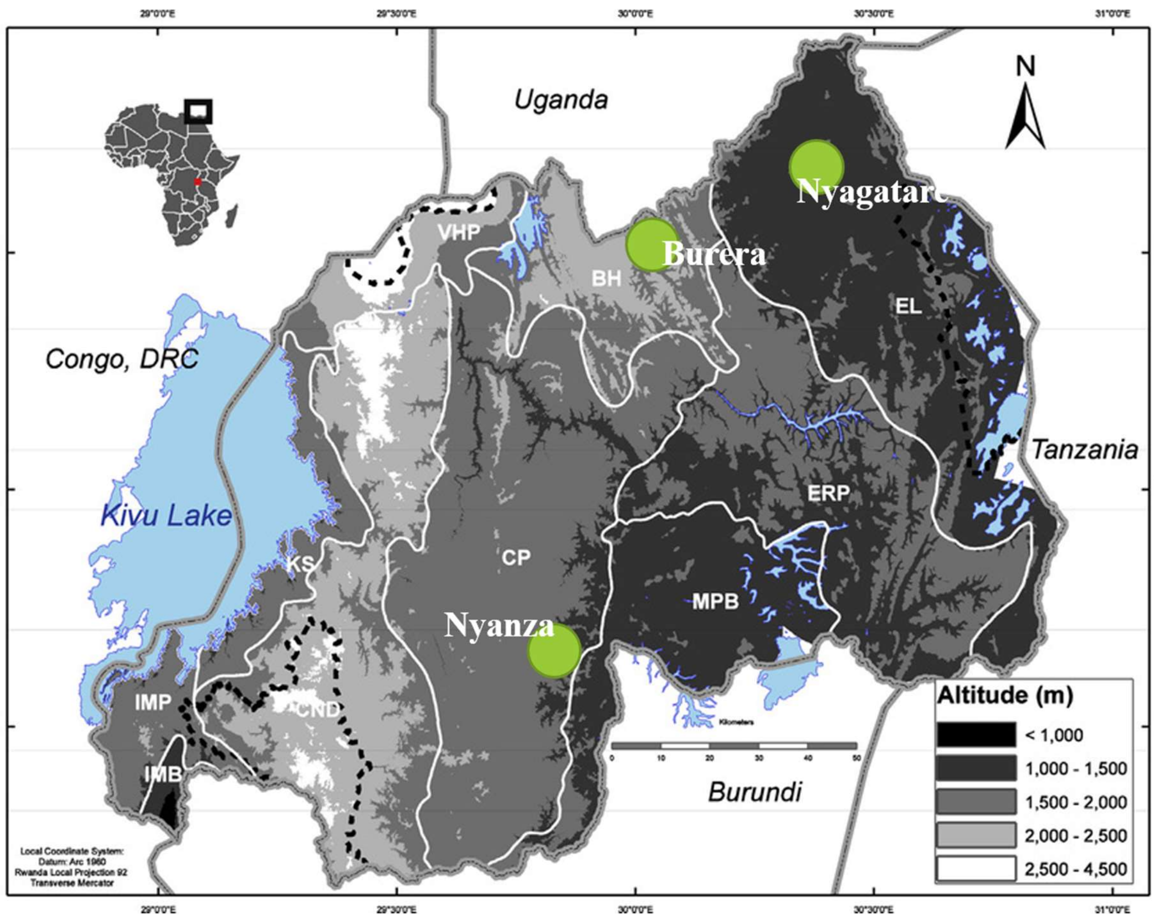

Fig. 1. A map of the three study districts and their locations in the AEZs. Sourced from Mukashema et al. (2014).

Table 1. AEZ-level variables between the study areas.

	Burera (AEZ 1)	Nyagatare (AEZ 2)	Nyanza (AEZ 3)
Regional physical			
Sector	Nemba	Tabagwe	Rwabicuma
AEZ classification	Buberuka highland	Eastern savanna	Central plateau
Grazing system	Zero grazing	Extensive/semi-intensive grazing	Zero grazing
Annual precipitation[1] (mm)	1200-1300	800-1000	1000-1500
Temperature[1] (°C)	15-18	>21	18-20
Elevation[1] (m above sea level)	1900-2000	1200-1400	1100-1700
Soil characteristics			
Texture[2]	Silty clay loam	Loam	Loam to silty clay loam
pH (H_2O)[3]	6.2	5.9	5.1
C[3] (%)	4.65	2.86	1.49
N[3] (%)	0.47	0.22	0.13
P[3] (ppm)	25.13	45.28	7.50
Demographic			
Population density[4] (inhabitants per km^2)	522	242	482
Number of members per household	5.8	6.5	5.1
Farming system			
Farm size	0.74	4.22	1.55
Number of cow	1.5	4.5	2.2
Main cultivated crops	Maize, common bean, Irish potato	Maize, Common bean, banana	Common bean, sorghum, banana

[1]Annual precipitation, temperature, and elevation are derived from Iiyama et al. (2018).

[2]Soil texture was determined visually on a soil data map derived from the ISRIC Soilgrids. (https://maps.isric.org/mapserv?map=/map/wrb.map) in ArcGIS.

[3]Secondary data from literatures. Data of Buberuka highland and Eastern savanna was derived from soil samples in Burera and Bugesera district respectively (Reckling, 2011); data of Central plateau was derived from Simbi district (Bucagu et al., 2014).

[4] Rwanda 4th Population and Housing Census, 2012 (NISR)

Other parameters are mean values obtained from the household survey (N=36).

3.2. Conceptual framework

To capture the farm heterogeneities in the study areas, the socio-ecological niche concept (Ojiem, 2006) was used in the study to guide the data collection for forage niche characterization and matching for optimal forage-niche combination. Adapting from his socio-ecological niche framework, six criteria influencing the forage integration suitability were identified (Table 2). The criteria have set boundaries limiting the choice of forage varieties of a household. Determinants or boundaries defining each criterion were selected through reviewing theories from previous research.

Criterion 1: Agro-ecological environment

Regional agro-ecological environment predominantly determines the adaptability of a forage species into the farming system. Significant variations in dry matter yield, plant height, germination rate, and biological nitrogen fixation of legume forages were found in different agro-ecological zones (Paul et al., 2016; Ojiem, 2006; Davey & Simpson, 1990). Therefore, agro-ecological characteristics including elevation, average annual precipitation, annual temperature, soil pH, carbon, nitrogen, and phosphorus content were chosen to describe the forage niche.

*Criterion 2: Cultural environmen*t

Type of livestock rearing system influences farmer's habit in livestock feeding, determining how much farmer prefer to integrate forages in their farm. In extensive grazing systems, planting forage on-farm is less preferred by farmers (Paul et al., 2016). Forage plants are also incorporated into livestock production systems in various ways. A review by Rao et al. (2015) indicates that grasses are commonly used in grazing systems or making processed feeds, while legumes have less application in processing feed. Moreover, forages that can survive in treading and manure patches would be more adaptive in extensive grazing systems than those does not.

Criterion 3: Socio-economic environment

In this research, the distance to the market refers to the geographical distance from the observed farm to the nearest market that trades crop and livestock. As an alternative, if data is available, distance to a market can be characterized collectively as travel time to market, taking account the facilitation by intermediate agencies (Staal et al., 2002). Markets interact with crop-livestock systems by exchanging crop and livestock products with food, feed, and cash. Having access to markets for forage or animal products can increase the adoption of improved forages even if the farm is less unlikely an adopter (Gebremedhin et al., 2003).

Criterion 4: Institutional support

Institutional support such as adequate extension services, well-developed seed dealerships, supportive policies and subsidies facilitates the diffusion of the improved forage technologies, especially those with higher integration complexity (Rudel et al., 2015). For example, transitioning to legume-Brachiaria systems might not only introduce a new crop variety but often needs a series of changes like new management in the cropping systems.

Criterion 5: Production objectives

Borrowing the on-farm survey results from the study in Kenya (Ojiem, 2006) into our research context, we assume that farmers integrate forages on farm out of their interests in feeding livestock and producing food. Biomass production was reported by Paul et al. (2016) as the top criterion for farmers to plant forages among farmers in Sud-Kivu, DR Congo. Metabolizable energy (ME) and metabolizable protein (MP) in forages strongly determine their nutritional value. Taking into account the objectives of climate-smart agriculture, quantifying methane emission from enteric fermentation is also important to characterize a forage niche. Enteric methane production is affected by the content of structural carbohydrates in the plant-based feeds, which can be measured by the neutral detergent fiber (NDF) (Moe & Tyrrell, 1979).

Criterion 6: Farm production environment

According to Gebremedhin's analysis on determinants of improved forage adoption, labour availability and land availability have positive influence on adoption rate and intensity (Gebremedhin et al., 2003). Households with larger farm area are more willing to adopt a new technology because there is more spare land.

Forages not only differ in DM yield in relation to agro-ecological conditions, they also have their specialties in filling the milk yield gap and accomplishing farmers' objectives. For example, legume forages have higher protein content than grass forages because of their nitrogen-fixing ability. Thus, legume can supplement grass-based diets with high protein content when protein supply is low. By comparing the forage characteristics and the boundaries of a niche, scores were given to the proposed forages to quantitatively predicting the suitability of its integration into the niche (see Section 3.4. for details on matching).

