

## Farming Typology and Socio-Economic Analysis in Sub-alpine Ecosystem, Simien Mountain National Park, Ethiopia

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**Abstract:** Protected areas, particularly alpine ecosystems, are globally recognized. Despite the immense ecological values of protected areas, they are vulnerable to human pressures. The Simien Mountains National Park (SMNP) is one of the UNESCO World Heritage Sites in the Ethiopian highlands, exemplifying the complex balance between biodiversity conservation and sustainable livelihoods in the mountain areas. This study investigates local farming systems in the study area to assess their resilience and potential policy pathways for adaptation. A combination of principal component analysis (PCA) and hierarchical clustering (HC) was used to construct farm typology in the study areas using farm household survey data collected from 104 respondents. A focal group discussion (FGD) and key-informant interview (KII) were also conducted to obtain qualitative information on local perceptions of livelihood activities and farming. Three distinct farm typologies shaped by biophysical, socioeconomic, and cultural factors, Typology I, Typology II and Typology III. Typology I (57.7%) features mixed crop-livestock systems with off-farm income; Crop-production Typology II (36.53%), Typology III (6.2%) is dominated by livestock-based livelihoods. Persistent human-wildlife conflict, degraded grazing resources, and high production costs threaten livestock viability and genetic diversity, raising concerns about inbreeding and loss of locally adapted traits. Despite adaptive efforts, limited access to animal health services, forage, and improved genetics constrains resilience. The findings emphasize the need for globally informed, locally grounded conservation strategies that integrate sustainable resource use with genetic improvement and ecosystem-based management. Supporting smallholders through capacity-building, climate-resilient innovations, and participatory policy can safeguard both community livelihoods and the ecological integrity of World Heritage landscapes like SMNP.

**Keywords:** *Alpine ecosystems, Biodiversity conservation, Farming systems, Livestock production*

### Introduction

Alpine ecosystems host biodiversity that is critical both to humankind and to achieving sustainable livelihood in mountain areas and beyond. They play vital roles in maintaining carbon sequestration, water balance, ecological security, and human well-being (Theobald *et al.*, 2024; ALPARC, 2023). These regions are home to approximately half of the world's biodiversity hotspots, areas of particularly rich, unique, and threatened biodiversity, as well as about 30% of the world's key biodiversity areas, which contribute significantly to the global persistence of biodiversity (Payne *et al.*, 2020). Yet, these invaluable natural resources are under increasing threat from multiple pressures, including

climate change and high-intensity human activities like expanding agriculture and land-use conflicts (Schirpke *et al.*, 2021; Winkler, 2020). Globally, alpine environments are fragile and characterized by extreme climatic conditions, including low temperatures, short periods of UV radiation, and high elevations, resulting in hypoxic stress (Hou *et al.*, 2024; Sati *et al.*, 2024; Testolin *et al.*, 2020). In addition to climate change, the African alpine and sub-alpine ecosystem is increasingly threatened by anthropogenic land-use change (De Deus Vidal *et al.*, 2025; Bhandari *et al.*, 2024). In Ethiopia's high mountains, these patterns are mirrored, and in these zones, crop-livestock integration and crop-oriented farming are often central to both livelihoods and land-

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use patterns (Belay *et al.*, 2022; Kidane *et al.*, 2022; Carbutt, 2020). Balancing biodiversity conservation with the sustainability of farming systems is a pressing global policy issue (Yang *et al.*, 2023; Romeo *et al.*, 2021).

The Simien Mountains National Park (SMNP), one of Africa's few alpine parks, hosts globally important flora and fauna, including endemic species. The conspicuous giant Lobelias, red-hot pokers (*Kniphofia* spp.), and 10 species of grass are examples of endemic vegetative species from higher Afro-alpine communities (SNPark, 2025; SMNP, 2015). The Walia ibex (*Capra walie*, VU), Ethiopian wolf (*Canis simensis*, EN), and Gelada baboon (*Theropithecus gelada*), which are endemic to the Ethiopian highlands, are the flagship large mammal species found in the park. The biophysical, cultural, and economic factor shapes the farming system while it faces disruption from conservation restrictions, climate variability, and resource competition (Desalegne *et al.*, 2025; Assan, 2023). Developing a farm typology can be an essential step for agricultural development in heterogeneous farming systems. A Detailed classification of farm typologies and their implications for conservation and resilience remains limited. Understanding farm typologies also allows more effective allocation of resources and support mechanisms, promotes inclusive and sustainable agriculture (Gómez-Limón *et al.*, 2024; Hassall *et al.*, 2023; Alvarez *et al.*, 2014).

The Simien Mountain National Park is an Afro-alpine ecosystem in the African continent that is occupied by humans and domestic livestock. The communities living in and around the SMNP, mainly relying on a mixed farming system, off-farm practices, and livestock production is one of the few available opportunities for income generation at the household level (Girmay *et al.*, 2023; Tsegaye and Bekele, 2010; Zaibet *et al.*, 2010; Ellis-Jone, 1999). The park has witnessed extremes of soil degradation and erosion, overgrazing, high disease prevalence, extreme cold, and feed and water scarcity (Asefa *et al.*, 2020). These farmers have been practicing conventional farming, and they developed their adaptation mechanism to overcome the climate shocks, feed shortage/grazing restrictions, and disease prevalence (Asefa *et al.*, 2020; Alemu *et al.*, 2017; Hurni *et al.*, 2008). They are also known for their efficient use of limited arable land and their livestock's in are remarkable for their adaptation to the high altitude and resource-limited environment (Yohannes *et al.*, 2020; Gedefaw *et al.*, 2018).

Thus, to design urgent and strategic interventions that ensure sustainable agro-ecological farming, there is a need to explore the correlations between the smallholder livestock production trends and dynamics and socioeconomic characteristics (Pfeiffer *et al.*, 2022; Nontu *et al.*, 2025; Bahta and Nyaki, 2024). This will contribute to a better understanding of their current state, constraints, and available opportunities while highlighting the potential hotspots for productivity improvement. This study intended to characterize the

farming system and socioeconomic features of the community living in the Simien Mountain National Park.

