Delineating a typology for co-designing whole farm prototypes under smallholder mixed farming systems in Malawi

Exploring Options for Sustainable Intensification Through Legume Integration in Different Farm Types at Mtunthama Extension Planning Area (EPA) In Malawi

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The Sustainable Intensification of Mixed Farming Systems Initiative aims to provide equitable, transformative pathways for improved livelihoods of actors in mixed farming systems through sustainable intensification within target agroecologies and socio-economic settings.

Through action research and development partnerships, the Initiative will improve smallholder farmers' resilience to weather-induced shocks, provide a more stable income and significant benefits in welfare, and enhance social justice and inclusion for 13 million people by 2030.

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

Contents

Abbreviations and acronyms

ABC	Alliance of Bioversity International and the International Center for Tropical Agriculture (CIAT)
AEDO	**Agricultural Extension Officers**
CA	Conservation agriculture
CADECOM	Catholic Development Commission in Malawi
CIMMYT	International Maize and Wheat Improvement Center
DARS	Department of Agricultural Research Services- Malawi
EPA	Extension Planning Area
GESI	Gender and Social Inclusion
IITA	International Institute of Tropical Agriculture
ILRI	International Livestock Research Institute
IRRI	International Rice Research Institute
IWMI	International Water Management Institute
K2 TASO	K2 Tigwiranemanja AIDS Support Organization
MCA	multiple correspondence analysis
PCA	Principal Component Analysis
SDG	Sustainable Development Goals
SI-MFS	Sustainable Intensification of Mixed Farming Systems Initiative
UKZN	University of Kwazulu Natal
WP	Work Package
WUR	Wageningen University & Research

Abstract

Smallholder farming in Malawi is characterized by mixed crop-livestock farming, with immense pressure on a degraded natural resource base and limited capacity for smallholders to provide external inputs. These systems can benefit from redesign to achieve sustainable intensification to better meet farmers production, environmental and human objectives. The complexity of smallholder farms, shown by diversity in spatial distribution, resource endowment, production and consumption decisions often hinder the design, targeting, implementation and scaling of agricultural development projects. Understanding farm heterogeneity is crucial for targeting interventions that can potentially improve crop productivity, food security and livelihood sustainability.

Famers in Mtunthama EPA primarily cultivate tobacco as their main cash crop, while maize remains the key staple food for household consumption. Additionally, some farmers grow legumes, under limited production, often relying on locally sourced or recycled seed from previous years or passed on from others in the community. A wide range of farm sizes are found in this EPA with a considerable number of farmers having more than 5 acres of land. With respect to agroecological conditions, Central Region has high crop production potential, providing significant opportunities for intensive and diversified farming practices. The larger farm sizes in Mtunthama enable farmers to implement more sustainable and intensive mixed farming systems (MFS), incorporating both crop and livestock production.

This study was conducted in Mtunthama Extension Planning Area (EPA), in Kasungu District, Central Region, Malawi, selected as one of the Malawi action sites for the One CGIAR Initiative on Sustainable Intensification of Mixed Farming Systems (SI-MFS). The initiative aims to enhance agricultural productivity and improve livelihoods by enhancing sustainability using several socio-technical innovation bundles (STIBs). These include the introduction of climate-smart practices, improved soil fertility management, and the use of high-yielding crop varieties, all aimed at enhancing food security and resilience to climate change. The effects of these STIBs on farmers' livelihoods must be reliably monitored and evaluated using robust indicators.

The current study consisted of two steps, first summarizing the heterogeneity of farms in Mtunthama EPA by systematically allocating them to homogenous groups with respect to selected structural and functional indicators using statistical methods. A second step consisted of redesigning model farms per farm type, based on evaluation of farm performance and optimizing for production, environmental and profitability using the SI-MFS STIBs, and employing the FarmDESIGN model. Data was collected from focus group discussions (FGDs), and 44 household interviews carried out with smallholder farmers hosting mother trials in the initiative. Principal component analysis (PCA), multiple correspondence analysis (MCA) and cluster analysis were used to analyse quantitative and qualitative data variables and aggregate farms into farm types according to production means, socio-economics and demographics.