3.3. Identifying and characterizing niches

Rapid farming systems characterization can identify the regional enabling factors and constraints (Descheemaeker et al., 2016). In this study, a rapid farming systems characterization was conducted with the average values from the survey of 36 household. Differences among districts in farm size, household size, number of cow, and crops in different seasons were compared using the data retrieved from the household survey. Woodlots, banana (*Musa* spp., including cooking banana and fruit banana), and Napier grass (*Pennisetum purpureum*) were identified as the on-farm niches for forage production Though contributing greatly to the DM in the feed basket, it is low in protein content. Shifting from Napier grass in pure stands to grass-legume intercropping shows potential in increasing milk yield, thus it is identified as an on-farm niche in this study. To validate the status of these niches in our study sites, the percentage of the farm area allocated to each niche to the total farm area was calculated per farm. Borrowing the definition of social norms (Bicchieri et al., 2018), forage planting norms are behavioral patterns of how farmers normally interact with forages. Regional variation in forage planting norms can be distinguished by detail on-farm survey (Ojiem, 2006). Participatory evaluation was used by Paul et al. (2016) to identify farmers' preferences on on-farm forage planting. In this study, norms of on-farm forage planting were indicated through the area and percentage of land planted with Napier grass, input, labour, and its distance from homestead. Climatic and soil information were collected from literatures or geographic maps from the International Soil Reference and Information Centre soil database (ISRIC Soilgrids).

At farm level, baseline characteristics of the 6 selected farms throughout a year were investigated through detailed farm characterization. Household labour availability was calculated by multiplying the number of household members working on-farm with 249 working days and 8 hours per day. Working hours for off-farm employment during the dry season were subtracted. Hired and unpaid laborers were not included in the household labour availability. Net farm income was calculated by the sum of livestock and crop product sales minors the costs on crop and livestock production and costs on hiring off-farm laborers (including permanent and temporary employments). Off-farm cash flows were not recorded by the survey, therefore these were not included in total net farm income calculation. Milk production and enteric methane emission intensity were simulated through the Ruminant model (Herrero, 1998) using the feed basket composition in the household survey. Due to inadequate records on feed quantity and milk production in different lactation periods, feed quantity was estimated by the dry matter (DM) intake capacity (DMI) in relation to cow body weight (BW=250 kg, DMI=3% BW in long rainy season, DMI=2% BW in short rainy and short dry season, DMI=1.5% BW in long dry season). The DM quantity of each feed in the feed basket was estimated by multiplying the total feed quantity by the percentage of each feed in the basket. The baseline of daily milk yield and methane emission were generated from the estimated feed quantity using the Ruminant model (Herrero, 1998). Feed parameters were calibrated using the nutrient values from Feedipedia and from Shikuku et al. (2017).

3.4. Matching forages and niches

The information collected from the 6 selected farms was used to evaluate niches' boundary for forage integration according to Table 2. Each niche characteristic was given a condition of constraining, medium, or facilitating the forage integration. It sets the socio-ecological niche boundaries for matching forages and niches. Table 4 provides a list of suitable forage species/varieties and their yield range for each AEZs based on the results from demonstration plot, on-farm trial results, and farmers' report. Forage characteristics such as agro-ecological distribution (elevation, annual precipitation, annual temperature, soil pH, and soil fertility), common utilization in livestock systems, yield range, DM content, protein content, NDF content, water requirement, compatibility with the main crop, and shade tolerance of the forages were obtained from Feedipedia and Tropical forages (https://www.tropicalforages.info/). These data were used for evaluating the level of demand of each forage variety from the niche environment according to the criteria in Table 3. Comparative labour requirement in each niche were gathered through interviewing forage specialist in Rwanda for the reason that recording actual labour investment for each species and forage-niche combination is time-consuming. More importantly, some combinations were not practiced in the existing households. Only estimations can be given. The scores from each criterion were summed. Therefore, in total 58 forage-niche combinations had their final matching score.

To quantitatively evaluate the level of match of the forage-niche combination, scores were given to each forage species in the three selected niches following the niche characteristics shown in Table 2. Score of 1 to 3 was given to each characteristic. Score of 3 means a high match between the forage and niche, 2 means medium match, 1 means low match.

For agro-ecological supply and demand, the conditions were not judged. A score of 3 was given to a combination when the agro-ecological demand from the forage is within the agro-ecological condition of the niche. It received a score of 2 if the forage demand is different from the agro-ecological condition of the niche but sometimes found in those regions. A score of 1 was given to the combination in which the forage variety is rarely distributed in the regions with similar agro-ecological conditions as the niche. Scoring of the other characteristics followed the rules below.

A characteristic of forage-niche combination is given a score of 3 when:

1) The niche has facilitating boundary for forage-integration and the forage species have a high/medium/low demand in the corresponding characteristic.
2) The niche has medium boundary for forage-integration and the forage species have a medium/low demand in the corresponding characteristic.
3) The niche has a constraining boundary for forage-integration and the forage species have a low demand in the corresponding characteristic.

A characteristic of forage-niche combination is given a score of 2 when:

1) The niche has medium boundary for forage-integration and the forage species have high demand
2) The niche has constraining boundary for forage-integration and the forage species have medium demand

A characteristic of forage-niche combination is given a score of 1 when:

1) The niche has constraining boundary for forage-integration and the forage have high demand

Table. 2. Main niche characteristics and criteria for diagnosing its boundary of forage integration. "Facilitating" means the niche condition of that criteria is desirable for on-farm forage integration. "Constraining" means the niche cannot provide the desirable condition for forage integration. "Medium" refers to the condition in between "facilitating" and "constraining". Agro-ecological conditions were not evaluated as their level of supply is species-specific.The table is adapted from the socio-ecological niche concept framework by Ojiem (2006).

Niche characteristic	Niche boundary for forage integration		
	Constraining	Medium	Facilitating
Criterion 1: Agro-ecological conditions			
Elevation			
Annual precipitation			
Annual temperature	-	-	-
Soil pH			
Soil fertility			
Criterion 2: Cultural environment			
Norms on forage planting	No forage is planted on farm	Percentage of area allocated to forage production < 5%	Percentage of area allocated to forage production ≥ 5%
Livestock feeding habit	Extensive grazing	Semi-extensive grazing	Zero grazing
Criterion 3: Socio-economic environment			
Distance to the market	No market available	Market available at large distance (> 3 hours travel)	Market available at short distance (< 3 hours travel)
Income and capital[1]	≤ 500 USD/year	> 500 USD/year and ≤ 1000 USD/year	> 1000 USD/year
Household labour availability[2]	≤ 4482 hour/household/year	> 4482 hour/year and ≤ 6474 hour/household/year	> 6474 hour/household/year
Criterion 4: Institutional support			

Frequency of extension services	No extension services	Scarce extension services	Frequent and competent extension services are available
Seed/planting material accessibility	No access to improved seed/planting material	Have access to improved seed/planting materials of limited varieties	Have access to improved seed/planting materials of various varieties
Criterion 5: Production objectives			
Food security[3]	Severely food insecure	Moderately to mildly food insecure	Food secure
Feed availability	Feed deficit ≤ 1 month	Feed deficit > 1 month and ≤ 2 months	Feed deficit > 2 months
Feed quality	Sufficient feed quality is supplied	ME or MP is limiting	ME and MP are both limiting
Enteric methane production intensity[4]	≤ 131 L CH4/L milk	> 131 and ≤ 160 L CH4/L milk	> 160 L CH4/L milk
Criterion 6: Farm production environment			
Land availability	Farm land area per household member ≤ 0.1 ha/household member	Farm land area per household member > 0.1 and ≤ 0.2 ha/household member	Farm land area per household member > 0.2 ha/household member

Water availability	Water shortage and no irrigation	Sufficient rainfall, no irrigation	Generally favorable water availability, and be supplemented with irrigation in case of drought.
Crop compatibility	The crop is highly competitive	The crop can maintain its yield with another crop	The crop is not competitive and yield will strongly reduce with another crop
Shade	The existing crop provide shade that doesn't allow the targeted forage to survive	The existing crop provide shade that allows the targeted forage to survive though with compromised yield	The existing crop provide optimal shade condition to the targeted forage

[1]Total value of the household produced and off-farm income. Classified according to farm typology result from Hammond et al. (2020).

[2]Calculated from the average person available as labour force per household*239 working days/year*8 hours/day ± 1 person. Population data were obtained from NISR (2012).

[3]Food security is indicated by the Household Food Insecurity Access Scale (HFIAS) developed by USAID (Jennifer et al., 2007).

[4]The value represents the average level of methane emission from enteric fermentation of a dairy cow in Africa, calculated from Tier 1 enteric fermentation emission factor (46 kg CH_4/head/year with average milk production of 475 kg/head/year) suggested by IPCC (2006).

Table. 3. Main forage characteristics and criteria for evaluating its level of demand from the environment. "High", "Medium", and "Low" mean the forage have a high, medium, or low demand from the condition of the environment. Level of demand from agro-ecological condition were not evaluated solely on the forage characteristics as it can be only judged together with niche characteristics.