## Materials and Methods

### Study Area

This study was conducted in the Debark district of the Simien Mountains National Park (SMNP), located in the North Gondar Zone of the Amhara Region, Ethiopia (Figure 1). The park spans altitudes of 1900 to 4533 meters above sea level and forms part of the Afro-alpine and sub-Afro-alpine ecosystems of the African continent. SMNP extends across five districts: Debark, Adi Arkay, Beyeda, Janamora, and Tselmt, with Debark contributing the largest number of peasant associations. Debark lies at elevations ranging from 2850 to 3900 meters. Two villages within the park, Gomiya and Milligebsa (3000–3400 m), were selected for the study. The district encompasses five eco-climatic zones based on altitude and climate: cold to very cold moist highlands, tepid moist mid-highlands, and warm moist lowlands. It receives an average annual rainfall of 1,550 mm. Significant temperature variations from cold nights (-2°C to 4°C) to mild days (11°C to 18°C) due to altitude, experiencing wet (June -Sept) and dry seasons, and facing climate change impacts like rising temperatures and shifting rainfall, making it crucial for studying biodiversity hotspots and climate adaptation (SMNP, 2015).

### Household Survey

The study was conducted between September and October 2021, involving 104 randomly selected households, 52 from Gomiya and 52 from Miligebsa, located near the Simien Mountains National Park. These villages were chosen based on their proximity to the park's boundary and their high-altitude settlement patterns. Ethical clearance was granted by the BETin Ethical Review Committee (BETin-ERC/003/2021) before fieldwork. All participants were informed about the study's objectives and gave oral consent for both participation and the use of their data in scientific publications. A rain-fed agriculture and livestock rearing are their main livelihood sources, with tourism-related employment (guiding, lodge and mule/horse service). The representative households were identified in collaboration with local development workers. This ensured that the study targeted the appropriate population for understanding livestock management in this ecological zone.

Additionally, a total of 4 (four) FGDs were conducted across the selected villages consisted of 6–10 participants per group discussion. The group includes the representation of different social groups, including male and female household heads, elders and youth. Participants were selected in consultation with local administrators and development agents to capture diverse perspectives. The discussion was guided by a semi-structured checklist, such as: Livelihood sources and diversification strategies, livestock husbandry, feed availability and grazing systems, land degradation and

environmental change, human–livestock–wildlife interactions and constraints and coping strategies in the study area. Key informant interviews (KII) were conducted with District and Development agents, community leaders, and elders.

Trained enumerators used an Open Data Kit (ODK)-based, pre-tested structured questionnaire to conduct face-to-face interviews in the local language. Open and closed-ended questionnaires were considered for the interview. Interviewers read and explained each question to ensure clarity and accurate responses. The survey collected detailed demographic data (age, gender, household size, marital status and education), livestock practices, and socio-economic indicators such as farm income, crop production, off-farm income (Tour guide/woodlot activity), and landholding size. Specific livestock-related variables were also captured to understand herd composition and management strategies. Collected data were cleaned and standardized, especially for continuous variables, to maintain consistency. A principal component analysis (PCA) was performed to *reduce the dimensionality* of the data and *identify primary* patterns and *variability*, and clustering analysis was used to classify households into relatively homogeneous farm typologies.

### **Variable Selection and Typology Construction**

The relevant variables were selected based on a literature review (Bousbia *et al.*, 2024; Azeze *et al.*, 2024; Eshetae *et al.*, 2024; Azarov *et al.*, 2024; Innazent *et al.*, 2022; Shukla *et al.*, 2019) and discussions with local experts (District experts and development agents) to describe household socio-economic trends, the dynamics of the farming system, and livestock species composition. We performed the Kaiser-Maier-Olkin (KMO) test and Bartlett's sphericity test to indicate the answer dataset for 104 farmers' suitability for factor analysis. After multivariate analysis, we conducted hierarchical clustering (Shukla *et al.*, 2019). A total of 16 variables were used to construct a generalized household farm typology by describing the structural, functional, and dynamic aspects of the farming system and species composition. This kind of farm typology analysis provides valuable insights for the development of targeted and domain-specific agricultural development interventions in the area. The descriptions and categorizations of the variables used to cluster farm households in the study area are summarized in Table 1.

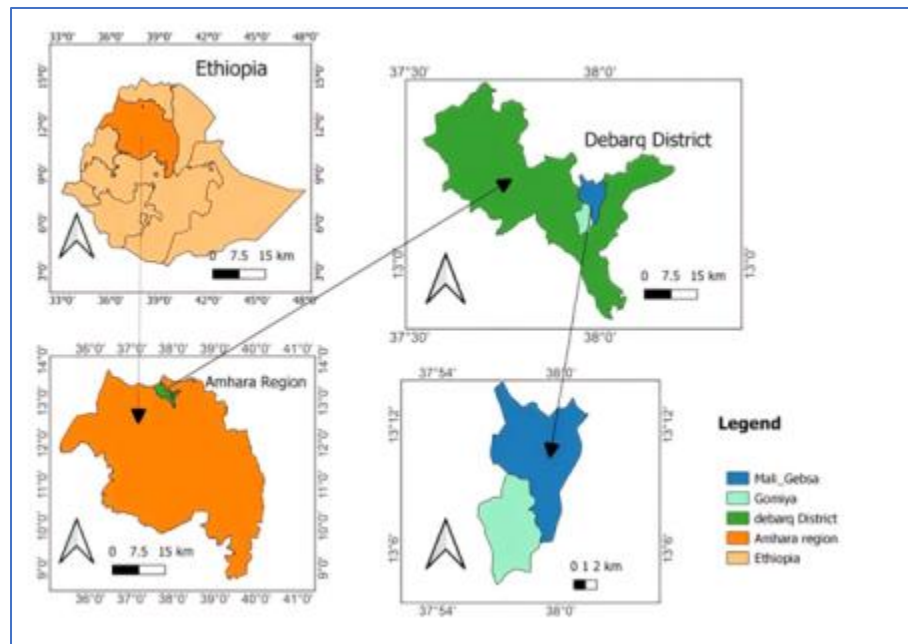


Figure 1. Map of the Study Area showing the locations of the village investigated. Map created using the Free and Open Source QGIS.

