

Assessing Sustainable Intensification Options for Maize Across Diverse Farm Types in central Malawi

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Abstract

Smallholder farming systems in Sub-Saharan Africa are highly heterogeneous in terms of resource endowment and livelihood objectives, posing challenges for the design of effective agricultural interventions. In this study we characterise farm system diversity in Mtunthama Extension Planning Area, Kasungu District, Malawi, and evaluate the suitability of sustainable intensification innovations across farm types. Data were collected through focus group discussions and household surveys involving 43 farming households. Principal Component Analysis was used to construct a farm typology, while innovation suitability was assessed using a multi-criteria decision analysis framework.

The analysis identified four distinct farm types reflecting differences in resource endowment and production orientation: High Resource-Endowed farms (HRE), Moderately resource-endowed farms with Mixed crop-livestock orientation (MCL), Diversified Cropping systems (MDV), and Resource-Constrained Maize-dominated farms (RCM). The multi-criteria assessment revealed substantial variation in suitability across types. Conservation agriculture recorded the highest overall score (0.68), followed by intercropping (0.54), while strip cropping showed the lowest (0.25). MDV achieved the highest overall innovation score (0.66), whereas MCL and RCM showed limited uptake.

These findings demonstrate that sustainable intensification effectiveness is shaped not only by resource endowment, but by distinct trade-offs between productivity, income, and sustainability. In particular, the decoupling of maize yield and household income suggests that intensification pathways are context-specific. The framework presented here provides a useful approach for identifying which practice combinations are most appropriate under different structural conditions, offering a practical basis for designing adaptive intervention strategies.

1 Introduction

The global population is projected to reach approximately 9.7 billion by 2050, creating an urgent challenge for food security (Jayne & Sánchez, 2021; Kim et al., 2021). To meet the growing demands of this expanding population, agricultural production must increase at a rate that keeps pace with population growth. However, agricultural productivity is constrained by several global factors, including land scarcity due to population pressures and the adverse effects of climate change (Jayne & Sánchez, 2021; Kim et al., 2021). These challenges are particularly pronounced in Sub-Saharan Africa (SSA), where rapid population growth coincides with a heavy reliance on subsistence farming (Okello et al., 2020). In SSA, the majority of farmers are smallholder farmers who primarily rely on subsistence agriculture for food and income (Giller et al., 2021; Kamara et al., 2019). However, these farmers face numerous challenges in producing adequate cereal and legume crops to meet their families' nutritional needs (Kamara et al., 2019). These challenges are exacerbated by limited access to resources (Giller et al., 2021; Kim et al., 2021), raising serious concerns about food security in Eastern and Southern Africa, where agriculture is predominantly rain-fed (Corbeels et al., 2020; Nyagumbo et al., 2020). In response to these challenges, global policy initiatives have emphasised the need for sustainable agricultural

development. In 2015, United Nations member states jointly pledged their support for 17 Sustainable Development Goals (SDGs), with SDG2 aiming to “end hunger, achieve food security and improved nutrition, and promote sustainable agriculture” by 2030 (Okello et al., 2020). However, achieving SDG2 in SSA remains a significant challenge, as rapid population growth is projected to triple the demand for major cereals and double the demand for animal-sourced food by 2050 (Jayne & Sánchez, 2021; Kim et al., 2021). Additionally, climate change is expected to alter rainfall and temperature patterns, potentially creating climate conditions with no present-day analogues. Given these challenges, farmers must adopt adaptive farming systems that align with their environmental conditions while addressing the ongoing need for soil fertility management to sustain agricultural productivity.

While many challenges faced by smallholder farmers are common across regions, the interaction of biophysical and socio-economic factors results in farm diversity within and across landscapes. In most regions of SSA, soil types and fertility management practices have led to variations in soil health across farms (see(Corbeels et al., 2020; Vanlauwe et al., 2019). Additionally, differences in resource endowment, land ownership, production orientation, and farm objectives further contribute to complex and dynamic farm typologies (Hammond et al., 2020; Huber et al., 2024; Kuivanen et al., 2021; Lopez-Ridaura et al., 2019; Nyambo et al., 2019). Recent advances in farm typology frameworks integrate ex-ante assessments and trade-off analyses to evaluate intervention impacts across heterogeneous systems (Huber et al., 2024; Komarek et al., 2019). The failure of agricultural technologies to account for this complexity has historically limited their adoption (Hermans et al., 2020; Jones-Garcia & Krishna, 2021), participatory and data-driven approaches now enable tailored interventions (Giller et al., 2021; van Wijk et al., 2020). Understanding farm diversity through these lenses is critical to move beyond one-size-fits-all recommendations (Giller et al., 2021; Huber et al., 2024). This approach improves the relevance, applicability, and adoption of agricultural innovations.

The concept of farm typologies helps identify farm groups based on similar attributes, including social, structural, and operational characteristics (Huber et al., 2024; Nyambo et al., 2019). Participatory approaches have been used to categorise farms accordingly (Carelsen et al., 2021; Huber et al., 2024). While community-based classifications offer advantages in farmer engagement, they may overlook individual farm-level variations. Since decision-making and production orientation are largely household-driven, farm classifications should reflect household characteristics rather than broad community traits. Increasingly, multivariate statistical techniques such as Principal Component Analysis (PCA), Multiple Correspondence Analysis (MCA), and Cluster Analysis have been used to identify farm typologies across diverse farming systems (Hammond et al., 2020; Huber et al., 2024; Kuivanen et al., 2021; Nyambo et al., 2019). Agricultural production and productivity are central to achieving livelihood sustainability and food security, particularly in smallholder systems (Huber et al., 2024; Mutyasira, 2020). One promising approach to addressing the challenges faced by smallholder farmers is through farm clustering or typology identification, which groups farms with similar structural and functional characteristics. This approach enables the development of tailored farm designs and interventions that are more closely aligned with the specific needs, resources, and goals of different farm types (Huber et al., 2024; Mutyasira, 2020; Nyambo et al., 2019). Beyond its role in improving farm-level decision-making, farm

typology analysis supports broader development goals by facilitating the scaling of innovations, targeting of extension services, and formulation of policies that reflect on-the-ground realities (Hammond et al., 2020; Kuivanen et al., 2021).