Four farm types were identified, viz (i) Farm Type I - High resource-endowed (ii)Farm Type II - Medium-high resource-endowed (iii) Farm Type III - Medium-low resource-endowed legume growers, and (iv) Farm Type IV - Low resource-endowed maize growers with no livestock income (resource constrained). Type I farms are characterized by larger land size and higher household income compared to the other farm types. Labor was identified as a major challenge, with high labour cost relevant for type I farms, while household size has more bearing for type II, III and IV farms. The farms types exhibited variable livelihood strategies, and all participated in markets to varying extents. Strengthening market links is therefore imperative for the community.

The use of multivariate methods allowed for the identification of the most discriminating variables for farm type delineation and subsequent clustering of farms. This forms the basis for further exploring variability across farm types for the targeting of management interventions for livelihood sustainability. Recommendations include crops rotation, strip cropping, conservation agriculture, access to micro loans facilities, agroforestry and other context-specific practices that address the unique conditions of each farm type to foster more sustainable and productive farming systems. By integrating various MFS activities in central Malawi, the Mtunthama EPA serves as a critical site for demonstrating the potential of sustainable intensification practices. This integration aims to enhance agricultural productivity and sustainability within the region.

Keywords: diversity, livelihood, maize-Legume, tobacco, multivariate analysis, targeted interventions, typology, sustainability

1. Introduction

Objectives of the study

1. To determine a farm typology that captures the diversity in farming systems and identifies similar farm types in the Mtunthama Extension Planning Area (EPA)
2. To identify the best socio-technical innovation bundles (STIBs) for each farm type to improve performance in sustainable intensification

2.0 Materials and methods

2.1 Site description

This study was conducted in Mtunthama Extension Planning Area (EPA) in Kasungu District, Central Region, Malawi (Figure 1). The climate in Kasungu district features distinct seasonal variations. from May to August, the region experiences a cool and dry winter season, with mean temperatures ranging from 17 to 27°C. This is followed by a hot and dry season extending from September to October, with average temperatures ranging from 25 to 37°C. Annually, Kasungu receives between 800 and 1,000 mm of rainfall, falling between November and April. However, with climate change, this has become shorter, often characterized by a late start, an erratic mid-season with dry spells and early cessation. Additionally, local variations in temperature and precipitation patterns are influenced by the area's complex topography (Chimonyo et al., 2023).

The district is characterized by medium-textured sandy loamy soils, which are prone to erosion and fertility decline. Patches of clay loam soils, which higher crop production potential can also be found in the area (Mvula, 2017). Poor agricultural practices such as monocropping without any soil conservation measures is contributing to the soil degradation and loss as reported by Mvula (2017). Kasungu District is well-known for its tobacco cultivation, however, other crops, such as maize and legumes, are also commonly grown in the area. Legumes are often intercropped with maize or cultivated on adjacent plots (Ngwira et al., 2013). In addition to tobacco, farmers also grow crops like cassava and sweet potatoes as cash crops (Chimonyo et al., 2023).

Farmers in Kasungu face significant challenges due to their dependence on unpredictable rainfall, limited land holdings, minimal use of agricultural inputs, and poor access to markets. Consequently, many households struggle to meet their nutritional needs, with one in three households unable to satisfy their daily per capita caloric requirements. In terms of livestock, the density of cattle in Kasungu is relatively low, ranging from 5 to 15 cattle per square kilometre. Farmers in the district rear various types of livestock, including cattle, sheep, goats, pigs, poultry, and rabbits, with a consistent increase observed in the populations of all these categories in recent years. However, the production and consumption of animal products remain very low, and irrigation practices are employed only on a small scale (Mvula, 2017). As a result, Kasungu experiences persistent food shortages at both the district and household levels (Chimonyo et al., 2023).

Mtunthama Extension Planning Area (EPA) is positioned at approximately 13.2756°S latitude and 33.2374°E longitude. The study was conducted across eight different sections within the EPA. Land holdings in Mtunthama EPA are larger, with considerable number of farmers having more than five acres, compared to southern Region of Malawi.