### **Data Analysis**

All data were analyzed using the R software (Lê *et al.*, 2008). Multivariate statistical analyses were used to summarize the qualitative and quantitative data and identify explanatory variables that could assist in classifying individuals into homogeneous groups. Following (Shukla *et al.*, 2019) Factorial analysis of mixed data (FAMD) is used to reduce the number of variables

into uncorrelated factors with enhanced explanatory power.

Dimensions exceeding one eigenvalue were considered, and we considered seven dimensions for the analysis. Before FAMD analysis, missing data were imputed using the imputation algorithm of the FAMD imputation function (Josse and Husson, 2016). The distortions in the statistical analysis and variables under the dataset underwent a meticulous examination to

identify potential outliers. These outliers were identified and eliminated using box plots, and variable contributions were verified using the function *dimdesc* FactomineR package (Lê *et al.*, 2008). We considered five groups of variables after consulting with local experts, and these variables represent the characteristics of Livestock rearing household. The Factorial Analysis of Mixed Data (FAMD) procedure was performed in R using the FactoMineR package v3.5.1 (Lê *et al.*, 2008). These groups of variables include: 1) household demographics; 2) feed resources and grazing practices; 3) livestock management practices; 4) reproductive performance; and 5) species composition, number of livestock owned, and livestock population trends.

The HCPC function of the FactoMineR package was used to perform Hierarchical Clustering on Principal Components analysis (HCPC) of the FAMD, to identify clusters that minimize variability among clusters while maximizing differences between clusters. A two-step clustering approach was used to identify the farming systems: (1) hierarchical clustering of principal

components (HCPC) of FAMD using the HCPC function of the FactomineR package for hierarchical, agglomerative clustering; and (2) a hierarchical tree was generated using the hierarchical agglomerative clustering algorithm, using Ward's method and Euclidean distance matrix (Murtagh and Legendre, 2014). The number of clusters was determined relative to the inertia gain values, and the majority of clusters were determined by the cutoff level. The choice of the optimum number of clusters was made relative to the inertial gain values and the majority number of clusters suggested by the indices result of the 'NbClust' package (Charrad *et al.*, 2014). The v-test value was used to compare the average value of each household characteristic in each of the resulting clusters to the global mean for that characteristic and to delineate the categories according to their association with the factorial axes. A v-test value  $> 1.96$  (i.e.,  $p$ -value  $\leq 0.05$ ) indicates that the mean of the variable in the cluster is statistically different from the population mean (Lê *et al.*, 2008).

Table 1. List of variables used to characterize and cluster farm households into different farm types.

Data Type	Variables	Description	Unit/Code
Demography	Age	Age of the household head	Number
	Gender	Gender	1 if Male and 2 Female
	Education	Level of education	0 Elementary school, 1 secondary school, 2 informal education, 3 college/university, 4 writing and reading
	Marital Status	Marital status	1 Single, 2 Married, 3 Divorced, 4 Widowed
	Farming experience	Year farming started	Number
Socio-economic	Household size	Household size	Number
	Total land owned by the household	Land owned	Ha
	Source of income	Livestock rearing, crop farming, off-farm activities (tourist guide, woodlot)	Category
	Livestock and crop production	Livestock Number	Number of livestock owned per household
Livestock and crop production	Species composition	Species composition per household	Number
	Animal reproductive performance	First calving, Pregnancy rate, kidding/lambing interval, litter size,	Category
	Soil fertility reduction/ Rangeland degradation	Having a soil fertility problem on their farming land	1 yes 0 no
		Occurrence of land degradation in the last 15years	1 yes 0 no
		Having a problem of grazing area	1 yes 0 no
Livestock farming system	Livestock husbandry practices, feeding, housing, veterinary service,	Livestock husbandry practice	Category

## Results

### **General Household and Demographic Information**

The main source of income in both villages is mixed crop-livestock farming, with an average land holding size of 0.5 and 0.45 ha in Milligebsa and Gomiya, and an average family size of 5.73 and 5.01 persons in Milligebsa

and Gomiya village, respectively (Table 2). Male respondents comprised a higher proportion of both Milligebsa and Gomiya villages, 89.40% and 87.29%, respectively. Approximately 41% of the respondents had attended primary school in both villages. The respondents' ages ranged from 22 to 66 years, and they

had an average of 20 years of farming experience. Sheep rearing was the most common activity in the district, followed by rearing cattle and goats (make it in percent).

### ***Kaiser-Maier-Olkin (KMO) and Bartlett's Sphericity Test Results***

The Kaiser—Meyer Olkin (KMO) test and Bartlett's sphericity test results confirmed that the survey dataset for 104 farmers was suitable for factor analysis, with a KMO value ( $> 0.71$ ) and a significance level for Bartlett's

test of less than 0.01. This suggests that all variables in the dataset can be used to create farm typologies and identify underlying factors. Additionally, factors with eigenvalues less than 1 were excluded to determine the number of components required, resulting in ten principal components (Table 3). Based on the hierarchical clustering results, three farm types were identified (dendrogram in Figure 2). Similarly, the k-means clustering approach revealed the same number of groups.

Table 2. Demographic and socio-economic characteristics of the sample respondents.

Category	Milligebsa	Gomiya	Test statistics
Farming experience	20.04±9.90	18±0.99	t=-1.43 <sup>NS</sup>
Family size	5.73±1.80	5.01±2.90	t =-2.18*
<b>Gender:</b>			
Male (%)	89.40	87.29	
Female (%)	10.60	12.71	X <sup>2</sup> = 0.0 <sup>NS</sup>
<b>Education:</b>			
Primary school (%)	21.20	20	
Secondary school (%)	1.90	2	
Writing and reading (%)	26.90	38	
Never been to school (%)	50	40	X <sup>2</sup> = 1.63 <sup>NS</sup>

NS= Not significant  $> 0.05$  p-value, \*  $< 0.05$  p-value significant.