Forage characteristic	Corresponding niche characteristic	Forage demand		
		Low	Medium	High
Criterion 1: Agro-ecological condition				
Elevation	Elevation	-	-	-
Annual precipitation	Annual precipitation			

Annual temperature	Annual temperature			
Soil pH	Soil pH			
Soil fertility	Soil fertility			
Criterion 2: Cultural environment				
Frequency presented in feed basket	Norms on forage planting	Being planted on-farm and frequently presents in the feed basket	Sometime presents in the feed basket in a small amount	Never presents in the feed basket
Intended forage use	Livestock feeding habit	Can be used in pasture, cut-and-carry		Have only one intended use or can only be fed freshly
Criterion 3: Socio-economic environment				
Market value	Distance to the market	Mainly for on-farm utilization		Marketable
Purposes of the forage	Income and capital	Can be used as feed, mulch, fuel wood and more	Can be used as feed and mulch	Only used as feed
Labour requirement	Household labour availability	Require less effort per ha than planting Napier grass	Require similar effort per ha as planting Napier grass	Require higher effort per ha than planting Napier grass
Criterion 4: Institutional support				
Complexity of the technology	Frequency of extension services	Simple innovation such as substitution of another crop		Complicated innovation that requires systemic changes

Seed/planting material accessibility	Seed/planting material accessibility	Commercially available or can be propagated by farmers	Commercially available but difficult to buy	Not commercially available
Criterion 5: Production objectives				
Food production	Food security	Edible		Not edible for human
Biomass yield	Feed availability	Average yield > 20 t DM/ha	Average yield ≤ 20 t DM/ha and > 10 t DM/ha	Average yield ≤ 10 t DM/ha
Protein content	Feed quality	CP content > 100 g/kg		CP content ≤ 100 g/kg
NDF content	Enteric methane production intensity	NDF content < 400 g/kg DM	NDF content ≥ 400 g/kg DM and <600 g/kg DM	NDF content ≥ 600 g/kg DM
Criterion 6: Farm production environment				
Yield per unit of land area	Land availability	Average yield > 20 t DM/ha	Average yield ≤ 20 t DM/ha and > 10 t DM/ha	Average yield ≤ 10 t DM/ha
Water demand	Water availability	Can tolerate dry season for more than three months	Can tolerant dry season for less than three months	Requires regular irrigation
Crop compatibility	Crop compatibility	Can grow with most of the crops	Can grow with limited types of crops (e.g. only grasses or legumes)	Not commonly grow with another crop
Shade tolerance	Shade	Can tolerant heavy shade	Can tolerant light shade	Full light

Table 4. Selected forage species of the three AEZs with yield range in t DM/ha. Yields range of *Brachiaria brizantha and Panicum maximum* were obtained from Ohmstedt & Mwendia (2018). Others were obtained from Feedipedia.

Burera (AEZ 1)		
Promising species	Forage type	Yield range (t DM/ha)
Pennisetum purpureum French Cameroon	Grass	20-80
Brachiaria brizantha	Grass	10-18
Calliandra calothyrsus	Tree legume	7-20
Desmodium intortum	Herbaceous legume	12-19
Nyagatare (AEZ 2)		
Promising species	Forage type	Yield range (t DM/ha)
Pennisetum purpureum Kakamega 1	Grass	20-80
Brachiaria brizantha	Grass	10-18
Tripsacum laxum	*Grass*	18-22
Chloris gayana	Grass	10-16
Panicum maximum	Grass	20-40
Mucuna pruriens	Vine legume	10-35
Desmodium intortum	Herbaceous legume	12-19
Medicago sativa	Shrub legume	8-15
Leucaena leucocephala	Shrub legume	3-30
Nyanza (AEZ 3)		
Promising species	Forage type	Yield range (t DM/ha)
Pennisetum purpureum Kakamega 1	Grass	20-80
Brachiaria brizantha	Grass	10-18
Setaria sphacelata	Grass	10-18
Desmodium intortum	Herbaceous legume	12-19

3.5. Forage integration scenarios

Productivity and environment are two common domains for assessing farm sustainability (Marinus et al., 2018). Considering households' objectives on farming activities and the aims of climate-smart agriculture, milk yield per day and enteric methane emission intensity were selected as indicators to assess the performance under each domain. Following a similar method in baseline simulation, milk yield and methane emission from the scenarios were simulated by the Ruminant model.

Two scenarios with forage integration were simulated for banana field (Table 5) to quantitatively examine the utility of operationalizing the socio-ecological niche concept and potential impacts from forage integration. In the grass integration scenario (GI), the grass forage with the highest matching score was added into the current feed baskets as supplement to lactating dairy cow (the initial quantity of each feed composition remain unchanged). Forage DM production was assumed to be differ between rainy and dry seasons where the highest recorded yield was used to calculate the daily feed supplement in long and short rain seasons and the lowest yield was used for long and short dry seasons. In the legume integration scenario (LI), the legume forage with the highest matching score was added to the feed basket with the same method as in GI.

Niche areas were estimated based on the available household survey. Forages were integrated into the cropping system by intercropping (or as understory crop in agroforestry system). Forage yield (FY) in DM of the integration was calculated as:

FY in banana intercropping niche (kg DM) =50% of banana field area (ha) x forage yield (kg DM/ha)

The calculation was suggested by Umunezero et al. (2016) and was adapted to our study sites and assumptions. It was assumed that 50% of the banana field area would be available for forage plantation. We also assumed that there is no plant-plant interactions other than a shading effect from the other crop after forage integration. In this study, shading effect was avoided by limiting the available area for forages (i.e. only 50% of the banana field area can be available for forage integration).

Table 5. Current dairy cow feed baskets and scenarios. Only forage-banana niche was assessed. BU, NG, NZ refer to Burera, Nyagatare, and Nyanza districts respectively. GI is grass-integrated scenario and LI is legume-integrated scenario. LR, SR, LD, SD refer to long rain season, short rain season, long dry season, and short dry season respectively.

	Feed composition	LR	SR	LD	SD
	BU2				
Baseline feed basket	Natural grasses (kg DM/day)	8.2	6.5	4.0	6.5
	Napier grass (kg DM/day)	1.6	1.1	2.0	1.1
	Maize stover-green (kg DM/day)	4.9	2.2		2.2
	Banana trunk/leaves (kg DM/day)	1.6		1.2	
	Pulse straw-dry (kg DM/day)		1.1	0.6	1.1
	Leucaena (kg DM/day)			0.2	
Scenario GI	*Brachiaria brizantha* (kg DM/day)	1.5	1.5	1.5	1.5
Scenario LI	*Desmodium intortum* (kg DM/day)	0.4	0.4	0.4	0.4
	NG1				
	Natural grasses (kg DM/day)	4.9	2.2	1.6	2.2
	Napier grass (kg DM/day)	6.5	4.4	0.8	4.4
	Pulse straw-dry (kg DM/day)	4.9			
	Maize stover-green (kg DM/day)		4.4		4.4
	Maize stover-dry (kg DM/day)			0.8	
	Banana trunk/leaves (kg DM/day)			4.8	
Scenario GI	*Chloris gayana* (kg DM/day)	0.5	0.5	0.5	0.5
Scenario LI	*Leucaena leucocephala* (kg DM/day)	0.7	0.7	0.7	0.7
	NZ1				
	Natural grasses (kg DM/day)	9.8	5.5	2.4	6.5
	Napier grass (kg DM/day)	3.3	2.7	3.2	3.3
	Setaria (kg DM/day)	3.3	2.7		1.1
	Irish potatoes vines (kg DM/day)			2.4	
Scenario GI	*Pennisetum purpureum* (kg DM/day)	2.1	2.1	2.1	2.1
Scenario LI	*Desmodium intortum* (kg DM/day)	0.6	0.6	0.6	0.6

	NZ2				
	Natural grasses (kg DM/day)	3.3	4.9	1.6	2.2
	Napier grass (kg DM/day)	6.5	3.3	0.8	4.4
	Pulse straw-dry (kg DM/day)	6.5			
	Irish potato vines (kg DM/day)		2.7		
	Banana trunk/leaves (kg DM/day)			5.6	
	Pulse straw-dry (kg DM/day)				4.4
Scenario GI	*Pennisetum purpureum* (kg DM/day)	3.8	3.8	3.8	3.8
Scenario LI	*Desmodium intortum* (kg DM/day)	1.2	1.2	1.2	1.2

Statistical analyses were conducted to compare the significant difference between baseline and scenario values using IBM SPSS Statistics 26 software. Univariate analysis of variance was used to analyze the difference in mean values among districts in the farm characterization. Paired sample T-tests were used to test statistically significant difference ($p<0.05$) between baseline farm parameters and those after forage integration.

4. Results

4.1. Baseline characteristics of the selected farms and their potential forage niches

Figure 2 shows the difference among the three districts in terms of household size, number of ruminants on farm, and total farm area. No significant difference was found in household size, which is in line with the survey sample selection intention. The average farm area per household was 0.7 ha in Burera, 4.2 ha in Nyagatare, and 1.5 ha in Nyanza. Significant difference ($p<0.005$) is found in the number of ruminants kept by the households with an average of 1.5 in Burera, 2 in Nyanza, and 8.5 in Nyagatare. There was little difference in number of crop species among districts. However, the number was lower during the dry season than the long and short rain seasons. The most planted crops in the dry season were Napier grass (52.8% of the households) and banana (including fruit and cooking banana, 50.0% of the households).