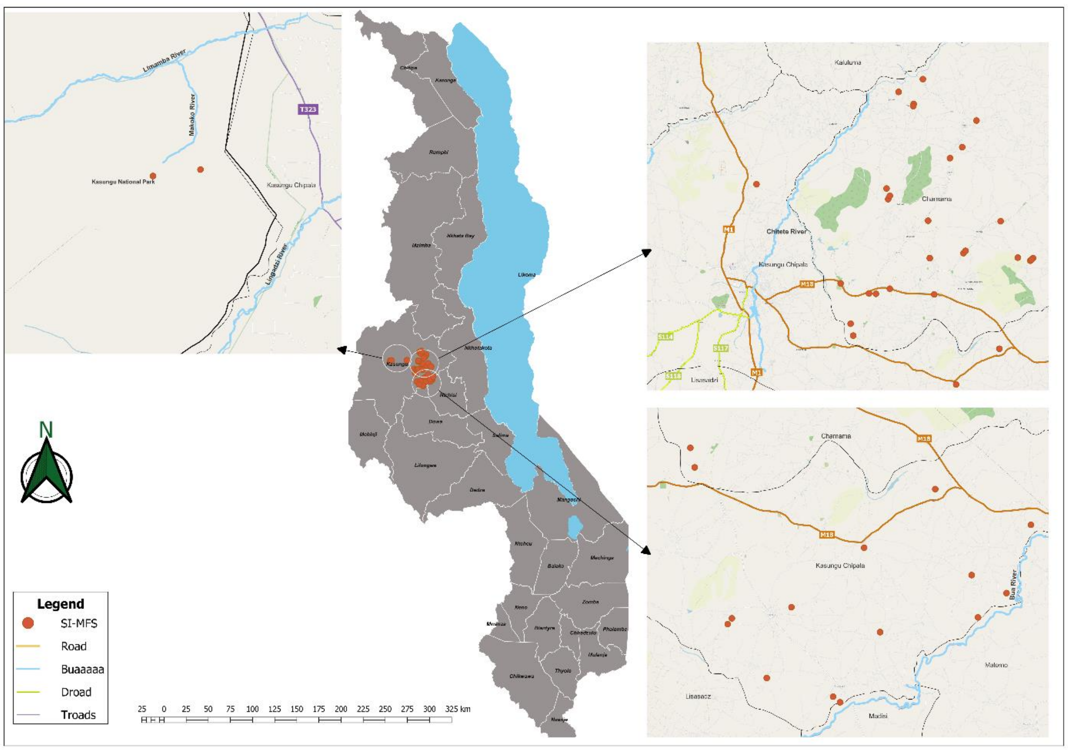

Figure 1 : Map of Malawi showing study areas

Data collection

In the 2023/2024 cropping season, a household survey was conducted to collect data to characterize local farming systems and their diversity, and to develop a statistical farm typology. This typology aimed to categorize farms into similar types and thereafter facilitate the selection of representative farms for modelling of whole farm performance in the FarmDESIGN model. The typology study formed the foundation for a comprehensive farming system diagnosis and the exploration of innovations using the whole-farm model FarmDESIGN. The exploration with this computer model generated recommendations for system redesign aimed at enhancing the productive, economic, social, human, and environmental performance of the farms compared to the current conditions.

Typology

Household survey data collection for typology in Katsikidzi section

In this study, farm types were delineated using two multivariate analyses: Principal Component Analysis (PCA) and K Means Clustering Analysis. These analyses were conducted with the statistical software R, utilizing the ade4 package, on a dataset of 44 baseline farms. The initial phase of the research involved early engagement with farmers, which was crucial to enhance contextual knowledge for determining the key characteristics that distinguish between different farm types. An early expert consultation served to develop a hypothesis on important farm characteristics to use to distinguish between farm types. Farms vary with respect to farming resources (land and labour) and their current integration of grain legumes into maize production. This hypothesis guided the selection of variables for PCA. The selected variables related to farm structure (operated area/ farm size, tropical livestock units), labour resource and constraints (total labour inputs, cost of hiring labour, proportion of total labour input used for land preparation and for weeding), income sources (crop, livestock and off-farm incomes) and legume practices (proportion of total operated area cultivated with legumes, years of experience in growing legumes and farmer's legume evaluation). The hierarchical clustering allowed classification of the farms into different farm types. The typology method was based on the guidelines set out in Alvarez et al. (2014).

Data analysis

Principal Component Analysis (PCA)

Principal Component Analysis (PCA) is used where the data involves multiple variables that may be highly correlated, to reduce the dimensionality of the data while retaining most of the original variance (Lattin et al. 2003). In our study, PCA was used to group quantitative variables that influence farm productivity into uncorrelated principal components. The primary goal was to identify and simplify the complex relationships among the variables to better understand their collective influence on farm type classification and productivity. To ensure that all variables were comparable despite being measured on different scales, standardization was performed, as recommended by Mooi & Sarstedt (2011). This process standardized the variables, allowing them to be treated equally in the analysis.