Table 3. The principal components with eigenvalues and percentages of variance derived from farm typologies.

Dimensions	Eigen Value	Variance percent
Component 1	4.59	7.18
Component 2	3.89	6.08
Component 3	2.86	4.47
Component 4	2.76	4.32
Component 5	2.53	3.95
Component 6	2.42	3.77
Component 7	2.32	3.62
Component 8	2.13	3.33
Component 9	2.09	3.26
Component 10	1.93	3.03
		43.04

### ***Construction of Smallholder Farming Typology***

The first ten principal components explained 43.04% of the variation in the dataset (Table 3). The selected principal components are considered greater than 1 eigenvalue. Three farm typologies were identified by Principal Component Analysis (PCA) and HCPC analysis (Figure 2). The contribution of variance to the dimensions is provided in the supplementary data (Table S1). The primary sources of income (11.31), livestock housing (2.12), coping mechanism of feed shortage (6.67), species preference (2.09), weaning age for sheep and goat (2.47), age at first parturition for cattle (0.77), calving interval (3.79), twinning incidence for sheep and goat (8.25), kidding interval (2.08), livestock population trend (6.56), color preferences (6.19), herding (2.19), grazing system (2.42), land size trend (8.67), and education level (2.18) all contributed to a higher percentage of component1. This highlights the

importance of these variables in explaining differences in livestock farming practices between households. This suggests that a farmer's income level is a key factor in determining their species preference, the number of livestock they own, and animal management practices. Species preference (4.66), land size trend (2.08), twinning incidences (2.63), education (0.31), herding (3.65), production constraints (3.04), livestock population trend (2.69), primary source of income (8.93), twinning occurrence (2.63), coping mechanism of feed shortage (10.54), weaning age for sheep and goats (6.43), parturition age for sheep and goats (3.06), partition age for cattle (6.35), and age at first service for cattle (6.44) were the major contributors to component2. This implies a correlation between variables for improved livestock production and productivity, and the number of livestock and species composition per household.

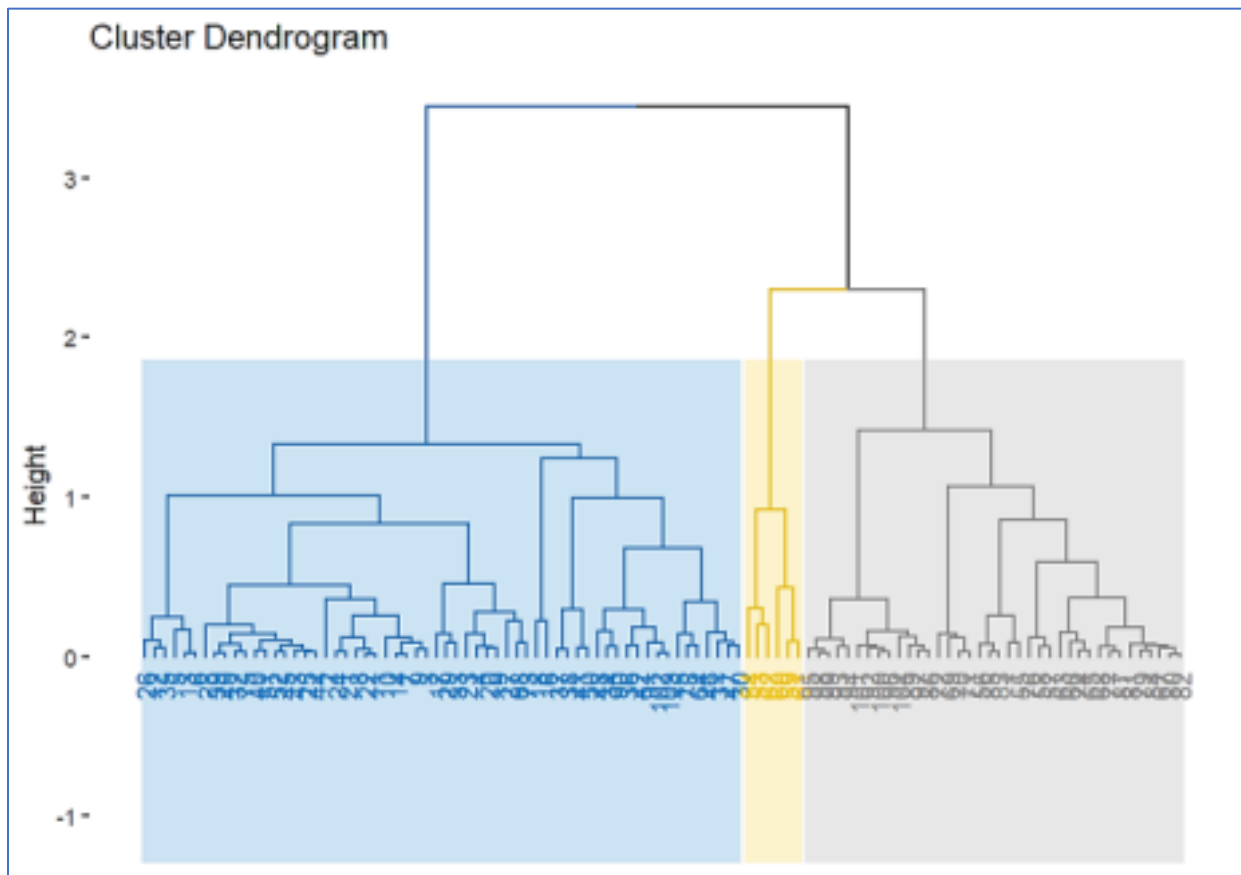


Figure 2. Cluster dendrogram.