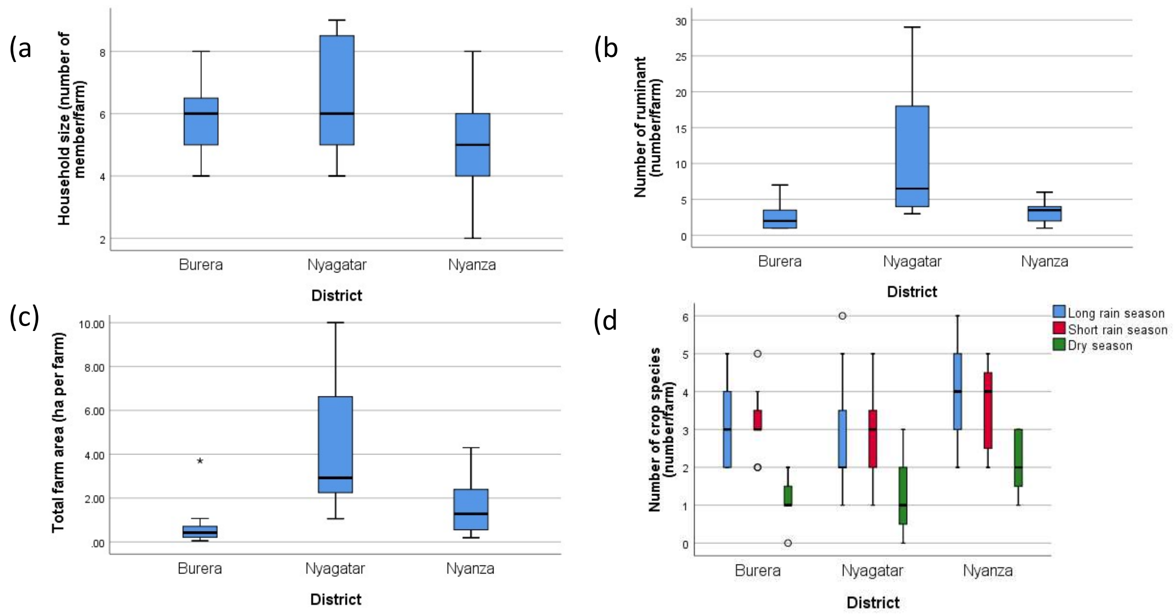

***Figure 2**.* Farming systems differences among the study districts in terms of household size (a), farm size (b), number of ruminant (c), and number of crop varieties (d). Statistical data are derived from 36 households (12 from each district. Values and details from each household see supporting information). One-way ANOVA test were conducted to compare the difference between districts. No difference in household size (p=0.125); significant difference in number of ruminants (p<0.005); significant difference in farm area per household (p<0.005).

The percentages of the farm area that were allocated to banana, woodlot, or Napier grass plantation are shown in Figure 3. Among all the households, 66.7% had plots allocated to banana. Woodlots were only found in 5 households in Burera and 6 in Nyanza. Over 50% of the households had plot for planting Napier grass, with an area ranging from 0.004 to 0.98 ha. No significant differences are found in the percentage of area allocated to banana, woodlot, and Napier grass among the districts.

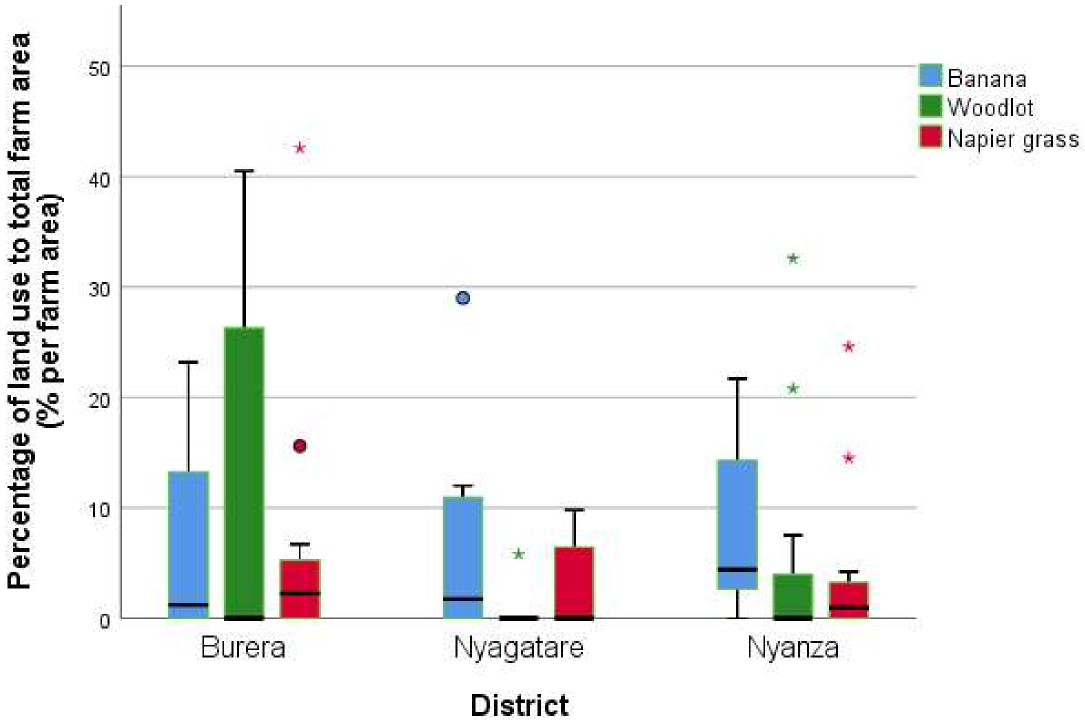

Figure 3. Percentage of the total farm area used for fallowing, banana plantation, woodlot, or Napier grass plantation.

Land scarcity has been identified as one of the characteristics in Rwanda. However, difference in cultivated area per household member shows a gradient in the severity of land scarcity. An average of 0.12 ha per household member is found while the values in Nyanza and Nyagatare are 0.32 and 0.70 ha per household member, respectively. It reveals a more acute issue in land availability in Burera. Surprisingly, intercropping was not a popular practice in all the households. One third of them has intercropped during the long rain season, among them, common bean was usually planted with maize and sometimes maize planted with a tuber crop.

Six farms were selected as prototype representing the average household size, farm area, and number of ruminants of their districts. Table 6 shows the baseline features of the selected farms from the survey data and the Ruminant model outputs. BU1 had severe land constraint with only 0.1 ha of farm area per household member. Cost of external labour was low compared to other households. The main cost was on crop production while the return from crop and livestock products were comparable. BU2 had a negative net farm income with the most cost spent on external labour and low return from livestock sales. NG1 had most of its income from crop product sales. Its high return rates from crop and livestock production contributed to its comparable net farm income. NG2 had a negative net farm income mainly due to its high cost on external labour and low return rate from crop production. In the year data was collected, the household spent 353.5 USD on marketing the crop products, which was 97% of its crop input cost. NZ1 should be highlighted for its high return from cow milk and manure production. Regarding to the household labour availability, BU1 and NZ1 had the highest supply (7968 hour/year) while NG2 and NZ2 had the lowest (3984 hour/year). Milk yield in most of the households were limited by energy intake, where protein limitation sometimes happened in the long rain and long dry season.

Table 6. Baseline features of the six study farms in Burera (BU), Nyagatare (NG), and Nyanza (NZ). Total farm area, household size, number of cow, and net farm income were calculated from household survey. Food insecurity was indicated by the answer to the question "Was there ever no food to eat of any kind in your household because of lack of resources to get food?" Milk yield and enteric methane emission intensity were generated from the Ruminant model using the feed compositions in four seasons recorded by the household survey. MP: metabolizable protein; ME: metabolizable energy.

Baseline features	Burera		Nyagatare		Nyanza	
	BU1	BU2	NG1	NG2	NZ1	NZ2
Farm physical characteristics						
Total farm area (ha)	0.81	0.61	3.06	2.78	1.20	1.36
Cultivated area (ha)	0.76	0.58	3.01	2.73	1.13	0.93
Household size (number of member)	8	6	6	6	5	4
Number of cow	1	2	5	3	4	2
Socio-economic characteristics						
Household labour availability (hour/year)	7968	6736	7968	3984	7968	3984
Land availability (ha/household)	0.1	0.1	0.5	0.5	0.2	0.3
Net farm income (USD)	180	-144	259	-189	427	139
Cost of external labour (USD)	25	184	50	253	194	265
Input cost for crop production (USD)	58	15	4	364	8	32
Input cost for livestock production (USD)	9	6	8	3	10	1
Returns from crop sales (USD)	122	58	295	385	53	172
Returns from livestock sales (USD)	150	3	21	46	586	265
Production constraints						
Food insecurity	Severe food in secure	Moderately to mildly food insecure	Food secure	Severely food insecure	Severely food insecure	Moderately to mildly food insecure
Month(s) of feed deficit	2.5	1	3	3	3	3

Water shortage (in the past 5 years)	0	0	0	0	2	0
Milk yield limiting factor						
Long rain season	ME	MP	ME	ME	ME	ME
Short rain season	ME	ME	ME	ME	ME	ME
Long rain season	ME	ME	MP	ME	ME	MP
Short rain season	ME	ME	ME	ME	ME	ME

There was no external input in any of the possible forage niche plots (Table 7). The major inputs were farmyard manure (FYM) and mulch which were both produced on-farm. The percentage of farm area occupied by the niches was small in general but showed a large range from almost ignorable to 37%. The Napier grass plot in BU1 had exceptionally high labour intensity invested mainly due to the extended days spent on harvesting, gathering the harvest, and transporting. Except for the plots that were newly established (NZ1 Napier grass and NZ2 banana), the main activities were manure application, weeding, harvesting, and transport. Mulching was specific to banana plots while transportation was more common for Napier grass. There was no obvious trend in niche type and its distance from homestead. The information on woodlot management and characteristics are lacking in the survey.

Table 7. Characteristics of the forage niches in the selected households. Only area and distance of the plot from homestead were recorded for woodlots in the survey. FYM: farmyard manure.