In Malawi, as in much of Sub-Saharan Africa, smallholder farmers form the backbone of agricultural production. Legume integration is a cornerstone of sustainable intensification strategies due to its multifunctional roles: it can enhance soil fertility through biological nitrogen fixation, provide protein-rich food for improved nutrition, and offer marketable products for income diversification. Crucially, legumes present a diverse array of integration options, such as rotation, intercropping, and strip cropping, that can, in principle, be tailored to fit varying resource endowments and labour availability (Gwenambira-Mwika et al., 2021; Muoni et al., 2024; Mupangwa et al., 2021; Ngwira et al., 2020). Yet, the persistent mismatch between uniform technology recommendations and diverse farmer realities means this potential remains underutilised.

Our study addresses this gap by applying a farm typology approach to better understand and classify the diversity of smallholder farming systems in Mtunthama Extension Planning Area (EPA), a representative smallholder farming region in central Malawi. By integrating multivariate statistical methods with participatory insights, the study identifies distinct farm types and their associated constraints. These types serve as a basis for designing more context-appropriate legume-based interventions, such as improved varieties, rotations, and resource-conserving practices, tailored to the specific capacities and challenges of each farm type. Ultimately, this research aims to contribute to more effective, equitable, and scalable agricultural innovations that enhance food security, soil fertility, and resilience in Malawi's smallholder sector.

The objective of this study was to characterize the diversity of farming systems in Mtunthama Extension Planning Area (EPA) in Kasungu District, central Malawi, with a particular focus on resource endowment and legume cultivation practices, and to generate actionable insights that could inform the design and targeting of sustainable intensification (SI) interventions at the farm level. Data from farm interviews and focus group discussions were analyzed to identify constraints and opportunities across different farm categories, thus providing a nuanced understanding of the farming landscape.

2 Materials and methods

2.1 Site description

The climate in Kasungu district (Fig. 1) is characterised by distinct seasonal variations. A cool and dry winter season occurs from May to August, with mean daily temperatures ranging from 17 to 27°C. This is followed by a hot and dry season from September to October, with average daily temperatures between 25 and 37°C. The warm, wet season extends from November to April, bringing the majority of annual rainfall (800–1,000 mm) through convective storms, with mean daily temperatures of 20–30°C. Peak rainfall typically occurs between December and March, coinciding with the cropping season. However,

local variations in temperature and precipitation patterns are influenced by the area's complex topography.

The district's soils are predominantly medium-textured sandy loam, which are prone to erosion and fertility depletion. Patches of clay loam soils, which are more suitable for crop cultivation, are also found in the area. Poor agricultural practices, such as monocropping without soil conservation measures, contribute to soil degradation and fertility loss (Corbeels et al., 2020; Vanlauwe et al., 2019). Maize is the staple food crop, while tobacco is an important cash crop in the district. Legumes, which are grown by 65% of farmers, rank third in economic importance, with soybean and groundnuts occupying 15–20% of cultivated area, often intercropped with maize (Gwenambira-Mwika et al., 2021; Ngwira et al., 2020). Both soybean and groundnut are grown for cash, while groundnut is also utilised at home for dietary purposes. Secondary crops such as cassava and sweet potatoes are also cultivated as food and climate-resilient alternatives.

Farmers in Kasungu face significant challenges due to their reliance on rain-fed agriculture, small landholdings, limited access to agricultural inputs, and poor market linkages. As a result, many households struggle to meet their nutritional needs, a challenge documented in recent research on maize–legume systems in Malawi (Muoni et al., 2024). Farmers rear various livestock species, including cattle, sheep, goats, pigs, poultry, and rabbits. However, livestock production remains low. Livestock production remains limited, reducing the contribution of animal products to household food security and income (Giller et al., 2021). While livestock populations have increased, the production and consumption of animal products remain low, exacerbating the food and nutrition issues highlighted previously (Giller et al., 2021).

The research was conducted across eight of twelve sections in Mtunthama EPA, providing a setting in which farm diversity can be examined under relatively lower land-fragmentation constraints. An Extension Planning Area (EPA), as defined by the Malawi Ministry of Agriculture in 2023, is a sub-district administrative unit that serves as the primary operational hub for delivering decentralised agricultural extension services, bridging the gap between district-level policy and field-level implementation for smallholder farmers.

2.2 Focus Group Discussions

To understand smallholder farmers' perceptions, practices, challenges, and aspirations within Mtunthama EPA, a qualitative research approach was adopted using two Focus Group Discussions (FGDs). These discussions were part of the initial participatory activities under the Sustainable Intensification of Mixed Farming Systems (SI-MFS) initiative. The FGDs were conducted in August and September 2023 and took place at the Mtunthama EPA office, an accessible and centrally located venue for participants. Prior to the FGDs, introductory meetings were held with key stakeholders at the District Agriculture Office. These included officers from the crop, livestock, irrigation, food and nutrition, and planning departments. These preliminary engagements helped align the SI-MFS initiative with existing local development structures and provided valuable contextual insights into the district's agricultural

systems. Participants for the FGDs were purposively selected to ensure diversity across gender and age groups and to reflect a range of farming experiences. 45 farmers were involved in total, grouped into older men, younger men, and women. Each group comprised 15 participants, who were lead or representative farmers from different villages within the EPA. Local extension officers and the research team facilitated participant mobilisation.

The discussions were conducted using a semi-structured interview guide designed to generate in-depth and context-specific insights into farmers' lived experiences and farming systems. The guide was developed collaboratively by SI-MFS researchers and was structured around three core questions:

- What are your main challenges related to productivity, environment, nutrition, human capital, and profitability?
- What are the most important value chains in your farming system, and what production practices support them?
- What changes or improvements do you aim to implement on your farm in the coming years?

Each focus group session lasted approximately 90 minutes and was facilitated by a trained moderator from the SI-MFS research team with support from local translators where necessary. Sessions were conducted in a neutral and comfortable setting to promote open and inclusive participation. Separate facilitators led each group to ensure tailored engagement and to reduce response bias.