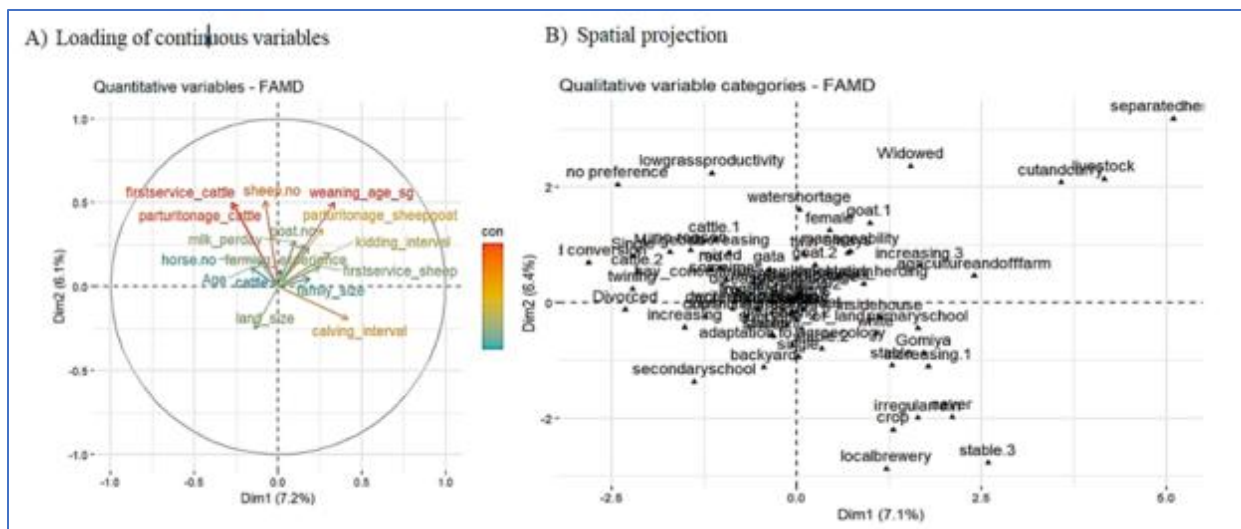


Figure 3. FAMD (PCA and MCA) output; (A) Correlation circle represents the loading of continuous variables on the 1 and 2 dimensions; (B) Spatial projection of categorical variables for the 1 and 2 dimensions.

**Characteristics of Farming Typology in the Study Area**

PCA and HCPC cluster analyses revealed the existence of three farming typologies (Figures 2, 3, 4, 5). The dominant farm type in the study area was farm type 1 (57.69%), followed by farm type 2 (36.53%), and farm type 3 (6.24%) (Figure 4). The v-test for the most continuous and categorical variables in each typology was greater than 1.96, indicating significant differences

in the typology mean compared to the population mean. The typology summarizes the major differences in household farming characteristics.

**Typology I: Mixed farming system:** This group consists of farmers engaged in diversified off-farm, crop, and livestock production-oriented farmers (n=60, 57.69%; 52 households from Milligebsa and eight

households from Gomiya) (Table 4). The primary source of income (85.29 %) for the households was mixed farming, which included crop production, livestock rearing, and horseback riding for tourists and eucalyptus plantations. As family size increases, landholding size decreases, which is expected from the family to share their land among their children when they get married. Mixed herding systems, in which all livestock species (horses, goats, sheep, cattle, and donkeys) herd together, are commonly practiced. The most prevalent livestock diseases in this cluster were dermatophilosis (100 %) and

gastrointestinal parasites (24.14%). In addition, sheep and goats exhibited twinning incidences. During periods of extreme feed shortages, farmers supplement their livestock with crop residue, grass hay and concentrates from different cereals, prioritizing pregnant late gestation and lactating animals. Sheep and goats were typically housed in separate structures behind the main family house, although 25.98% of the respondents kept their livestock in the main family house. Red and white coats were the most preferred by farmers across all livestock species.