AEZ	ID	Niche	Area (ha)	Percentage of total farm area	Input type	Input cost (USD)	Labour intensity (hour/ha)	Distance from homestead (m)
Buberuka highland	BU1	Woodlot	0.09	11%	NA	NA	NA	400
		Napier grass	0.02	2%	FYM	0	32875	350
	BU2	Banana	0.08	13%	FYM, mulch	0	1430	0
		Woodlot	0.23	37%	NA	NA	NA	400
Eastern savanna	NG1	Banana	0.18	6%	Mulch	0	537	300
		Napier grass	0.30	10%	None	0	420	650
	NG2	Napier grass	0.20	7%	FYM	0	1636	0
Central plateau	NZ1	Banana	0.03	3%	FYM	0	5200	300
		Napier grass	0.05	4%	None	0	157	500
	NZ2	Banana	0.06	4%	FYM, mulch	0	2931	200
		Woodlot	0.01	0%	NA	NA	NA	100
		Napier grass	0.02	2%	None	0	2048	200

4.2. Matching forages to the socio-ecological niches

The total score from each forage-niche combination is shown in Tables 8 to 10. Subtotal scores on individual criteria can be found in Appendix 4.1-4.6. In general, there was little variation among the scores, ranging from 46 to 59 out of 60. Total scores under *criterion 1* were the same for each species under the same district. They showed little variations ranging from 12 to 13 in Burera, 13 to 15 in Nyagatare, and 12 to 13 in Nyanza. Therefore, variation between different niches lies in the different production objectives and farm production environment among households. Difference between forages under the same type of niche varied because of both adaptability to the AEZ and to the heterogeneity among households.The suitability of forage integration is influenced by the initial land use of the niche. Among the different land use, combination of banana field and forages had the highest average score in all districts. Intercropping Napier grass with another forage had the lowest score in every districts.

Among all the species and forage-niche combinations, *Brachiaria brizantha* received the lowest matching score. *Pennisetum purpureum* had a relatively high score in all niches compared to other grass forages, while *Brachiaria brizantha* fluctuated the most, even though they have comparable scores in fitting agro-ecological characteristics. Among all the promising species in Burera, *Pennisetum purpureum and Desmodium intortum* have the same highest average score whereas *Leucaena leucocephala* is the highest in Nyagatare.

Table 8. Matching score of the promising forage species in Burera district. WL: woodlot, NG: Napier grass, BNN: banana. *Pennisetum purpureum* is not applicable for Napier grass intercropping niche, therefore receiving no score. Values in the bracket are the subtotal score of *Criterion 1* (agro-ecological condition).

Forage species	BU1 WL	BU1 NG	BU2 BNN	BU2 WL	Mean	Standard deviation
Pennisetum purpureum	50 (12)	-	54 (12)	54 (12)	53	2.3
Brachiaria brizantha	49 (12)	48 (12)	50 (12)	50 (12)	49	1.0
Calliandra calothyrsus	53 (13)	52 (13)	52 (13)	52 (13)	52	0.5
Desmodium intortum	51 (13)	50 (13)	58 (13)	51 (13)	53	3.7

Table 9. Matching score of the promising forage species in Nyagatare district. WL: woodlot, NG: Napier grass, BNN: banana. *Pennisetum purpureum* is not applicable for Napier grass intercropping niche, therefore receiving no score. Values in the bracket are the subtotal score of *Criterion 1* (agro-ecological condition).

Forage species	NG1 BNN	NG1 NG	NG2 NG	Mean	Standard deviation
Pennisetum purpureum	55 (13)	-	-	55	0.0
Brachiaria brizantha	53 (14)	52 (14)	47 (14)	51	2.6
Tripsacum laxum	54 (15)	53 (15)	48 (15)	52	2.6
Chloris gayana	54 (15)	54 (15)	49 (15)	52	2.4
Panicum maximum	54 (15)	54 (15)	51 (15)	53	1.4
Mucuna pruriens	54 (15)	53 (15)	53 (15)	53	0.5
Desmodium intortum	54 (14)	53 (14)	50 (14)	52	1.7
Medicago sativa	54 (14)	54 (14)	53 (14)	54	0.5
Leucaena leucocephala	59 (15)	58 (15)	55 (15)	57	1.7

Table 10. Matching score of the promising forage species in Nyanza district. WL: woodlot, NG: Napier grass, BNN: banana. *Pennisetum purpureum* is not applicable for Napier grass intercropping niche, therefore receiving no score. Values in the bracket are the subtotal score of *Criterion 1* (agro-ecological condition).

Forage species	NZ1 BNN	NZ1 NG	NZ2 BNN	NZ2 WL	NZ2 NG	Mean	Standard deviation
Pennisetum purpureum	50 (12)	-	51 (12)	51 (12)	-	51	0.5
Brachiaria brizantha	50 (13)	49 (13)	49 (13)	49 (13)	48 (13)	49	0.6
Setaria sphacelata	50 (13)	49 (13)	50 (13)	50 (13)	49 (13)	50	0.5
Desmodium intortum	49 (13)	49 (13)	52 (13)	52 (13)	51 (13)	51	1.4

4.3. Assessing the impacts of forage integration through scenarios analysis

Table 11 shows the percentage changes of milk yield and enteric methane emission intensity in the two forage-integrated scenarios in the banana fields compared to the baseline feeding regimes. The average changes in milk yield increased by 129% under GI scenario and 193% in LI scenario. On average, enteric methane emission intensity would decrease in both scenarios by 28% and 35%. Seasonal variations were found in the two scenarios. In general, they boosted milk yield in all seasons, particularly during the short rainy season followed by short dry season. Under scenario GI, the largest decrease in enteric methane emission intensity was found in the long dry season. Enteric methane emission intensity has greater decrease under scenario LI than GI, however, the seasonal difference was not significant. Households experienced various consequences as a result of the scenarios. BU2 owned the highest mean increase in milk yield and the most decrease rate in enteric methane emission intensity in both scenarios. Though all the households had positive average increase in milk yield under GI scenario, decreases were presented in NG1 with the long and short rain and short dry season feed baskets. Decrease in milk yield was not found under LI scenario.

Table 11. Simulated milk yield and enteric methane emission intensity changes in the two forage-integrated scenarios compared to their baseline feed baskets. Description of the LR, SR, LD, SD and the two scenarios are presented in Table 5. Milk yield and methane were not able to be simulated for LD in BU2 because the number of feedstuff exceed model limit. The indicators in the baseline are shown in absolute values and are shown as percentage changes compared to the baseline.

Indicators	ID	Baseline				Scenario GI					Scenario LI				
		LR	SR	LD	SD	LR	SR	LD	SD	Mean	LR	SR	LD	SD	Mean
Milk yield	BU2	2.0	0.4	2.2	0.4	35.0	600.0		475.0	370.0	70.0	1050.0		800.0	640.0
(L/day/head)	NG1	4.0	3.4	0.8	3.4	-5.0	-5.9	50.0	-2.9	9.0	10.0	17.6	37.5	2.9	17.0
	NZ1	3.0	3.0	5.5	1.8	60.0	63.3	32.7	105.6	65.4	46.7	50.0	23.6	72.2	48.1
	NZ2	4.1	6.5	0.8	3.5	12.2	16.9	250.0	14.3	73.4	17.1	27.7	200.0	20.0	66.2
Mean						**25.5**	**168.6**	**110.9**	**148.0**	**129.4**	**35.9**	**286.3**	**87.0**	**223.8**	**192.8**
Methane emission	BU2	64.3	260.0	54.2	260.0	-21.5	-79.0		-78.4	-59.6	-32.2	-87.4	-100.0	-86.0	-76.4
(L CH4/L milk/day)	NG1	36.5	41.0	147.3	41.0	4.3	5.3	-26.1	2.5	-3.5	-6.3	-11.5	-24.4	-1.8	-11.0
	NZ1	48.7	46.2	28.9	68.4	-32.6	-29.7	-15.8	-43.1	-30.3	-74.6	-24.9	-12.6	-35.0	-36.8
	NZ2	34.4	25.8	142.4	40.1	-3.4	-7.2	-60.6	-9.0	-20.1	-7.3	-11.3	-56.5	-11.9	-21.7
Mean						**-13.3**	**-27.7**	**-34.2**	**-32.0**	**-28.4**	**-30.1**	**-33.8**	**-48.4**	**-33.7**	**-36.5**

5. Discussion

5.1. Socio-ecological niches differ among AEZs

On-farm pure-stand banana plot, woodlot, and Napier grass plot were identified as suitable ecological niches for forage technology integration because of their popularity in the regions and potential space for another crop. Banana planted in pure stands was found in 24 among 36 households, taking up on average 7% of the total farm area. It not only was a source of income but also provided stems and leaves as feed during the dry season. It is of higher importance to poor farmers to compensate the low forage grass production because of limited land (Klapwijk et al., 2014). Only 3 households had intercropped another crop in their banana field, and only during the rainy seasons. Therefore, planting another crop in banana fields is achievable and can provide weed control, conserve soil moisture and improve livestock diet (Tixier et al., 2011; Umunezero et al., 2016).

Households with on-farm woodlot were located in Burera and Nyanza districts. Surprisingly, the area and percentage of farm area allocated to woodlot was the highest in Burera. It is the opposite of the finding from Bucagu et al. (2013) that wealthier farms have larger woodlot areas than moderate and poor farms. Households in Burera had a poorer economic condition than in Nyanza with 54.8% and 50.2% of the population identified as non-poor, respectively. Noteworthy, on-farm forage plantation was not rare amongst the study districts, which could potentially facilitate the implementation of integrating forage on farm.

Napier grass was the most popular forage variety and one of the basal ingredients in the cow's diet (CIAT, 2018; Klapwijk et al., 2014). It can also be reflected from the fact that around half of the households planted Napier grass on their cropland. Some of the farms had already planted Napier grass with maize as intercrop during the rainy seasons. Plots planted with Napier grass took up on average 3.7% of the total farm area (n=36) in the three study districts. The total farm area planted with Napier grass was the highest in Nyagatare, however, the percentage of land allocated to Napier grass was half of that in Burera. It can be explained by the overall larger farm size and its dominated extensive grazing system. This Napier grass planting regime can possibly enable the development of socio-ecological niche for forages by familiarizing farmers with forage planting practices especially grass forage similar to Napier grass.