Principal components were then generated based on a correlation matrix and rotated using Varimax rotation (Lattin et al. 2003). The Varimax rotation technique was employed to eliminate multi-collinearity among the components, making the interpretation of the results clearer by maximizing the variance of squared loadings for each principal component. The eigenvalue of each principal component, which represents the variance explained by that component, was used to determine which components were significant. Following the criteria set by Lattin et al. (2003) and Swan & Sandilands (1995), only principal components with eigenvalues greater than 1 were selected for further analysis, as these were considered to significantly explain the variability in farm types.

Within each principal component, variables with a factor loading greater than 0.5 were retained, as suggested by Jagadamma et al. (2008). Variables with lower factor loadings were discarded, as their contribution to the component was deemed minimal. In cases where multiple variables within a principal component were highly correlated, the variable with the highest loading coefficient was retained to represent the principal component, thereby reducing redundancy.

3.3. ***Multiple correspondence analysis (MCA)***

MCA was used to reduce data dimensions through exploration of relationships among the categorical variables. This analysis uses cross tabulations and gives graphical presentation of the relationships in a low dimensional plane. Correspondence analysis is based on the computation of a data matrix of frequencies (Savary *et al.*, 1995). Two dimensions of data presentation are commonly considered as adequately facilitating data visualization and interpretation (Gifi, 1996; Savary *et al.*, 1995). Similar, to PCA, eigenvalues are used to determine the significance of a dimension in accounting for variability. The sum of eigenvalues is called inertia and represents the chi-square statistic divided by the total number of observations (Greenacre, 1984). An inertia value > 0.2 and a Cronbach's alpha score, were used as basis for dimension selection and retention (Hair *et al.*, 1998; Johnson & Wichern, 2007). Discrimination measures plots and joint plots of category points were used to identify category relationships (Costa *et al.*, 2013).

3.4 Cluster analysis

Cluster analysis was used to identify homogenous groups of farms based on the PCA and MCA selected variables. The selected variables were subjected to a 2-step cluster analysis. The 2-step clustering procedure combines the principles of hierarchical and non-hierarchical (*K* means) methods (Mooi & Sarstedt, 2011). Hierarchical cluster analysis uses an agglomerative clustering algorithm which utilizes multi-dimensional distances between entries as the basis for separation and selection of number of clusters. In *K* means clustering, cluster solutions are optimized until maximum homogeneity within clusters is achieved through reassigning of cases to clusters (Hair *et al.*, 2010). Two step cluster analysis has the advantage of allowing grouping of cases using a mixture of continuous and categorical variables in a single pass.

Table 1: Loading variables in the selected principal components

	Principal Component			
	1	2	3	4
Age	0.110173	0.191907	0.02264151	0.104639987
Household income	0.361127	0.746552	0.60282815	0.815989612
Percentage Farm Income	0.412231	0.144288	0.29504549	0.108408239
Total Livestock Units	0.480014	2.392391	0.76746623	0.633344074
Total Land	0.311172	0.541947	0.26382083	0.394244304
Average Maize yield (kgs)	0.356402	1.486135	0.15871185	0.486531366
Percentage Legume Area	1.013331	0.486036	0.37531874	0.188559587
Count_intens_options	0.406364	1.064209	0.57735027	0.289182757
Count_sust_practices	0.411459	0.836036	0.32732684	0.390326561

Table 2: Quantitative variables used in principal component analysis (n = 43).

Variable	Minimum	Maximum	Mean	Standard Deviation
Age	32	66	44.7209	7.1124
Household income	50000	7000000	0.8556	1366549.4733
Percentage Farm Income	0.1	1	0.5453	0.1756
Total Livestock Units	0	4	5.7035	0.7362
Total Land	1	25	2465.5349	3.8662
Average Maize yield (kgs)	250	10000	0.4140	2158.3808
Percentage Legume Area	0	0.71	1.3256	0.1658
Count in terms of options	0	3	2.5349	0.8923
sustainable practices	0	6	2.7209	1.4532

3.0 Results

The local farming systems were grouped into four farm types mainly according to their resource endowment, income source and labour constraints (Table 1). These farm types represent characteristics that contribute to agricultural productivity, economic viability, social conditions, nutritional outcomes, and environmental sustainability (Timler et al., 2023).