2.3 Typology construction

A structured household survey was conducted through face-to-face interviews with 44 smallholder farmers in Mtunthama EPA. These farmers were purposively selected as they were participants in the SI-MFS mother-baby trials, serving as key contact points for the co-design and testing of sustainable farming innovations. Data were collected using KoboToolbox, a digital survey tool that enabled efficient and accurate data capture in the field (www.kobotoolbox.org). The survey gathered detailed quantitative information on farm characteristics, resource endowments, management practices, and production constraints, providing a foundation for typology development and guiding targeted interventions. One household was subsequently excluded from the typology analysis due to incomplete survey response, resulting in a final analytical sample of 43 households. The variables used for typology construction were selected based on literature (Huber et al., 2024; Nyambo et al., 2019), insights from the FGDs, and expert judgment. These variables captured differences in farming resources (land, labour), income streams (including off-farm income), integration of legumes (acreage, years of experience in growing legumes), tropical livestock units (TLU), total labour inputs, cost of hiring labour, proportion of labour used for land preparation and weeding, crop and livestock enterprises, and the farmer's evaluation of legumes.

2.4 Ethical considerations

Ethical clearance for this study was obtained from the Department of Agriculture Research Services prior to data collection. Informed consent was obtained from all participating farmers, and confidentiality of

individual responses was maintained throughout the study.

2.5 Data analysis

2.5.1 Cluster analysis

All statistical analyses were conducted in R version 4.5.2, using the packages FactoMineR, cluster, and agricolae for PCA, MCA, and cluster analysis.

Farm typologies were derived using a two-step cluster analysis. First, hierarchical clustering (agglomerative method, Gower's distance) suggested an initial number of groups. Second, k-means clustering was applied to the principal components from the PCA and dimensions from the MCA to finalize the farm groupings and maximize within-cluster homogeneity. The optimal number of clusters was determined by evaluating statistical metrics (fusion coefficients, discrimination measures > 0.3) and ensuring alignment with qualitative insights from the FGDs, following established typology development frameworks (Hammond et al., 2020; Huber et al., 2024; Nyambo et al., 2019).

2.6 Multi-criteria analysis for targeting sustainable intensification options

A Multi-Criteria Decision Analysis (MCDA) was used to evaluate and rank Sustainable Intensification (SI) options for suitability across the identified farm typologies. The analysis served as a decision-support framework to use farm typologies to derive tailored recommendations for technology use. It assessed disaggregated SI components (e.g., legume rotations, micro-dosing) against five weighted criteria: productivity potential, feasibility of adoption, economic viability, resource use efficiency, and scalability. This approach aligns with frameworks that emphasize context-specific evaluation of agricultural innovations (Cicciù et al., 2022; Hammond et al., 2021; Iocola et al., 2020; Schaafsma et al., 2025).

2.6.1 SI innovation disaggregation

The sustainable intensification (SI) options evaluated in this study were identified from practices currently implemented by farmers in the study area, based on focus group discussions and household survey data. These practices were not assessed as fixed technological packages but were instead operationalised as distinct innovation categories reflecting key management strategies observed in the field. The innovations considered included conservation agriculture, intercropping, small livestock integration, legume–maize rotation (cover cropping), and strip cropping.

Rather than evaluating individual technical components (e.g., minimum tillage or residue retention) in isolation, each innovation was represented using indicators derived from farmer-reported adoption and related management variables. These indicators were subsequently standardised on a 0–1 scale to enable comparison across farm types. The scaled scores were then aggregated to generate farm-type-specific performance values for each innovation, as well as an overall innovation score. This approach allowed for a comparative assessment of the relative performance and adoption of different SI practices

across farm typologies, while reflecting the integrated nature of how these innovations are implemented in practice. Similar approaches have been used in multi-criteria assessments of farming systems to capture variation in technology performance across heterogeneous smallholder contexts (Cicciù et al., 2022; Lopez-Ridaura et al., 2019; Schaafsma et al., 2025), while research on sustainable intensification stresses the need to assess trade-offs across productivity, feasibility, and environmental outcomes (Haggar et al., 2020).

2.6.2 Criteria definition and justification of evaluation criteria

Five evaluation criteria were selected to reflect key dimensions of sustainable intensification in smallholder farming systems, while remaining consistent with the variables available in the dataset. These criteria captured both biophysical performance and socio-economic feasibility, and were operationalised using quantitative indicators derived from household and farm-level data. In addition to generating composite innovation scores, each criterion was also retained as a separate indicator to allow for disaggregated analysis across farm types.:

- **Productivity potential:** was assessed using observed crop yields, particularly maize and legume yields derived from farmer records and plot-level data. These indicators capture the capacity of each innovation to contribute to crop output under existing management conditions.
- **Feasibility of adoption:** was approximated using household resource endowment indicators, including landholding size (acres), livestock ownership (TLU), and labour availability (proxied by household size and labour-to-land ratios). These variables were standardised to a 0–1 scale and combined to reflect the relative capacity of households to implement different innovations.
- **Economic viability:** was represented using farm income indicators, particularly income per hectare, as a proxy for the economic performance of farming activities.
- **Resource use efficiency:** was assessed using indicators related to management practices, including the adoption of sustainable practices and integration of crop–livestock systems. Variables such as the count of sustainable practices and livestock density (TLU per acre) were used as proxies for the efficient use and recycling of farm resources.
- **Scalability and replicability:** were inferred from the observed prevalence and distribution of innovations across farm types. Innovations that were widely adopted across multiple farm types were considered more scalable, while those concentrated within specific groups were interpreted as more context-dependent.

These criteria were selected not only for their relevance to smallholder contexts but also to comprehensively address the five pillars of Sustainable Intensification: productivity, economic viability (Giller et al., 2021; Hammond et al., 2021; Schaafsma et al., 2025).

2.6.3 Scoring and Weighting Procedure

Each farm type's performance under each SI innovation component was scored on a standardised 0–1 scale using min–max normalisation. Scores based on quantitative indicators (e.g., yield, income, land size, livestock units) were computed directly from household survey data and aggregated to farm type means.

For criteria where direct quantitative measurement was not feasible (e.g., residue utilisation and scalability), scores were derived through expert-informed assessment, based on consultations with extension officers and field observations collected during the study. In these cases, scoring reflected the relative suitability of each innovation for different farm types given their resource endowment profiles. For example, farm types with higher land, labour, and livestock resources were assigned higher feasibility scores for labour- and capital-intensive practices.

To ensure consistency, all scoring procedures were guided by predefined criteria and cross-checked across the research team.