Though the above on-farm locations were ecologically suitable for forage integration, their suitability as socio-ecological niches varied because of the diverse social and economic conditions. In Burera, farm area was significantly smaller than the other two districts due to the highest population density and land fragmentation, indicating that land scarcity was stronger constraint in Burera than in the other two districts. Despite land scarcity, its soil erosion rate is much higher due to the hilly topography and higher annual precipitation (Karamage et al., 2016). Therefore, efficient while sustainable land use should be emphasized. One of the universal approaches to overcome land scarcity is to increase productivity per ha of land (van der Lee et al., 2016). Zero-grazing is encouraged in Burera and Nyanza by the Rwanda government. The on-farm forage niche development can be encouraged by the less time spent on cut-and-carry for stall-feeding. Intensifying crop production by intercropping a forage is another approach to improve land productivity. Without changing the current cropping plan, high yield and high quality forages from on-farm production can be added into the diet. This intensification scenario is assumed to increase milk yield of crossbred cow by 81% (Paul et al., 2018).

Given these two main limitations in Burera, forage integration as intercrop or understory species in agroforestry system can carry out multiple benefits. Productive forages that can withstand seasonal high precipitation, such as *Desmodium intortum,* and forages with significant erosion control ability, such as *Chloris gayana*, would be advantageous.

In Nyagatare, the main constraint to implement forage integration technology lies on its extensive grazing system, borrowing the theory from Paul et al. (2016) on forage technology adoption preference. Farmers in free livestock roaming systems show less interest in planting forage. Additionally, lack of labour for managing the comparatively larger size of land might also limits the implementation. Therefore, forages, such as *Leucaena leucocephala,* that require less management effort and can supplement the proteins generally lacking in grasses will be suitable for the households in Nyagatare. In spite of forage intensification by intercropping, improved pasture with low labour requirement may be a better choice in Nyagatare considering that 45% of the farm area was pasture.

The production objectives were diverse between households depending on their resource endowment (Tittonell et al., 2008). Interestingly, most of the households in Burera did not sell milk products, while all the households in Nyanza and Nyagatare sold their milk. Lack of market interaction might be an indication of low productivity or market unavailability. Food insecurity was not acute in the study households. Therefore, improved crop residues or multi-purposes forages with high productivity per unit area such as *Mucuna pruriens* would be better choices to minimize food-feed competition for land. However, using the quantity of food cannot fully indicates the food security and their production objective on food, assessing their nutrient security and dietary diversity are also important to fulfill a balanced requirement for macro- and micro-nutrients (Headey & Ecker, 2012; FAO, 1996).

The highly grass-based diet in the study sites though provides carbohydrates, it is deficient in protein and potentially increases enteric methane production. Corresponding to the detail farm characterization results, the higher milk yield in rainy seasons were due to a higher grass supply providing more energy than dry seasons. Protein supply limitation usually happens in long dry season, with exception of occurrence in long rain season in BU2. Therefore, it confirms that increasing the quantity of feed will be a priority while supplementing proteins can be further improved especially for households with poor resource endowment (Klapwijk et al., 2014).

5.2. Matching approach to select best-bet forage-niche combination

The approach for matching provides a guideline for researchers and extension workers to tailor-made forage intensification scenarios to farmers. This tentative matching approach shows a possibility to quantitatively differentiate the suitability of the forage-niche combinations in the socio-ecological niche framework. Subtle differences among the forage technologies and among the respective contexts can be unraveled.

The nominated forages within the same AEZ (Table 4) received similar subtotal scores in *Criterion 1* because they have already proven to be suitable for the local agro-ecological conditions through experiments. However, soil characteristics and climatic variations can differ even within the same zone, particularly in a hilly environment. Therefore, more refinement is possible such as on-farm soil measurements to improve the matching accuracy. The variations in their final score were largely determined by socio-economic condition and production objectives of individual household. For example, though *Brachiaria brizantha* has a comparable score for *Criterion 1* as other grass forages, its low final score in NG2 Napier grass field is a result from the low match of household's limited income, low labour availability, food insecurity, and high enteric methane emission from dairy cows to the forage's characteristics. A comparable result of *Brachiaria* was also found in Kenya where converting Napier grass to *Brachiaria,* even though *Brachiaria* might present higher drought tolerant (Osele et al., 2018). Though *Brachiaria* spp. has the highest protein content in the grass forages, its matching score may suggest that alternative forages such as *Tripsaum laxum* and *Chloris gayana* may perform better in fitting the farming systems than the ones with higher feed quality. Households with severe constraints in their production environments, such as NG2 and NZ1, might choose perennial multi-purposes legume forages rather than grasses to have better forage integration.

Limited seed or planting material sources has been reported to be responsible for low forage technology adoption. The suggested forage species in this study are supported by Rwanda Agriculture Board (RAB) and/or CIAT, therefore issues on seed accessibility is minor. Distance to the market only significantly determines the matching process when the farm is market-oriented. The forage and milk production were merely for home consumption in the selected households. The parts of production that were sold were mainly to their neighbors and brokers, which means their distance to markets was short and their interaction with markets was fairly simple if the distance to markets is defined as the time spent on moving from plot to the market. In a nutshell, institutional support in this case is less relevant

Some improvements can be made to refine the accuracy of the matching score. For example, the importance of each variables can be weighed differently under different farming systems. Study on tree species and canopy densities in specific farms can be further elaborated. Timewise, the period of growth and conservation of the forages is also important. As protein limitations often occur during long dry season, conserving feedstuff high in protein for dry season use is crucial to narrow the milk yield gap. The time before having harvestable yield should be considered into judging its profitability.

5.3. Impacts of the two forage-integrated scenarios

Though giving scores to the forage-niche combinations can prioritize the most suitable forage into the household's agro-ecological and socio-economic context, potential impacts on milk yield and enteric methane emission should be analyzed. The Ruminant model approach in our study predicts the milk yield and enteric methane emission when feeding the improved diet under two scenarios. Result shows that either integrating grass or legume forage into the banana field can raise the milk yield by over 100% while decreasing enteric methane emission intensity.

Lower enteric methane emission intensity is found with higher milk yield. This is in line with the finding by FAO (n.d.) and Rao et al. (2015) indicating that increasing milk productivity is an efficient way to reduce methane production intensity while also providing other social and economic benefits. Though enteric methane production is significant influenced by the amount of DMI, the nutrient composition of the diet may affect the emission factor (Niu et al., 2018). This is confirmed by the different in reducing methane emission intensity between the two scenarios with grass and legume-added diets.

Scenario GI has the most benefit in BU2 compared to other households. It is most likely resulted from the higher protein content in the *Brachiaria brizantha* comparing to the other selected grass forages (i.e. *Chloris gayana* and *Pennisetum purpureum*). The larger plot size in BU2 might have also contributed to the result. Exceptionally, grass-integrated diet had an undesirable impact in NG1, which underpins the necessity of ex-ante assessment before implementing the intervention. Model output presents decreases in MP and ME supply from the diet though DMI is constant. As a result, the decrease in milk yield could be attributed to decreased feed digestibility (Appendix 4.3). Scenario LI is more effective in improving milk yield and reducing enteric methane emission intensity than scenario GI.

The Ruminant model might have underestimated the DMI since the predicted feed refusal rate (above 50% DM) is much higher than the previous research in which almost no feed is refused (Klapwijk et al., 2014). In reality, milk production throughout the year is not realistic. However, the results can provide an insight on how and when to allocate the produced forages for the most efficient milk production while reducing methane emission intensity.

6. Conclusions and recommendations

Banana, woodlot, and Napier grass fields were identified as the potential on-farm socio-ecological niches for forage integration. More than half of the study households had plots allocated to banana and Napier grass production, while woodlots were only found at a small scale in Burera and Nyanza. The percentages of the niche areas per household ranged from 0 to 42.6%, but there is no significant difference among the districts. Intercropping was not a common practice in these niches, which gives opportunities for growing forages as understory crops and soil covers. Except for farmyard manure and mulching material, inputs on the identified niches were rare.

The study households showed different levels of constraining or facilitating conditions to the choices of forage varieties. According to the final matching scores of the selected forage species and niches, *Pennisetum purpureum* and *Desmodium intortum* are the most suitable forages for the identified socio-ecological niches. *Leucaena leucocephala* might be more favoured in farming systems in Nyagatare district than other species. In households with severe constraining conditions, the species with high scores are commonly multi-purposes legumes such as *Leucaena leucocephala* and *Mucuna pruriens*.

Matching forages into socio-ecological niches can not only likely to increase forage technology adaptions but also potentially increase milk production and mitigate enteric methane emission intensity. Predicted results from the Ruminant model demonstrated that grass produced from the socio-ecological niche can increase milk yield from 2.8 l/day to 3.9 l/day when added to the initial dairy cow diet. Adding legumes increased milk yield to 4.2 l/day. Both addition of grass and legumes reduced enteric methane emission intensity by more than 30%.

In the research, obtaining data on feed quantity had been a challenge. Further feed assessments in the study sites will help to improve the reliability of diagnosing the milk production limiting factor and to validate the results from the Ruminant model. Biological aspect, feed conservation skills of the households is lacking in this socio-ecological matching approach, which might needs further research. More efficient land use on off-farm niches is also likely to close the gap in milk yield, though more intense communication and agreements should be discussed among households and the institutions than integrating forages in on-farm socio-ecological niches.

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Appendices

Appendix 1. Feed parameters for Ruminant inputs.