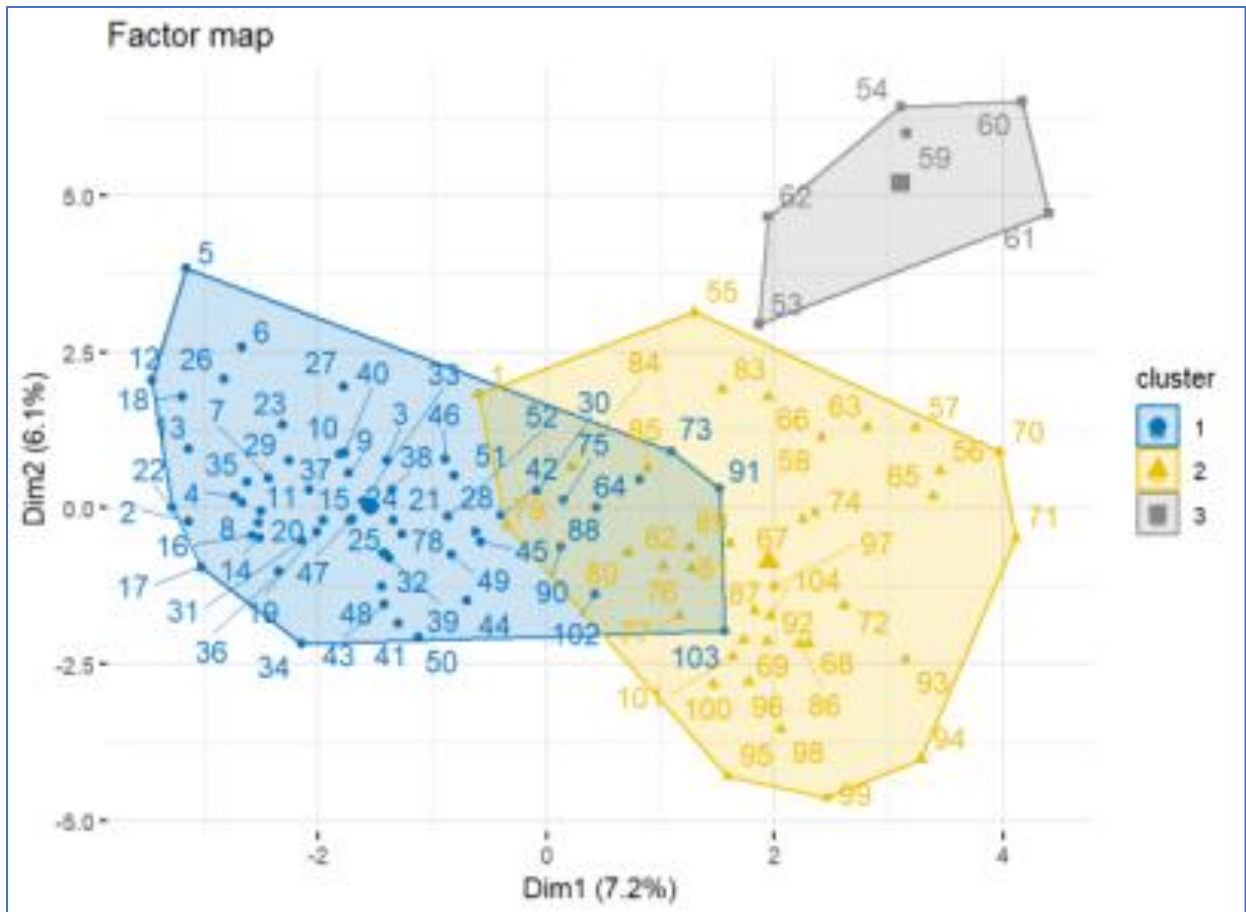


Figure 4. Factor map of the two dimensions; factor map showing that the sampled farmers can be categorized into three farm types.

#### Typology II: Crop production-oriented farmers:

This group includes 36.53% of the respondents ( $n = 38$ ) from Gomiya (Table 4). Crop farming was the primary source of income for 96.15% of these households, while 3.85 also practice mixed farming. The trend in land holding size appeared stable for 72.73 % of respondents, although 13.23% reported a decrease in land holding size due to an increase in family size and land degradation. The main challenges to livestock farming in this group were gastrointestinal parasites (Nematodes) (75.86%) and feed shortage. During periods of feed scarcity, respondents supplemented their livestock with crop residue, spent grains, local brewery byproducts and grass hay. Twining is infrequently observed in sheep and goats, with 17.02% of the respondents reporting low

occurrence of twinning. At night, livestock are typically sheltered inside the family homestead, and 21.81% of respondents have constructed sheds for their livestock, primarily for sheep and goats, with occasional use for equines to protect their livestock from theft and predators. Similar to other farm typologies, red and white coat colors are preferred by livestock owners for breeding, while black and grey coat colors are more often considered for sale.

#### Typology III: Livestock production-oriented farmers:

This group represents 9% of respondents from Gomiya ( $n = 6$ ) (Table 4) and is characterized by a dominant focus on livestock farming. Respondents in this cluster had a higher proportion of goats in their

flocks, with 20% reporting an increasing trend in the number. Approximately 75% of the respondents practiced species-specific herding, keeping livestock separated by type. Pasteurellosis (30%) is the most prevalent disease affecting their goat and feed scarcity remains a significant challenge. Respondents indicated that goats were the first livestock species they began to raise, and they preferred to continue raising sheep and goats because of their ease of management. Goats became favored for their perceived better adaptation to feed shortages.

#### **Socioeconomic Characteristics of Animal Production**

Typologies I and II exhibit relatively homogeneity concerning gender, education, and source of income. However, they differ in landholding trends and family sizes, with respondents in typology two reporting smaller family sizes and more stable landholdings. Hierarchical clustering categorizes these typologies based on factors such as farming experience, gender, family size, education, and income. Notably, typology I had a higher percentage (30.77 %) of households that had attended primary school. In contrast, Typology III comprises the smallest number of respondents and exhibits distinct characteristics compared to the other two. More than half of the respondents in this typology were literate, and a significant proportion (42.86 %) relied on livestock production as their primary source of income. Land ownership, family size, and education did not significantly influence production methods.

#### **Characteristics, Species Composition, and Role of Livestock in Simien National Park**

From focus group discussions, it was determined that all livestock species in the study area, namely sheep, goats, cattle, horses, donkeys, and mule are capable of traversing steep terrains in search of forage and are well adapted to grazing/browsing. The composition of livestock within households was approximately 60.80% sheep; 17.70% sheep and goat; 8.8% sheep and cattle; 6.9% sheep, goat, and cattle; and 1.90% cattle alone. This composition is primarily influenced by factors such as family size, landholding, household economy, and agro-ecological adaptability. The cumulative effects of productivity constraints, along with unfavorable and unpredictable weather patterns, compel farmers to adopt diverse coping strategies. These include transitioning to off-farm activities, establishing plantations of woody species such as eucalyptus, and managing the composition of their livestock. Farmers with larger landholdings, those with available family labor, married individuals, and households with stronger economic resources tend to show a preference for larger livestock. Among the various livestock species, sheep are perceived as the easiest to manage and the most adaptable to the agro-ecological conditions of the region. Consequently, respondents expressed a default preference for raising sheep over cattle and goats, although the goat population is steadily increasing.

Participants reported that human-livestock-wildlife conflicts are a significant determinant of the increasing number of livestock. Notable predators identified include the spotted hyena (*Crocuta crocuta*), Ethiopian wolf (*Canis simensis*), and leopard (*Panthera pardus*), which pose threats to donkeys, horses, mules, cattle, sheep, and goats. Additionally, ongoing conflicts exist between humans and gelada baboons (*Theropithecus*), which prefer to consume fruits, grass, leaves, and cultivated crops. The respondents also reported that the main challenge to livestock development in the area was the scarcity of feed. Many plants traditionally used as animal feed are becoming extinct owing to the impacts of climate change and overgrazing. Dermatitis and gastrointestinal parasites are the most frequently reported constraints on livestock production, whereas respiratory diseases are also common, although cattle are less affected. Twining is common among sheep and goats, and goats produce a reasonable amount of milk that the respondents utilize for home consumption. Livestock plays a vital role in households' socioeconomic and cultural practices. They provide meat, milk, butter, fertilizer, fuel, skin, and hides, whereas manure is used for both fuel and fertilizer. However, the sale of milk and its byproducts is uncommon. During wedding ceremonies, parents often gifted livestock to the bride and groom, serving as their initial animals to establish their own herds.