To avoid bias in aggregation, all criteria were assigned equal weights in the base model, following recent sustainable-intensification assessment guidance (Cicciù et al., 2022; Iocola et al., 2020). Sensitivity analyses were conducted using alternative weighting schemes to test the robustness of the results. Because farm-type-by-criterion score data were not retained for a criterion-level re-weighting, this sensitivity check was implemented by re-weighting the five sustainable intensification innovations reported in Table 5 rather than the five underlying scoring criteria; results are presented in supporting information Table S1.

The final composite score for each SI innovation was calculated using a weighted additive model:

$$\text{Composite score} = \sum_{i=1}^n w_i \times s_{ij}$$

Where:

- w_i is the weight for criterion i ,
- s_{ij} is the normalised score of innovation j on criterion i ,
- n is the total number of criteria (5 in this case).

Multi-criteria analysis scores were used to rank SI innovations by their suitability for each farm typology. This process allowed for cross-type comparison and informed the most appropriate SI innovations per farm type. The MCDA thus complemented the farm typology and yield analysis by providing a structured, context-sensitive framework for matching SI interventions to the real-world constraints and opportunities faced by different smallholder farm households.

3 Results

3.1 Focus Group Discussions

The focus group discussions identified a range of constraints affecting agricultural production and livelihoods in Mtunthama Extension Planning Area (EPA). These constraints were grouped into productivity, environmental, economic, institutional, and nutritional domains (Table 1).

Limited access to inorganic fertilisers and reliance on recycled seeds were frequently reported constraints affecting crop productivity. Farmers reported that high input costs and transport expenses reduced their ability to purchase certified seed and fertiliser. Livestock production was constrained by shortages of feed, limited access to improved breeding stock, and disease outbreaks such as African swine fever and Newcastle disease.

Environmental challenges included unreliable rainfall patterns, soil erosion, and deforestation. Farmers reported late onset and early cessation of rains, which affected crop planning and yields.

Economic constraints included poor market prices, limited access to capital, and weak market linkages. Farmers indicated that crops were often sold to vendors at low prices due to lack of organised markets.

Institutional challenges included limited access to extension services due to a low extension officer-to-farmer ratio. However, some farmers reported accessing agricultural information through radio, television, and mobile phones.

Table 1
Agricultural constraints identified during focus group discussions in Mtunthama EPA.

Domain	Key constraints	Illustrative description
Productivity	Limited fertiliser access; recycled seeds; high input costs; limited improved livestock breeds	Farmers reported difficulty purchasing fertiliser and certified seed, reducing yields
Environment	Unreliable rainfall; soil erosion; deforestation	Erratic rainfall reduced crop productivity
Profitability	Poor market prices; lack of capital	Farmers reported selling crops at low prices
Social/Institutional	Limited extension services; weak group leadership	Extension coverage reported to be limited
Human/Nutrition	Poor dietary diversity; limited consumption of livestock products	Households prioritised crop sales over consumption

Farmers also identified the major crop enterprises cultivated in the area and their relative importance for food security and income generation.

Table 2
Relative importance of crop enterprises identified during focus group discussions

Enterprise	Importance score (1–10)	Primary role
Maize	10	Staple food crop
Tobacco	8	Main cash crop
Livestock	7	Income diversification
Vegetables	7	Household food and income
Groundnuts	5	Secondary food and cash crop
Soybean	4	Secondary cash crop
Cassava	3	Food supplement
Sweet potatoes	3	Food supplement

3.2 Farm Typology Construction

3.2.1 Principal Component Analysis

Principal Component Analysis (PCA) was conducted to reduce the dimensionality of the dataset and identify key underlying farm system characteristics. Four components with eigenvalues greater than one were retained based on the Kaiser criterion and scree plot inspection. Component 1 explained 34.6% of the variance, component 2 explained 17.1%, component 3 explained 13.5%, and component 4 explained 11.2%, together explaining 76.4% of the total variance.

The first component primarily reflected structural differences in land access and labour allocation, with strong but oppositely signed loadings from total land size, labour-to-land ratio, and maize area allocation. This indicates a gradient contrasting land-abundant systems with labour-intensive, land-constrained systems, rather than a single internally consistent construct. The second component represented a productivity–sustainability gradient, driven by maize yield and the adoption of sustainable practices. The third component captured variation in wealth and livestock integration, with high loadings from farm income and tropical livestock units (TLU). Only variables with loadings exceeding |0.5| were retained for interpretation, and component scores were used for subsequent cluster analysis. Given the multidimensional nature of farming systems, PCA components were interpreted as latent gradients rather than internally consistent scales.

Prior to the PCA, a correlation and variance inflation factor (VIF) check was conducted on the candidate typology variables. Pairwise correlations among variables were moderate (all $|r| < 0.67$) and VIF values were well below conventional thresholds for concern (all $VIF < 3.2$), indicating no severe multicollinearity among the variables entering the analysis.

Table 2
b. Principal component loadings for typology variables (retained components 1–4).

Variable	Comp1	Comp2	Comp3	Comp4
Age	0.099	0.634	-0.594	-0.146
Household income	0.826	-0.299	-0.250	0.049
% income from farm	-0.572	-0.349	-0.256	0.476
TLU (livestock units)	0.668	-0.104	-0.503	0.149
Total land	0.790	0.074	0.307	-0.250
Avg maize yield (kg/ha)	0.692	-0.199	-0.169	0.415
% legume area	-0.547	0.393	-0.180	0.375
Count of intensification options	0.325	0.818	0.061	0.140
Count of sustainable practices	0.374	0.220	0.566	0.580

3.2.2 Cluster Analysis and Identification of Farm Types

Cluster analysis identified four distinct farm types among the 43 surveyed households (Fig. 2 and Table 3), reflecting differences in resource endowment, productivity, and management strategies. The typology is further supported by the multi-criteria assessment and principal component analysis, which revealed underlying trade-offs between land, labour, sustainability, and wealth. The fusion coefficient plot showed a relatively gradual rise between five and three clusters (fusion heights of 8.05, 8.62, and 8.67, respectively), with the largest increase occurring between the three-cluster and two-cluster solutions (8.67 to 13.40, a 55% increase), rather than a sharp elbow uniquely at four clusters. Average silhouette widths for the four clusters were 0.256, 0.327, 0.075, and 0.047, respectively, indicating that internal cohesion was acceptable to borderline for two clusters but weak for the remaining two when judged against the conventional 0.3 threshold. The four-cluster solution was nonetheless retained over the statistically indicated two-cluster split because it aligned more closely with the qualitative distinctions identified in the FGDs and offered greater interpretive and targeting utility, consistent with typology development approaches that combine statistical and substantive criteria (Nyambo et al., 2019; Hammond et al., 2020; Huber et al., 2024); the weaker cohesion of two of the four clusters is acknowledged as a limitation in the Study limitations and future research section.