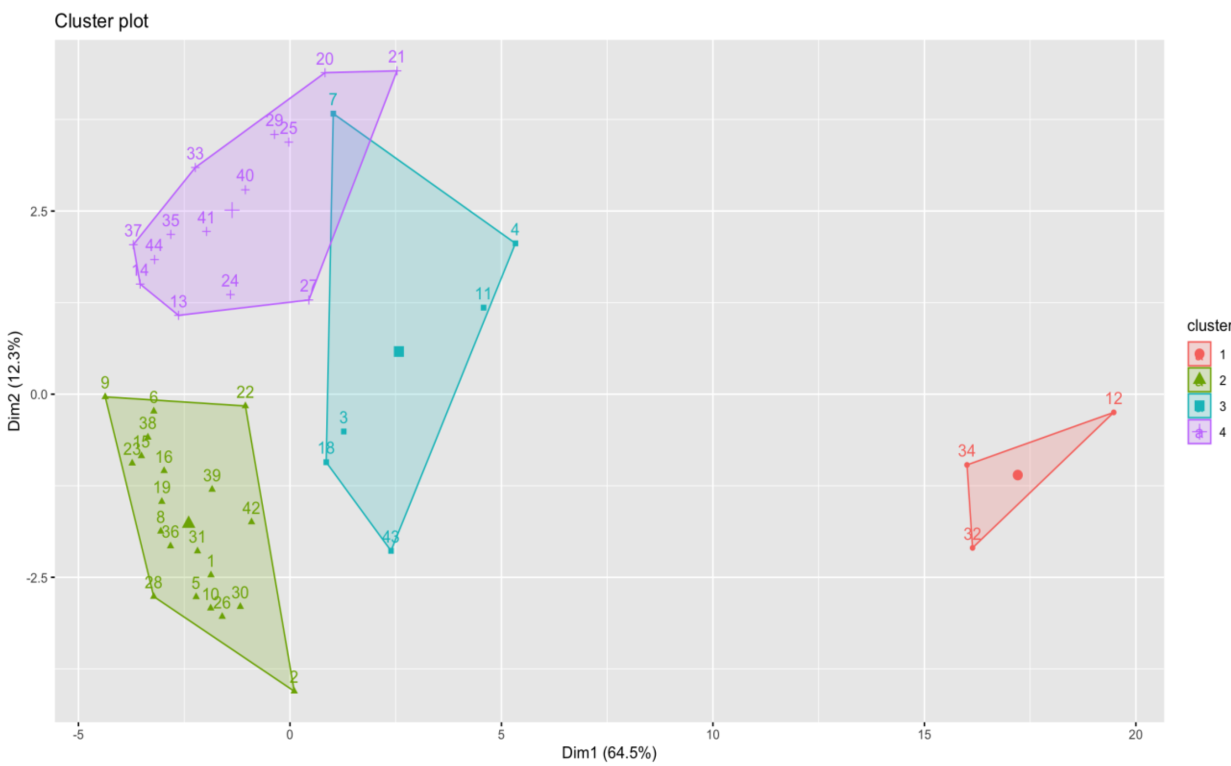

Figure 3: Cluster plot showing the farm types occurring at Mtunthama Extension Planning Area (EPA)

The results from the box plots (Fig 2) highlights key differences across the four-farmer types, Far type I - Large, Farm Type II - Young, Farm Type III - Intermediate (Interm), and Farm type IV - Older. The Older farm type has the highest average age (60 years), while the *young* farmers are, on average, around 40 years old. In terms of income, the *large* farms generate the highest household income, averaging approximately MK6,500,000, while the *young and older* farmers have significantly lower incomes of about MK1,000,000. Most farm types (Young, Intermediate, and

Older) derive around 70-80% of their income from farming, while the Large farms rely on about 65%. Livestock ownership is highest among the Large farms, with an average of 4 TLU (Tropical Livestock Units), compared to less than 1 TLU for the other farm types. Similarly, Large farms have the largest farm area (20 acres), while Young farmers manage the smallest (<5 acres). The Large farms also achieve the highest maize yield, averaging around 8,000 kg/ha, whereas the older farms have the lowest yield (<2,000 kg/ha). In terms of legume cultivation, the Intermediate and older farm types allocate a higher proportion of their farm area to legumes (around 50-60%), while the Large farms dedicate the least (20%). Regarding intensification options, the Intermediate farms adopt the most (4), while Large farms utilize fewer (2). Lastly, sustainable farming practices are more common among the Young and Intermediate farm types (4-5 practices), while the older farms average fewer (2). Overall, the Large farms excel in productivity and economic measures, while the Intermediate and Young farm types focus more on sustainability and diversification in their farming practices (Fig. 4)