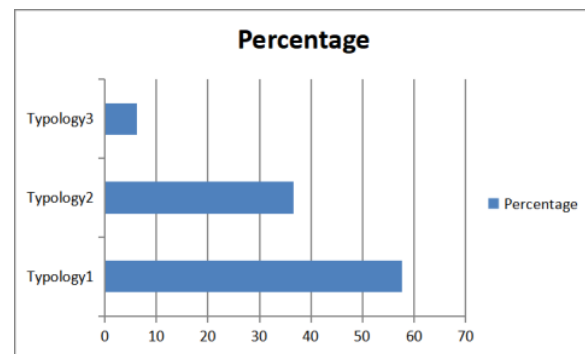


Figure 5. Distribution of farm typologies.

#### **Discussion**

Simien Mountain National Park represents a high-stress environment for both humans and livestock, making adaptive resilience and flexibility in production objectives crucial. The dynamics of agricultural farming systems could evolve and space in response to climate change, market demand, and socio-economic and consumer preferences. These elements are crucial in shaping the characteristics of farming systems and helps for assessing resilience to external shocks and identifying opportunities for tailored agricultural interventions. We identified the three farming typologies, differing by their socio-economic and biophysical characteristics. These include the mixed farming system, which is characterized by a diversified livelihood (Typology I); the crop-production system (Typology II); and livestock-based dominated livelihood (Typology III).

Table 4. Discriminatory variables, percentage, mean and standard error for identified farming typologies.

<b>Cluster 1 60 hh (52 hh from miligebsa, 8 hh from Gomiya)</b>	<b>Percentage</b>
Income=mixed	85.29***
Land size trend=decreasing	82.46***
Coping mechanism of feed shortage=grass hay, crop residue and concentrate supplementation	70.37***
Twining occurrence=sometimes	80.85***
Goat Population trend=decreasing	70.00***
Color preference=red	75.68***
Housing=gata	69.09***
Grazing=communal grazing	67.80***
Herding=mixed herding	60.00***
Frequent disease=dermatophilosis	100.00***
Education level=primary school	30.77***
Grazing=backyard herding	44.44***
Color preference=white	42.86***
Goat population trend=increasing	36.67***
Housing=inside house	25.93***
Frequent disease=parasites	24.14***
Coping mechanism of feed shortage= spent grains from the local brewery byproduct	6.67***
Twining occurrence=never	5.26***
Land size trend=stable	22.73***
Family size	5.8±1.65**
First service sheep/month	6.64±1.51**
Milk per day/kg	1.16±1.25**
Kidding interval/month	8.96±1.81**
Calving interval/month	32.59±5.63***
Weaning age for sheep and goats/month	3.93±1.08***
<b>Cluster 2 36.53% (38 hh from Gomiya, 0 from Milligebsa)</b>	
Income=crop farming	96.15***
Land size trend=stable	72.73***
Frequent disease=parasites	75.86***
Coping mechanism of feed shortage=spent brewery, local brewery byproduct	93.33***
Twining occurrence=never	84.21***
Housing=inside house	70.37***
Marital status=married	40.42***
Twining types=single	50.00***
Production constraint=irregular rain	100.00***
Goat population trend=stable	100.00***
Twining types=twin	26.42***
Coping mechanism of feed shortage=grass hay, crop residue and concentrate supplementation	28.39***
Housing=gata	21.81***
Twining occurrence=sometimes	17.02***
Land size trend=decreasing	10.52***
Income=mixed	13.23***
Family size	5.08±1.65***
Calving interval/month	32.59±5.63***
Partition age cattle/month	40.10±5.96***
First service cattle/month	30.22±6.01***
<b>Cluster 3 7% (6 hh from Gomiya)</b>	
Coping mechanism of feed shortage =spent grain, local brewery byproduct and kitchen leftovers	62.50***
Goat population trend=increasing	20.00***
Herding=separated herding	75.00***
Species startup=goat	21.74***
Income=livestock farming	42.86***
Species preference=manageability	15.63***
Frequent disease=pasteurellosis	30.00***
Twining types=twin	11.32***
Marital status=widowed	33.33***
Color preference=white	11.90***
Income=mixed	1.47***
Coping mechanism=grass hay, crop residue, and concentrate supplementation	1.23***
Herding=mixed herding	3.00***
Weaning age sheep and goats	3.93±1.08***
Parturition age of sheep and goats	12.83±2.03***
Kidding interval	8.96±1.81***
Parturition age cattle	40.11±5.9***
First service cattle	30.22±6.01***

\*  $p < 0.05$ ; \*\*  $p < 0.001$ ; \*\*\*  $p < 0.0001$ .

Typology I is a dominant typology characterized by a diversified mixed farming system. Similar farm typology approaches have been applied in other small holder setting in Ethiopia (Azeze *et al.*, 2024; Eshetae *et al.*, 2024) and other countries link to a mixed farming system (Azarov *et al.*, 2024; Innazent *et al.*, 2022). Next to the mixed farming system, off-farm activities like horse riding for tourists and tour guides, and wage employment are being practiced by the farmers to secure household income. Which is also the rural tourism has also been practiced in Kabong district of Uganda (Akorio *et al.*, 2024) and a Tourism-Agriculture Nexus approach of farmers in Bale Mountains National Park (Welteji and Zerihun, 2018). Likewise, Adamseged *et al.*, (2023) reported similar findings across Ethiopia, where farmers are increasingly diversifying their income sources, like practicing small business ventures and employment to sustain their livelihood. This way, they could make an immediate cash flow and financial flexibility. Eucalyptus tree plantation activity is observed in this farming system which they are converting their agricultural lands into a woodlot. A previous study also reported the land use/land cover changes in eucalyptus expansion in Meja watershed (Jaleta *et al.*, 2016) and the traditional agroforestry practices in Wondo district, Ethiopia (Molla *et al.*, 2023). This cluster proves the evolving dynamics of livestock and crop farming systems, explaining how farmers adjust their livelihoods to cope with environmental change. This finding is an indicator that smallholder farmers are receptive to adopting agricultural interventions and adapting their farming strategies in response to the changing conditions. This mixed farming system offers valuable insights into how communities manage to coexist with environmental challenges while sustaining their livelihoods.