High Resource-Endowed farms (HRE; 7% of sample) represent high resource-endowed and economically dominant farms. These households operate the largest landholdings (average $\approx$ 16.3 acres) and exhibit the highest farm income per hectare, coupled with relatively high livestock density. They also perform strongly in cowpea productivity. However, they show lower labour intensity per unit land and only moderate adoption of sustainable practices, indicating a more extensive production system where scale and assets drive performance rather than intensive management.

Moderately resource-endowed farms with Diversified Cropping systems (MDV; 14% of sample) comprise medium-high resource-endowed farms with integrated and sustainability-oriented systems. These farms combine moderate landholdings and livestock ownership with the highest levels of sustainable practice adoption. Crop yields are moderate across maize and legumes, suggesting a balanced strategy that integrates productivity with long-term soil and system management. This group aligns closely with the “sustainability–productivity trade-off” identified in the PCA.

Moderately resource-endowed farms with Mixed crop-livestock orientation (MCL; 47% of sample) represent labour-intensive but resource-constrained farms. These households operate relatively small landholdings and have low livestock ownership, but exhibit the highest labour-to-land ratios. Despite limited asset endowment, they achieve moderate income per hectare, indicating reliance on labour-driven intensification. However, their crop yields remain relatively low, suggesting constraints in accessing productivity-enhancing inputs or technologies.

Resource-Constrained Maize-dominated farms (RCM; 32% of sample) reflect low resource-endowed but productivity-oriented farms. These households operate small landholdings with limited livestock and lower overall income levels. Despite this, they achieve the highest maize and lablab yields among all farm types. However, this productivity advantage is not matched by higher income or sustainability outcomes, as these farms exhibit low adoption of sustainable practices. This suggests a focus on short-term yield maximization, potentially at the expense of long-term system resilience.

3.3 Socio-Economic and Production Characteristics of Farm Types

Significant differences in key farm characteristics across the four farm types were further examined using one-way ANOVA followed by Tukey post-hoc comparisons (Table 3). The results confirm that landholding size, maize productivity, and adoption of sustainable practices vary systematically across farm types, although the nature of these differences differs by variable. One-way ANOVA F-statistics support these conclusions: household income ($F[3,39] = 17.85, p < 0.001$), total landholding ($F[3,39] = 21.54, p < 0.001$), maize yield ($F[3,39] = 10.45, p < 0.001$), legume area share ($F[3,39] = 5.76, p < 0.01$), and livestock ownership/TLU ($F[3,39] = 7.51, p < 0.001$) all differed significantly across farm types.

For total landholding size, Tukey post-hoc results indicate that HRE is significantly different from all other farm types ($p < 0.001$), operating substantially larger land areas. No statistically significant differences were observed among MCL, MDV, and RCM, suggesting that these groups are relatively similar in terms of land access despite differences in other characteristics.

In terms of maize yield, post-hoc comparisons show that RCM achieves significantly higher yields than both MCL ($p = 0.001$) and MDV ($p = 0.005$). Differences between RCM and HRE were marginal ($p = 0.061$), while no significant differences were observed among HRE, MCL, and MDV. This highlights RCM as the most productive group in maize, despite its relatively lower resource endowment.

For sustainable practice adoption, the results reveal that MDV adopts significantly more sustainable practices than both MCL ($p = 0.004$) and RCM ($p = 0.001$). No significant differences were observed between MDV and HRE, or among the remaining groups. This reinforces the characterization of MDV as the most sustainability-oriented system.

Maize productivity varied significantly across farm types ($p < 0.01$), although the pattern differs from earlier expectations. RCM recorded the highest maize yields (1872.00 kg/ha), significantly outperforming MCL and MDV, while differences with HRE were marginal. Despite these yield differences, household income remained highest in HRE (USD 2717.39) and declined progressively across MDV, MCL, and RCM ($p < 0.01$). This divergence indicates that higher maize productivity does not necessarily translate into higher overall income across farm types. Rather, income differences appear to reflect broader resource endowment factors, including landholding size and livestock ownership, as well as engagement in higher-value enterprises. These findings suggest that productivity and income are associated with farm typology, but not directly aligned at the individual variable level.

Farm resource endowment also differed significantly. HRE operated substantially larger landholdings (16.33 acres) compared to the other farm types ($p < 0.01$), while livestock ownership was highest in HRE (1.92 TLU), followed by MDV (0.92 TLU), with MCL and RCM showing significantly lower levels. Input use patterns were similarly differentiated, with fertiliser application and hired labour use highest in HRE and lowest in RCM ($p < 0.01$).

Land use patterns further highlight structural differences, with RCM allocating the largest share of land to legumes, while HRE and MDV maintained relatively higher tobacco area shares. Age of household heads did not differ significantly across farm types ($p = 0.111$).

The distribution of education levels (Table 4) shows that primary education dominates across all farm types, particularly in MDV and RCM, while secondary education is more prevalent in MCL. Tertiary education is rare and observed only in HRE. Overall, these results indicate that farm types differ significantly in terms of resource endowment, production outcomes, and input use, while demographic characteristics such as age and education show relatively limited variation.

Table 3
Socio-economic and production characteristics of farm types

Variable	HRE	MDV	MCL	RCM	p-value
Age (years)	45.7 ^a	44.2 ^a	41 ^a	50.9 ^a	0.111
Household income (USD)	2717.39 ^a	766.76 ^b	666.79 ^b	426.63 ^b	< 0.01
Livestock ownership (TLU)	1.92 ^a	0.92 ^b	0.20 ^c	0.53 ^b	< 0.01
Farm area (acres)	16.33 ^a	7.67 ^b	4.75 ^c	4.52 ^c	< 0.01
Mean Maize yield (kg/ha)	1217.95 ^a	1178.23 ^a	1296.32 ^a	1872.00 ^a	< 0.01
Mean Legume area share (%)	16 ^a	37 ^b	39.35 ^b	51 ^b	< 0.01
Tobacco area share (%)	7.5 ^a	7.0 ^a	5.0 ^a	0.0 ^a	< 0.01
Fertiliser use (kg/acre)	166.6 ^a	133.4 ^a	131.0 ^a	82.2 ^a	< 0.01
Hired labour (%)	100 ^a	33 ^b	24 ^b	0 ^b	< 0.01

Means sharing the same superscript letter are not significantly different at $p < 0.05$.