Feedstuff	NDF (g/kg)	CP (g/kg)	Ash (g/kg)	Fat (g/kg)	Starch	Rate BCHO	BCHO	Rate ACHO	ACHO	Rate BCP	BCP	Rate ACP	ACP
Natural grass (fresh)	601.5	60	513.0	0	0	0.045	0.6	0.3	120	0.07	0.5	0.15	0.3
Napier grass	715	97	138	0	0	0.04	0.6	0.3	200	0.07	0.47	0.2	0.246
Banana trunk/leaves	200	35	113	0	0	0.12	0.7	0.3	660	0.15	0.55	0.3	0.35
Pluse straw (fresh)	511	107	72	0	0	0.03	0.5	0.3	310	0.07	0.5	0.15	0.3
Pluse straw (dry)	697	71	89	0	0	0.03	0.5	0.3	143	0.07	0.5	0.15	0.3
Sweet potato vine	427	165	112	0	0	0.03	0.5	0.3	296	0.07	0.5	0.15	0.3
Maize stover green	699	68	68	0	0	0.03	0.5	0.3	165	0.07	0.5	0.15	0.3
Maize stover dry	750	39	71	0	0	0.03	0.5	0.3	140	0.07	0.5	0.15	0.3
Irish potato vine	427	165	112	0	0	0.03	0.5	0.3	296	0.07	0.5	0.15	0.3
Leucaena leucocephala	409	233	85	0	0	0.04	0.55	0.3	273	0.07	0.47	0.2	0.2
Setaria sphacelata	695	91	111	0	0	0.04	0.6	0.3	103	0.07	0.47	0.2	0.2
Calliandra calothyrsus	556	208	63	0	0	0.04	0.7	0.3	173	0.07	0.47	0.2	0.2
Brachiaria brizantha	650	120	100	10	0	0.044	0.64	0.3	120	0.07	0.5	0.15	0.3
Desmodium intortum	514	155	75	0	0	0.04	0.581	0.3	256	0.07	0.5	0.15	0.3
Tripsacum laxum	724	88	85	0	0	0.04	0.599	0.3	103	0.07	0.5	0.15	0.3
Chloris gayana	750	90	90	0	0	0.04	0.604	0.3	70	0.07	0.5	0.15	0.3
Panicum maximum	755	72	55	0	0	0.04	0.577	0.3	118	0.07	0.5	0.15	0.3
Mucuna pruriens	385	160	79	0	0	0.04	0.681	0.3	376	0.07	0.5	0.15	0.3

Appendix 2. Results of the diagnosis of the niche supply. C refers to "Constraining", M refers to "Medium", and F refers to "Facilitating".

Criteria	Criteria boundary	BU1 WL	BU1 NPG	BU2 BNN	BU2 WL	NG1 BNN	NG1 NPG	NG2 NPG	NZ1 BNN	NZ1 NPG	NZ2 BNN	NZ 2 WL	NZ2 NPG
Agro-ecological conditions	Elevation												
	Annual precipitation												
	Annual temperature												
	Soil pH												
	Soil fertility												
Cultural environment	Norms on forage planting	M	M	C	C	C	C	C	C	C	C	C	C
	Livestock feeding habit	F	F	F	F	M	M	M	F	F	F	F	F
Socio-economic environment	Distance to the market	F	F	F	F	F	F	F	F	F	F	F	F
	Income and capital	C	C	C	C	C	C	C	M	M	C	C	C
	Household labour availability	F	F	F	F	F	F	C	F	F	C	C	C
Institutional support	Frequency of extension services	F	F	F	F	F	F	F	F	F	F	F	F
	Seed accessibility	F	F	F	F	F	F	F	F	F	F	F	F
Production objectives	Food security	C	C	M	M	F	F	C	C	C	M	M	M
	Feed availability	F	F	C	C	F	F	F	F	F	F	F	F
	Feed quality	M	M	F	F	F	F	M	M	M	M	M	M
	Enteric methane production intensity	C	C	F	F	M	M	C	C	C	M	M	M
Farm production environment	Land availability	M	M	M	M	F	F	F	F	F	F	F	F
	Water availability	M	M	M	M	M	M	M	C	C	M	M	M
	Crop compatibility	M	C	M	M	M	C	C	M	C	M	M	C
	Shade	M	M	M	M	M	M	M	M	M	M	M	M

Appendix 4.1-4.6 Matching score of each forage species and niche types and subtotal score under each criterion.

Appendix 4.1. Matching score in BU1.

		BU1 Woodlot				BU1 Napier grass			
Criteria	Criteria boundary	*Pennisetum purpureum*	*Brachiaria brizantha*	*Calliandra calothyrsus*	*Desmodium intortum*	*Pennisetum purpureum*	*Brachiaria brizantha*	*Calliandra calothyrsus*	*Desmodium intortum*
Agro-ecological conditions									
	Elevation	3	3	3	3		3	3	3
	Annual precipitation	2	2	3	3		2	3	3
	Annual temperature	1	1	1	1		1	1	1
	Soil pH	3	3	3	3		3	3	3
	Soil fertility	3	3	3	3		3	3	3
Cultural environment									
	Norms on forage planting	3	2	2	2		2	2	2
	Livestock feeding habit	3	3	3	3		3	3	3
Socio-economic environment									
	Distance to the market	3	3	3	3		3	3	3
	Income and capital	2	1	3	1		1	3	1
	Household labour availability	3	3	3	3		3	3	3
Institutional support									
	Frequency of extension services	3	3	3	3		3	3	3
	Seed accessibility	3	3	3	3		3	3	3
Production objectives									
	Food security	1	1	1	1		1	1	1

	Feed availability	3	3	3	3	3	3	3
	Feed quality	2	3	3	3	3	3	3
	Enteric methane emission	1	1	2	2	1	2	2
Farm production environment								
	Land availability (ha/household member)	3	3	3	3	3	3	3
	Water availability	2	3	3	3	3	3	3
	Crop compatibility	3	3	2	2	2	1	1
	Shade	3	2	3	3	2	3	3

Appendix 4.2. Matching score in BU2.

Criteria	Criteria boundary	BU2 Banana				BU2 Woodlot			
		Pennisetum purpureum	*Brachiaria brizantha*	*Calliandra calothyrsus*	*Desmodium intortum*	*Pennisetum purpureum*	*Brachiaria brizantha*	*Calliandra calothyrsus*	*Desmodium intortum*
Agro-ecological conditions									
	Elevation	3	3	3	3	3	3	3	3
	Annual precipitation	2	2	3	3	2	2	3	3
	Annual temperature	1	1	1	1	1	1	1	1
	Soil pH	3	3	3	3	3	3	3	3
	Soil fertility	3	3	3	3	3	3	3	3
Cultural environment									
	Norms on forage planting	3	1	1	1	3	1	1	1
	Grazing system suitability	3	3	3	3	3	3	3	3
Socio-economic environment									
	Distance to the market	3	3	3	3	3	3	3	3
	Income and capital	2	1	3	1	2	1	3	1
	Household labour availability	3	3	3	3	3	3	3	3
Institutional support									
	Frequency of extension services	3	3	3	3	3	3	3	3
	Seed accessibility	3	3	2	3	3	3	2	3

Production objectives								
Food production	2	2	2	2	2	2	2	2
Biomass production	3	2	2	2	3	2	2	2
Feed quality	3	3	3	3	3	3	3	3
Enteric methane emission	3	3	3	3	3	3	3	3
Farm production environment								
Land availability	3	3	3	3	3	3	3	3
Water availability	2	3	3	3	2	3	3	3
Crop compatibility	3	3	2	2	3	3	2	2
Shade	3	2	3	3	3	2	3	3

Appendix 4.3. Matching score in NG1.

		NG1 Banana									NG1 Napier grass								
Criteria	Criteria boundary	*Pennisetum purpureum*	*Brachiaria brizantha*	*Tripsacum laxum*	Desmodium intortum	*Chloris gayana*	*Panicum maximum*	*Mucuna pruriens*	*Desmodium intortum*	*Leucaena leucocephala*	*Pennisetum purpureum*	*Brachiaria brizantha*	*Tripsacum laxum*	Desmodium intortum	*Chloris gayana*	*Panicum maximum*	*Mucuna pruriens*	*Desmodium intortum*	*Leucaena leucocephala*
Agro-ecological conditions																			
	Elevation	3	3	3	3	3	3	3	3	3		3	3	3	3	3	3	3	3
	Annual precipitation	1	2	3	3	3	3	3	3	3		2	3	3	3	3	3	3	3
	Annual temperature	3	3	3	3	3	3	3	3	3		3	3	3	3	3	3	3	3
	Soil pH	3	3	3	2	3	3	3	2	3		3	3	2	3	3	3	2	3
	Soil fertility	3	3	3	3	3	3	3	3	3		3	3	3	3	3	3	3	3
Cultural environment																			
	Norms on forage planting	3	1	1	1	1	1	1	1	2		1	1	1	1	1	1	1	2
	Grazing system suitability	3	3	3	3	3	3	3	3	3		3	3	3	3	3	2	3	3
Socio-economic environment																			

Distance to the market	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Income and capital	2	1	1	1	1	1	3	1	3	1	1	1	1	1	2	1	3
Household labour availability	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Institutional support																	
Frequency of extension services	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Seed accessibility	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Production objectives																	
Food production	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Biomass production	3	3	3	3	3	3	2	3	3	3	3	3	3	3	3	3	3
Feed quality	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Enteric methane emission	2	2	2	3	2	2	3	3	3	2	2	3	2	2	3	3	3

Farm production environment																		
Land availability (ha/household member)	3	3	3	3	3	3	3	3	3		3	3	3	3	3	3	3	3
Water availability	2	3	3	3	3	3	2	3	3		3	3	3	3	3	3	3	3
Crop compatibility	3	3	2	2	3	3	3	3	3		2	1	1	3	3	1	3	2
Shade	3	2	3	3	2	2	1	2	3		2	3	3	2	2	2	2	3

Appendix 4.4. Matching score in NG2.