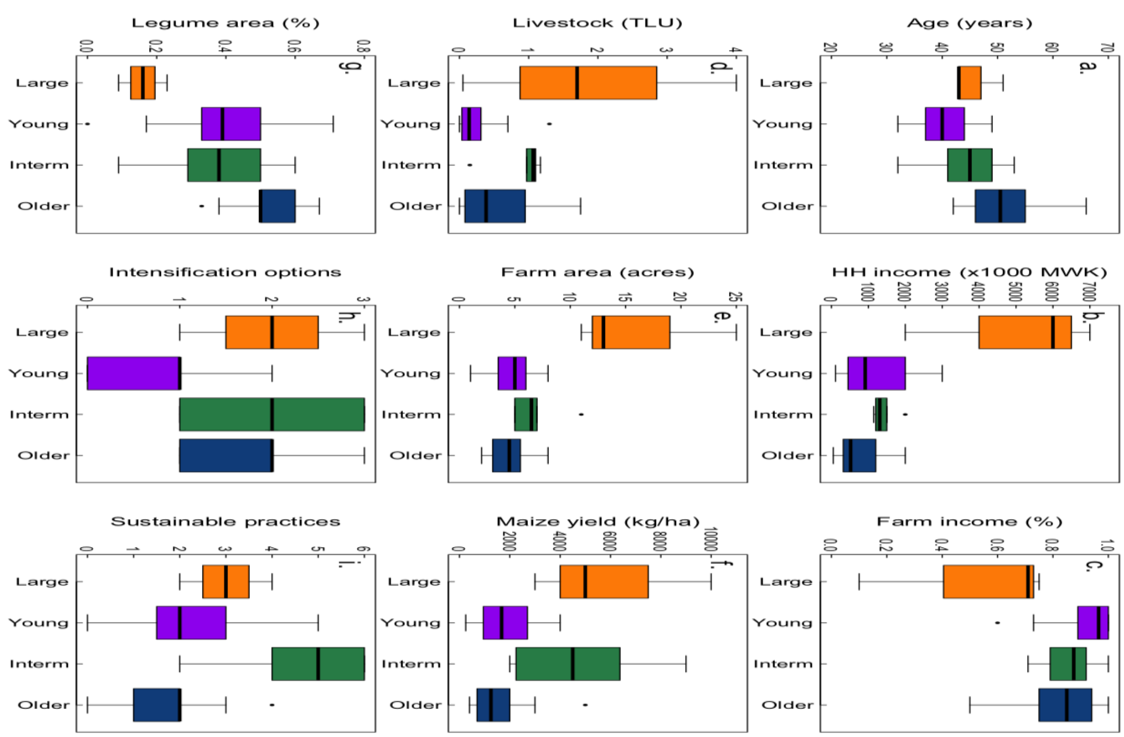

Figure 4: Box plot showing comparison of key variables across the groups of farmers delineated in Mtunthama EPA

Farm type 1: High resource-endowed, high crop yield, and animal income farms

This farm type is the smallest, representing only 6.9% of the surveyed farms. It was classified as the resource-endowed commercial oriented farm type. Land holding on these farms is the largest, with an average of 16 acres, of which a significant proportion is utilised for crop production (Table 4). Maize is produced on average at 6t while household income is large relative to the other farm types (Table 3). Household heads within type I farms are aged between 40–59 years. These farms (3 farms) have the largest number of animals among all farm types. These farms also have the highest proportion of farmers engaged in cash crop production such as tobacco. To optimize their profits, they dedicate more labour to farming activities compared to other farm types. Family members also contribute significantly to on-farm labour besides hired labour, and these farms also use herbicides. Their farms feature a variety of crops, including maize, groundnuts and tobacco, and raise livestock such as cattle, goats, and chickens. Their farm sizes offer the flexibility needed for sustainable intensification, with potential for incorporating practices like rotational grazing, crop rotation, agroforestry and many others for soil healthy improvement. While these farms have considerable experience in legume cultivation, they allocate a relatively small proportion of their cultivated area to legumes compared to other types.