Table 4
Education level of household heads across farm types (%).

Education level	HRE	MCL	MDV	RCM	Total
None	0.00%	5.00%	0.00%	0.00%	2.30%
Primary	33.30%	35.00%	66.70%	71.40%	51.20%
Secondary	33.30%	60.00%	33.30%	28.60%	44.20%
Tertiary	33.30%	0.00%	0.00%	0.00%	2.30%

To facilitate a visual comparison of farm characteristics, key variables related to productivity and resource use were standardized (scaled from 0 to 1) and presented using a radar plot (Fig. 3). The variables included yields of major crops (lablab, maize, and cowpea), livestock density (TLU), total landholding, farm income per hectare, adoption of sustainable practices, and labour availability per unit land.

HRE emerged as the best performing group exhibiting a resource-endowed and economically strong profile, characterized by the highest values in total land, farm income per hectare, and livestock density, as well as relatively strong performance in cowpea yield. However, it showed comparatively lower labour intensity and moderate adoption of sustainable practices, suggesting a more extensive production system.

MDV displayed a balanced and sustainability-oriented profile, achieving the highest level of sustainable practice adoption while maintaining moderate levels across most other indicators, including livestock

density, land size, and crop yields. This suggests a more integrated and management-intensive farming system.

MCL reflected a labour-intensive but resource-constrained system, with the highest labour-to-land ratio and relatively strong income per hectare, but generally low performance across crop yields, landholding, and livestock ownership. This indicates reliance on labour rather than asset-based intensification.

RCM demonstrated a productivity-oriented profile, with the highest maize and lablab yields among all groups. However, this came alongside relatively lower farm income per hectare, limited landholding, and low adoption of sustainable practices, suggesting a focus on yield maximization that may not yet translate into broader economic or sustainability gains.

3.4 Multi-Criteria Analysis of Sustainable Intensification Innovations

Sustainable intensification innovations were evaluated across the four farm types using multi-criteria analysis. Scores were calculated based on productivity potential, feasibility, economic viability, resource efficiency, and scalability.

The scaled innovation scores show clear variation across farm types. Conservation agriculture recorded the highest overall score (0.68), indicating the widest adoption across farm types, followed by intercropping (0.54). Strip cropping had the lowest overall score (0.25), with adoption concentrated in MCL.

To test the robustness of the equal-weighting assumption, alternative weighting schemes emphasising economic viability and resource use efficiency were applied by reweighting the five SI innovations reported in Table 5, since farm-type-by-criterion score data were not retained for a criterion-level sensitivity check (Table S1). MCL and RCM retained the two lowest composite scores across all three weighting schemes, confirming that these farm types consistently show the most limited uptake of sustainable intensification innovations regardless of weighting. However, the top rank was sensitive to the weighting scheme applied: MDV scored highest under equal and resource-use weighting, while HRE scored highest under economic weighting, indicating that the relative ordering of the top two farm types is not fully robust to the weighting choice, even though their status as the two best-performing farm types is.

MDV achieved the highest overall innovation score (0.66), followed by HRE (0.60), while MCL and RCM recorded lower scores of 0.29 and 0.23, respectively. HRE showed maximum adoption in intercropping, livestock integration, and conservation agriculture, whereas MDV demonstrated consistently high scores across multiple innovations, including rotation and conservation agriculture. In contrast, MCL relied primarily on strip cropping, while RCM showed generally low adoption across most innovations.

Table 5
MCDA scores for sustainable intensification innovations.

Innovation	HRE	MCL	MDV	RCM	Average
Conservation Agriculture (Intensification)	1	0	0.87	0.84	0.68
Intercropping	1	0.17	1	0	0.54
Small Livestock Integration	1	0	0.42	0.19	0.40
Legume–Maize Rotation (Cover Crop)	0	0.3	1	0.11	0.35
Strip Cropping	0	1	0	0	0.25
Overall Score	0.6	0.29	0.66	0.23	0.45

4 Discussion

Integrating legumes into cropping systems through practices such as crop rotation, intercropping, and conservation agriculture is widely recognized as a pathway toward sustainable intensification. These practices can improve soil fertility, enhance land-use efficiency, and contribute to more resilient farming systems when appropriately matched to local conditions (Muoni et al., 2024; Mupangwa et al., 2021; Ngwira et al., 2020; Nyamayevu et al., 2024; Vanlauwe et al., 2019). However, the results of this study highlight that the benefits and adoption of such practices are not uniform across farm households, but instead vary systematically with underlying differences in resource endowment, production strategies, and management capacity. This reinforces the broader understanding that smallholder farming systems are highly heterogeneous, and that uniform agricultural interventions often fail to capture this complexity (Hammond et al., 2020; Huber et al., 2024; Kuivanen et al., 2021; Nyambo et al., 2019)

4.1 Farm diversity and its implications for agricultural development

The findings emphasise that farm diversity in Mtunthama EPA is not merely descriptive but has important implications for agricultural development planning. While the results clearly show variation in resource endowment and production strategies, the key insight is that such diversity fundamentally shapes how farmers respond to interventions and opportunities. This reinforces the argument that agricultural development approaches must move beyond aggregate recommendations and instead account for differences in capacity, incentives, and constraints across farm types (Giller et al., 2021; Hammond et al., 2020; Huber et al., 2024; Mutyasira, 2020).

An important implication emerging from this study is that similar external constraints such as input access limitations or climate variability do not translate into uniform outcomes across households. Rather, farm-level responses are mediated by underlying structural characteristics, particularly access to land, livestock, and labour. This highlights the risk of overgeneralising smallholder systems and supports

growing evidence that heterogeneity is a defining feature of African farming systems, requiring differentiated analytical and policy approaches (Huber et al., 2024; Nyambo et al., 2019).