We identified several key constraints in the study area, including land degradation, human-livestock-wildlife conflict, livestock feed shortage and disease prevalence. Land degradation is mainly observed in typologies I and II. A previous study also reported that the incidence of land degradation in the Ethiopian highlands (Jacob *et al.*, 2016; SNP, 2020). Even though land degradation was identified as a major constraint in the study area, its effect might be manifested through several interlinked constraints, including reduced numbers of shrubs and plants, grazing capacity, effective land holding size and decrease in herd size. Correspondingly previous study reported the consequences of land degradation on livestock productivity and rural livelihood (Slayi *et al.*, 2024; Solomon *et al.*, 2024; Gashu and Muchie, 2018; Abdulmalik and Zewide, 2021). Internal and external parasites, along with diseases such as pasteurilosis, dermatophilosis, and black leg, are increasingly common, negatively impacting livestock health and straining household finances due to the high costs of treatment and prolonged recovery times. Parasitic diseases contribute to significant losses by reducing weight gain, feed conversion efficiency, and reproductive performance (Waller, 2005; Ros-García *et*

*al.*, 2013). Dermatophilosis has also been reported in Ethiopian highland cattle (Sarba & Borena, 2017), and it has been reported as a cause of reduced productivity in dairy cattle (Sarba & Borena, 2017; Ojong *et al.*, 2016). Black leg is characterized as a major cause of livestock loss, particularly prevalent during the rainy season, and affects both sheep and cattle (Lorenz *et al.*, 2019; Rychener *et al.*, 2017).

Human-livestock-wildlife conflict has been observed across all three farming system typologies, though the nature of these conflicts varies. Human-wildlife and livestock conflicts were also observed, which are mainly tied to ecological pressures, human settlement, unsustainable agricultural practices, overgrazing, predator, zoonotic disease, deforestation for charcoal production and collection of firewood. In Typology I, conflicts primarily involve *Walia ibex*, *Gelada baboons*, leopards, and spotted hyenas. The *Walia ibex* often grazes on crops, while *Gelada baboons* cause conflicts by raiding household food supplies and crops, with their vocalizations perceived as disruptive to the community. For instance, dietary competition between the endangered *Walia ibex* and domestic goats has been documented, highlighting the potential for conflict between wildlife and livestock (Gebremedhin *et al.*, 2016). Leopards and spotted hyenas pose threats to humans and livestock, particularly goats and sheep. Additionally, livestock competes with wildlife for grazing resources, putting pressure on grasses that are also used by wild species. Human-wildlife conflict, predominantly predation on livestock, is similarly reported in Bale Mountain National Park, where farmers are complaining of frequent losses of their livestock due to predator (Eshete *et al.*, 2015; Sebsibe, 2022). In contrast, Type 2 farmers experience fewer direct conflicts with predators, whereas Type 3 farmers, whose livelihoods are primarily livestock-based, face frequent conflicts with leopards and spotted hyenas. Addressing these conflicts requires a conservation approach that safeguards the wildlife and livestock. A “one-conservation” strategy, as suggested by Pizzutto *et al.*, (2021), could help by establishing buffer zones to reduce conflict and supporting the ecological balance, as both wildlife and livestock are valuable components of the ecosystem.

Household income, agroecology, marital status, land and family size are influencing the composition of livestock species owned per household, which is also inconsistent with the findings of the rural OR Tambo district municipality in South Africa (Taruvinga *et al.*, 2022). Raising sheep and goats is largely associated with securing household food and nutrition and an immediate source of income, which is also in line with the findings of Danso *et al.* (2024) and Wodajo *et al.* (2020). Farmers having higher income, larger family and married are keeping a large number of cattle from their fellow farmers, and they are also keeping sheep and goats. This is an indicator that the availability of labor and financial resources enables these households to manage, feed and care for their animals. Additionally, the demand for

livestock production in the household drives the ownership of cattle, especially for those households with children less than five years.

## Conclusion

We identified three distinct farming typologies, namely mixed, crop-oriented, and livestock-based, in the landscape of Simien Mountains National Park. The communities living in this park are being challenged by intertwined ecological and socio-economic factors. The dominant farming typology is a mixed farming system; this system holds crop production, livestock rearing and off-farm activities including ecotourism. While the area is experiencing rangeland fragmentation, declining livestock populations and erosion of genetic diversity resulted from human-livestock-wildlife conflict. These dynamics could endanger biodiversity and community resilience, especially in ecologically fragile zones like SMNP Park. This finding underlines the urgent need for intervention specific to each farming typology, like introducing improved forage, sustainable soil management, and livestock genetic improvement. Safeguarding the biodiversity, cultural heritage and agro-ecosystem health in this World Heritage Site could be attained through a holistic “One-Conservation” approach.

Despite regulatory frameworks, continued grazing competition, predation, and crop damage highlight the ineffectiveness of current mitigation strategies. The identified farming typologies offer a foundation for designing system-specific policies that reflect local realities and vulnerabilities, promoting interventions such as animal health services, improved feeding systems, and livelihood diversification. Strengthening participatory natural resource management and co-developing conservation strategies with local communities can enhance ownership and long-term sustainability. Integrating ecosystem-based adaptation and expanding extension services focused on zoonotic disease control, climate-resilient husbandry, and genetic conservation will further build resilience. Aligning conservation goals with rural development through inclusive, adaptive policies will be a key to ensuring the sustainability of both the park’s ecosystems and its farming communities.

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## Conflict of Interests

The authors declare that they have no competing interests.

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