		NG2 Napier grass								
Criteria	Criteria boundary	*Pennisetum purpureum*	*Brachiaria brizantha*	*Tripsacum laxum*	Desmodium intortum	*Chloris gayana*	*Panicum maximum*	*Mucuna pruriens*	*Desmodium intortum*	*Leucaena leucocephala*
Agro-ecological conditions										
	Elevation		3	3	3	3	3	3	3	3
	Annual precipitation		2	3	3	3	3	3	3	3
	Annual temperature		3	3	3	3	3	3	3	3
	Soil pH		3	3	2	3	3	3	2	3
	Soil fertility		3	3	3	3	3	3	3	3
Cultural environment										
	Norms on forage planting		1	1	1	1	1	1	1	2
	Grazing system suitability		3	3	3	3	3	2	3	3
Socio-economic environment										
	Distance to the market		3	3	3	3	3	3	3	3
	Income and capital		1	1	1	1	1	2	1	3
	Household labour availability		1	2	3	2	2	3	3	3
Institutional support										
	Frequency of extension services		3	3	3	3	3	3	3	3
	Seed accessibility		3	3	3	3	3	3	3	3

Production objectives								
Food security	1	1	1	1	3	3	3	1
Biomass production	3	3	3	3	3	3	3	3
Feed quality	3	2	3	2	2	3	3	3
Enteric methane emission	1	1	2	1	1	3	3	2
Farm production environment								
Land availability	3	3	3	3	3	3	2	3
Water availability	3	3	3	3	3	3	3	3
Crop compatibility	2	1	1	3	3	1	3	2
Shade	2	3	3	2	2	2	2	3

Appendix 4.5. Matching score of household in NZ1.

Criteria	Criteria boundary	NZ1 Banana				NZ1 Napier grass			
		Pennisetum purpureum	*Brachiaria brizantha*	*Setaria sphacelata*	*Desmodium intortum*	*Pennisetum purpureum*	*Brachiaria brizantha*	*Setaria sphacelata*	*Desmodium intortum*
Agro-ecological conditions									
	Elevation	3	3	3	3		3	3	3
	Annual precipitation	2	3	3	3		3	3	3
	Annual temperature	1	1	3	1		1	3	1
	Soil pH	3	3	1	3		3	1	3
	Soil fertility	3	3	3	3		3	3	3
Cultural environment									
	Norms on forage planting	3	1	2	1		1	2	1
	Grazing system suitability	3	3	3	3		3	3	3
Socio-economic environment									
	Distance to the market	3	3	3	3		3	3	3
	Profitability	3	2	2	2		2	2	2
	Household labour availability	3	3	3	3		3	3	3
Institutional support									
	Frequency of extension services	3	3	3	3		3	3	3
	Seed accessibility	3	3	3	3		3	3	3
Production objectives									
	Food production	1	1	1	1		1	1	1

Biomass production	3	3	3	2		3	3	3
Feed quality	2	3	2	3		3	2	3
Enteric methane emission	1	1	1	2		1	1	2
Farm production environment								
Land availability	3	3	3	3		3	3	3
Water availability	1	3	2	2		3	2	2
Crop compatibility	3	3	3	2		2	2	1
Shade	3	2	3	3		2	3	3

Appendix 4.6. Matching score in NZ2.

		NZ2 Banana				NZ2 Woodlot				NZ2 Napier grass			
Criteria	Criteria boundary	*Pennisetum purpureum*	*Brachiaria brizantha*	*Setaria sphacelata*	*Desmodium intortum*	*Pennisetum purpureum*	*Brachiaria brizantha*	*Setaria sphacelata*	*Desmodium intortum*	*Pennisetum purpureum*	*Brachiaria brizantha*	*Setaria sphacelata*	*Desmodium intortum*
Agro-ecological conditions													
	Elevation	3	3	3	3	3	3	3	3		3	3	3
	Annual precipitation	2	3	3	3	2	3	3	3		3	3	3
	Annual temperature	1	1	3	1	1	1	3	1		1	3	1
	Soil pH	3	3	1	3	3	3	1	3		3	1	3
	Soil fertility	3	3	3	3	3	3	3	3		3	3	3
Cultural environment													
	Norms on forage planting	3	1	2	1	3	1	2	1		1	2	1
	Grazing system suitability	3	3	3	3	3	3	3	3		3	3	3
Socio-economic environment													
	Distance to the market	3	3	3	3	3	3	3	3		3	3	3
	Profitability	2	1	1	1	2	1	1	1		1	1	1

Household labour availability	2	1	1	3	2	1	1	3		1	1	3
Institutional support												
Frequency of extension services	3	3	3	3	3	3	3	3		3	3	3
Seed accessibility	3	3	3	3	3	3	3	3		3	3	3
Production objectives												
Food production	2	2	2	2	2	2	2	2		2	2	2
Biomass production	3	3	3	3	3	3	3	3		3	3	3
Feed quality	2	3	2	3	2	3	2	3		3	2	3
Enteric methane emission	2	2	2	3	2	2	2	3		2	2	3
Farm production environment												
Land availability	3	3	3	3	3	3	3	3		3	3	3
Water availability	2	3	3	3	2	3	3	3		3	3	3
Crop compatibility	3	3	3	2	3	3	3	2		2	2	1
Shade	3	2	3	3	3	2	3	3		2	3	3

Appendix 5. Model outputs of the feed baskets from baseline and scenarios. The description of the abbreviations can be found in Table 11. The output from the diet in BU2 during LD was not able to obtain because the limited number of feedstuff that the model can run. Number in bold are the milk yield considering MP and ME constraints.

	Baseline				Scenario GI				Scenario LI			
	LR	SR	LD	SD	LR	SR	LD	SD	LR	SR	LD	SD
BU2												
DM intake (kg/d)	1.5	4.4	4.4	4.4	5.5	5.5		5.4	5.7	5.9		5.7
Methane (l/d)	128.6	104	119.2	104	136.3	153.1		129	148.4	154.1		142.3
ME supply (MJ/d)	45.9	37.6	10.8	37.6	48	48		46.2	52.4	54.8		50.9
MP supply (g/d)	231.3	217.9	253.9	217.9	261.4	295.9		278	293.6	348.2		314.8
Milk from ME (l/d)	2.2	**0.4**	**2.2**	**0.4**	2.8	**2.8**		**2.3**	3.9	**4.6**		**3.6**
Milk from MP (l/d)	**2**	1.7	2.5	1.7	**2.7**	3.5		3.1	**3.4**	4.7		3.9
Methane emission intensity	64.3	260.0	54.2	260.0	50.5	54.7		56.1	43.6	32.8		36.5
NG1												
DM intake (kg/d)	5.7	5.5	6.4	5.5	5.7	5.5	6.8	5.5	5.8	5.6	6.5	5.5
Methane (l/d)	145.8	139.3	117.8	139.3	144.4	138	130.6	138.6	150.3	145.1	122.4	140.8
ME supply (MJ/d)	52.5	50.2	72.2	50.2	51.8	49.5	72.5	49.8	54.2	52.5	73	50.8
MP supply (g/d)	347.1	319.2	180.7	174.6	341.6	314.5	197.7	316.4	365.3	342.8	192.6	325.2
Milk from ME (l/d)	**4**	**3.4**	9.7	**3.4**	**3.8**	**3.2**	9.4	**3.3**	**4.4**	**4**	9.8	**3.5**
Milk from MP (l/d)	4.7	4	**0.8**	4	4.5	3.9	**1.2**	3.9	5.1	4.6	**1.1**	4.1
Methane emission intensity	36.5	41.0	147.3	41.0	38.0	43.1	108.8	42.0	34.2	36.3	111.3	40.2
NZ1												
DM intake (kg/d)	5.7	5.4	5.6	4.4	5.9	5.9	6.4	5.2	5.9	5.9	6.1	4.9
Methane (l/d)	146	138.6	159.1	123.1	157.5	159.2	177.7	144.1	155.1	156.2	172	137.9
ME supply (MJ/d)	51.3	48.4	57.2	42.5	55.6	56.2	65	50.3	54.3	54.7	62.4	47.9
MP supply (g/d)	362.6	342.6	413.9	308	400.4	406	473.6	367.4	384.8	388.5	453.6	348

Milk from ME (l/d)	**3.0**	**3.0**	**5.5**	**1.8**	**4.8**	**4.9**	**7.3**	**3.7**	**4.4**	**4.5**	**6.8**	**3.1**
Milk from MP (l/d)	5.0	4.5	6.2	3.8	5.9	6.0	7.6	5.1	5.5	5.6	7.1	4.7
Methane emission intensity	48.7	46.2	28.9	68.4	32.8	32.5	24.3	38.9	12.3	34.7	25.3	44.5
NZ2												
DM intake (kg/d)	6.6	6	6.4	5.6	5.8	6.5	7.2	5.7	5.9	6.7	7.3	5.8
Methane (l/d)	141.1	168	113.9	140.4	152.9	182.2	157.1	146	153.2	190.2	148.7	148.4
ME supply (MJ/d)	54.5	61.3	78.9	50.7	54.9	66.2	80	52.6	55.7	69.5	84.4	53.3
MP supply (g/d)	399.3	28.7	179.4	327.4	373.3	487.3	267.6	348.1	380.8	505.3	249.5	349.7
Milk from ME (l/d)	**4.1**	**6.5**	11.9	**3.5**	**4.6**	**7.6**	11.3	**4**	**4.8**	8.5	12.8	**4.2**
Milk from MP (l/d)	5.9	6.9	**0.8**	4.2	5.3	7.9	**2.8**	4.7	5.4	**8.3**	**2.4**	4.7
Methane emission intensity	34.4	25.8	142.4	40.1	33.2	24.0	56.1	36.5	31.9	22.9	62.0	35.3