Furthermore, the observed distribution of farm types suggests that development strategies targeting only high-performing or highly resource-endowed farms may have limited impact at the population level. Instead, greater emphasis is needed on designing interventions that are inclusive of resource-constrained households, which constitute a substantial proportion of the farming population. This strengthens the case for typology-based targeting as a practical framework for improving the relevance, equity, and effectiveness of sustainable intensification efforts.

4.2 Resource endowment and farm performance patterns

The differences observed across farm types highlight the important, but not uniform, role of resource endowment in shaping farm performance. Consistent with the typology results, HRE is characterised by substantially larger landholdings and higher livestock ownership, while MCL and RCM operate under more constrained resource conditions. These structural differences align with broader evidence that access to land and livestock assets remains a key determinant of production opportunities in smallholder systems (Giller et al., 2021).

However, the findings also demonstrate that resource endowment does not translate linearly into productivity outcomes. While HRE exhibits the highest income levels and asset ownership, it does not achieve the highest maize yields. Instead, RCM records the highest maize productivity despite having relatively limited land and lower income levels. This suggests that farm performance reflects multiple interacting factors beyond resource access alone, including management strategies, crop choices, and possibly differential allocation of labour and inputs. Similar patterns have been reported in smallholder systems where yield outcomes are shaped by both resource availability and management intensity (Giller et al., 2021; Mutyasira, 2020).

Livestock ownership remains an important distinguishing feature across farm types, particularly in differentiating wealthier households. Its contribution in this context appears to be more closely associated with income diversification and asset accumulation rather than directly observable yield differences. While integrated crop–livestock systems are widely recognised for their role in enhancing soil fertility and resource cycling (Giller et al., 2021), the results of this study do not show a direct statistical relationship between livestock density and maize productivity. This reinforces the need to interpret livestock integration as part of a broader livelihood and system resilience strategy rather than a direct driver of crop yield in isolation.

The role of labour and input use also appears more complex than a simple intensification gradient. Although labour-to-land ratios differ across farm types, correlation analysis indicates a negative relationship between labour intensity and land size, suggesting that smaller farms rely more heavily on family labour. However, this does not consistently translate into higher productivity. Similarly, while fertiliser use and hired labour are higher among resource-endowed farms, their effects are not directly

reflected in maize yield differences across all groups. These findings highlight that constraints in input access and labour allocation interact with other structural and management factors, reinforcing the need for context-specific interpretations of farm performance.

4.3 Implications for targeting sustainable intensification innovations

The multi-criteria analysis demonstrates that the suitability of sustainable intensification innovations as perceived by farmers varied considerably across farm types. Rather than identifying a single dominant innovation, the results suggest that innovation outcomes are strongly conditioned by farm-specific resource endowments and management strategies. This supports the argument that typology-based targeting is essential for designing effective interventions in heterogeneous smallholder systems (Hammond et al., 2021; Kuivanen et al., 2021; Schaafsma et al., 2025).

Among the evaluated innovations, conservation agriculture and intercropping emerged as the most consistently adopted practices across farm types, indicating their relative adaptability within the study context. Conservation agriculture recorded the highest overall score, suggesting broad relevance, while intercropping also performed strongly, particularly among certain farm types. In contrast, practices such as strip cropping and legume–maize rotation showed more limited or uneven adoption, reflecting possible constraints related to labour, knowledge, or resource requirements. These adoption patterns should not be interpreted as simple technology choices, because sustained conservation-agriculture use is shaped by changing household circumstances, incentives, and local support systems (Hermans et al., 2020; Pangapanga-Phiri et al., 2024).

The variation in innovation scores across farm types further illustrates differentiated adoption pathways. HRE and MDV achieved higher overall innovation scores, with MDV demonstrating particularly strong performance across multiple practices, consistent with its characterization as a sustainability-oriented system. In contrast, MCL and RCM recorded lower scores, indicating more limited uptake of sustainable intensification practices. This pattern suggests that while some innovations are broadly applicable, their effective adoption is closely linked to household capacity and system characteristics.

Importantly, the results do not indicate a single innovation that performs optimally across all farm types. Instead, they highlight the need to consider trade-offs between feasibility, productivity, and resource requirements when promoting sustainable intensification practices. Similar findings have been reported in sub-Saharan Africa, where adoption of agricultural innovations is often uneven and shaped by local constraints and opportunities (Adolph et al., 2020; Hermans et al., 2020; Jones-Garcia & Krishna, 2021).

4.4 The role of typology-based targeting in sustainable intensification

The differentiated patterns observed across farm types underscore the importance of tailoring agricultural interventions to specific farm contexts. Typology-based approaches provide a structured

framework for linking farm characteristics with appropriate development strategies, allowing for more precise targeting compared to uniform recommendations.

For resource-endowed farms, such as HRE, interventions may focus on improving efficiency and sustainability within existing production systems. Given their greater access to land and assets, these households may be better positioned to adopt practices that enhance long-term soil health and system resilience, including conservation agriculture and improved crop–livestock integration.

MDV represents a group with strong potential for sustainable intensification, given its relatively high adoption of sustainable practices and balanced resource base. Supporting this group through improved extension services and access to complementary inputs could further enhance both productivity and sustainability outcomes.

For more resource-constrained farm types, particularly MCL and RCM, the results suggest that interventions should prioritise feasibility and risk reduction rather than complexity. Lower adoption of innovations among these groups indicates that constraints related to labour, capital, or knowledge may limit the uptake of more demanding practices. In such contexts, simpler and more flexible approaches, such as intercropping or incremental improvements in input use, may offer more realistic pathways for enhancing productivity and resilience.

Overall, these findings reinforce the value of typology-based targeting as a means of aligning agricultural interventions with the diverse realities of smallholder farmers. By accounting for differences in resource endowment, production strategies, and innovation capacity, such approaches can improve both the relevance and effectiveness of sustainable intensification efforts.

4.5 Enabling conditions for sustainable intensification

While farm-level innovations are important, broader institutional and policy environments play a critical role in enabling sustainable intensification. Collective action mechanisms, such as farmer cooperatives and producer groups, have been shown to improve market access, reduce transaction costs, and strengthen bargaining power for smallholder farmers (Mungai et al., 2024; Pangapanga-Phiri et al., 2024). In the context of Mtunthama EPA, strengthening farmer organisations could facilitate collective marketing of crops and livestock products while improving access to agricultural inputs.