Farm type 2: Medium-low resource-endowed, legume growers

This farm type represents nearly half of the surveyed households, making it the largest group. Households in this farm type have moderate resources, with landholdings of about 4.7 acres and an average income of Mk1,133,150. These farms balance subsistence and cash crop production, with a significant portion of land devoted to maize and legumes. They rely heavily on family labor for farming, indicating limited financial resources for hiring additional help. The average age of the farmers in this group is 40. These farmers dedicate approximately 33% of their land to legume cultivation. They own a limited number of livestock. Their focus on legume production gives a room for the adoption of sustainable intensification practices, such as strip cropping, which helps optimize land use. The presence of legumes also contributes to soil health by naturally fixing nitrogen (Chikowo et al., 2014), promoting environmental sustainability. Economically, farmers in this farm type operate on a smaller scale compared to those in Farm types 1 and 3, but they remain economically viable by allocating part of their land to high-value crops like legumes. These crops are both marketable and nutritious, providing a source of income while supporting food security (Thierfelder 2022).

Farm type 3: Medium-high resource-endowed, legume and maize growers, medium animal Income

The farmers in this group are characterized by a moderate farm and family size, intermediate animal numbers, and average income levels compared to other farm types (Table 1). These farms typically have around seven acres of land allocated for cultivation. There are six farmers in this farm type, resident in three sections within Mtunthama EPA. This farm type is characterized by moderate land and livestock ownership, which drives crop productivity and economic sustainability. Farmers in this group are also characterized by their higher maize yields than other farm types. These farmers are well-positioned to achieve food security and nutritional benefits since they also dedicate a considerable portion of their land to legumes and other crops like tobacco. This provides opportunities for diversifying agricultural production and income stability in their families.

Farm type 4: Low resource-endowed, maize growers, no livestock Income (resource constrained farmers)

This farm type includes about one-third of the households and represents resource-constrained farms. Farmers in this group dedicate their land to maize as a staple food, they are characterized with low resource endowment, minimal legume cultivation, and no livestock income. This group has fourteen farmers who are generally characterized by their relatively small size in terms of both family and farm area, as well as limited animal numbers. These farms exhibit similarities in household size, cultivated land area, crop diversity, per capita income, and total labour inputs compared to other farm types. Farmers in this category allocate a significant portion of their labour to farming activities such as land preparation, weeding, and harvesting. This is largely because they rely on family labour and do not use herbicides, which necessitates more intensive manual effort. Due to the lack of livestock and limited financial resources, these farmers face greater food insecurity compared to other farm types. The older mean age (50.9 years) may also limit the adoption of new practices or technologies, as older farmers may be less willing to take on the risk associated with innovation. These farmers dedicate the smallest proportion of their cultivated land to legume production. The limited resources and minimal legume cultivation contribute to the overall challenges faced by these households, making it difficult for them to achieve stable food security and economic stability.

Table 3: Farm type characteristics

Table 4: Farm type characteristics

Variable	Farm type			
	(%n=6.98)	(%n=46.5)	(%n=13.39)	(%n=32.56)
	Type I	Type II	Type III	Type IV
Mean Age	45.66667	40.4	44.1666667	50.92857143
Mean Household income	5000000	1133150	1410833.33	785000
Mean Percentage Farm Income	0.52	0.9245	0.86166667	0.826428571
Mean Total Livestock Units	1.916667	0.2415	0.92	0.525
Mean Total Land	16.33333	4.7	6.83333333	4.375
Average Maize yield (kgs)	6000	1823.15	4770.83333	1637.857143
Mean Percentage Legume Area	0.16	0.3935	0.37333333	0.515
Mean Count_intensification options	2	0.7	2	1.785714286
Mean Count_sustainable_practices	3	2.25	4.66666667	1.928571429
Categorical variables	% of N			
Age of household head				
20-29	0.0	0.0	0.0	0.0

30-39	0.0	40.0	16.7	0.0
40-49	66.7	60.0	66.7	35.7
50-59	33.3	0.0	16.7	57.1
60+	0.0	0.0	0.0	7.2
Proportion of land cultivated (%)				
0-4	0.0	40.0	0.0	50.0
5-9	0.0	60.0	83.3	50.0
10+	100.0	0.0	16.7	0.0
Household head highest education				
Never attended	0	5	0	0
Primary school	33.33	35	50	78.6
Secondary school	33.33	60	50	11.4
Tertiary	33.33	0	0	0

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