Digital technologies also offer promising opportunities for enhancing agricultural advisory services. Mobile-based extension platforms can deliver timely information on weather conditions, pest management, and market prices, helping farmers make better-informed management decisions. Studies have shown that mobile-based advisory services can significantly improve productivity and resilience among smallholder farmers, particularly in areas where traditional extension services are limited (Amadu, 2022; Marenja et al., 2023; Mungai et al., 2024). Evidence from conservation-agriculture research in Malawi and the wider region also shows that outcomes depend strongly on management quality, seasonal conditions, and the fit between practices and farm resources (Mhlanga et al., 2021; Nyagumbo et al., 2020, 2021).

Supportive policy frameworks are equally essential for promoting sustainable intensification. Agricultural policies that provide targeted input support, expand access to credit, and strengthen extension systems can help address the structural barriers faced by many smallholder farmers. Integrating typology-based approaches into policy design may also improve the effectiveness of agricultural development programs by ensuring that interventions are tailored to different categories of farmers. Recent evidence from Malawi further highlights the importance of coherent policy guidance, institutional collaboration, and adequate financing for conservation-agriculture implementation (Phiri et al., 2026).

5 Study limitations and future research

Although this study provides valuable insights into farm diversity and innovation targeting in Mtunthama EPA, some limitations should be acknowledged. First, the typology analysis is based on a relatively small sample of households, which may limit the generalizability of the findings beyond the study area. Second, the analysis relies partly on self-reported production data, which may introduce measurement errors or recall bias. Third, while the four-cluster solution was retained for its interpretive and qualitative alignment, average silhouette widths indicated only borderline-to-acceptable internal cohesion for two of the four clusters (0.256 and 0.327) and weak cohesion for the remaining two (0.075 and 0.047); a coarser, more statistically distinct two-cluster split was also supported by the fusion coefficients, and future work could usefully test the sensitivity of the typology and its policy implications to this alternative resolution.

In addition, the typology represents a static snapshot of farm characteristics at a single point in time. Farming systems are dynamic, and households may transition between typologies as their resource endowments, livelihood strategies, and environmental conditions change. Understanding these transitions is important for designing development interventions that support long-term improvements in agricultural productivity and resilience.

Future research could build on this work by incorporating longitudinal data to examine how farm households evolve over time and how different interventions influence these trajectories. Expanding the sample size and geographic scope of similar studies would also help strengthen the evidence base for typology-based approaches to sustainable intensification across Malawi and other smallholder farming regions in sub-Saharan Africa.

6 Conclusions

This study applied principal component analysis, cluster analysis, and a multi-criteria assessment to characterise farm diversity in Mtunthama Extension Planning Area (EPA), identifying four distinct farm types that differ in resource endowment, production strategies, and livelihood outcomes. The findings confirm substantial heterogeneity among smallholder households, particularly in terms of landholding size, livestock ownership, income levels, and adoption of sustainable practices. Importantly, the results show that resource endowment does not translate directly into productivity outcomes, as higher maize

yields were observed among relatively resource-constrained farms, while higher income levels were concentrated among more resource-endowed households. The multi-criteria analysis further revealed that the performance and adoption of sustainable intensification innovations vary across farm types, with conservation agriculture and intercropping emerging as the most widely applicable practices. These findings reinforce the need to move beyond uniform agricultural recommendations and instead recognise the complex and context-specific nature of smallholder farming systems.

The study demonstrates that typology-based approaches provide a practical framework for designing targeted sustainable intensification strategies that reflect the diverse realities of farming households. Resource-endowed farms are better positioned to adopt integrated and asset-intensive practices, while moderately resourced farms show potential for incremental improvements through enhanced access to inputs and extension support. In contrast, resource-constrained farms require low-cost, risk-reducing innovations that prioritise feasibility and resilience. While the analysis offers important insights, it is based on a relatively small, cross-sectional dataset and relies partly on self-reported information, which may limit generalisability. Future research could build on these findings by incorporating larger samples, longitudinal data to capture transitions between farm types, and more detailed biophysical indicators. Overall, the results highlight the importance of aligning sustainable intensification interventions with farm-specific conditions to improve adoption, productivity, and livelihood outcomes in smallholder systems.

Declarations

CRedit authorship contribution statement

Kamwana-Ngwira Florence: Conceptualisation, Methodology, Formal analysis, Investigation, Writing – original draft. **Chiduwa Mazvita:** Supervision / Writing – review & editing / Data curation. **Mabhaudhi Tafadzwanashe:** Methodology / Writing – review & editing / Supervision. Groot Jeroen: Writing – review & editing / Methodology / Funding acquisition. **Santiago Lopez-Ridaura:** Writing – review & editing / Conceptualisation / Funding acquisition. All authors have read and agreed to the published version of the manuscript.

This manuscript is original unpublished work, read and approved by all authors, and not being considered for publication elsewhere. All those listed as authors have contributed to the development of this paper and have approved the manuscript and this submission. We have no conflicts of interest to declare.

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Data availability statement

The datasets generated and analysed during the current study are available from the corresponding author on reasonable request.

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Figures

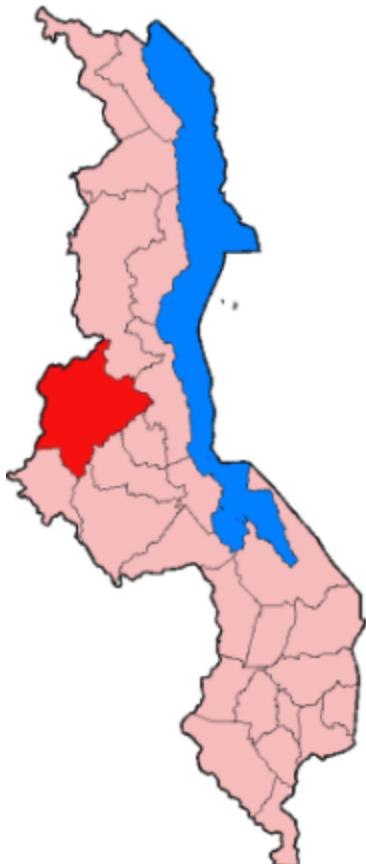


Figure 1

Map of Malawi showing district boundaries, highlighting the location of Kasungu District and the areas of interest, in red, with Lake Malawi visible on the north-eastern border in blue.

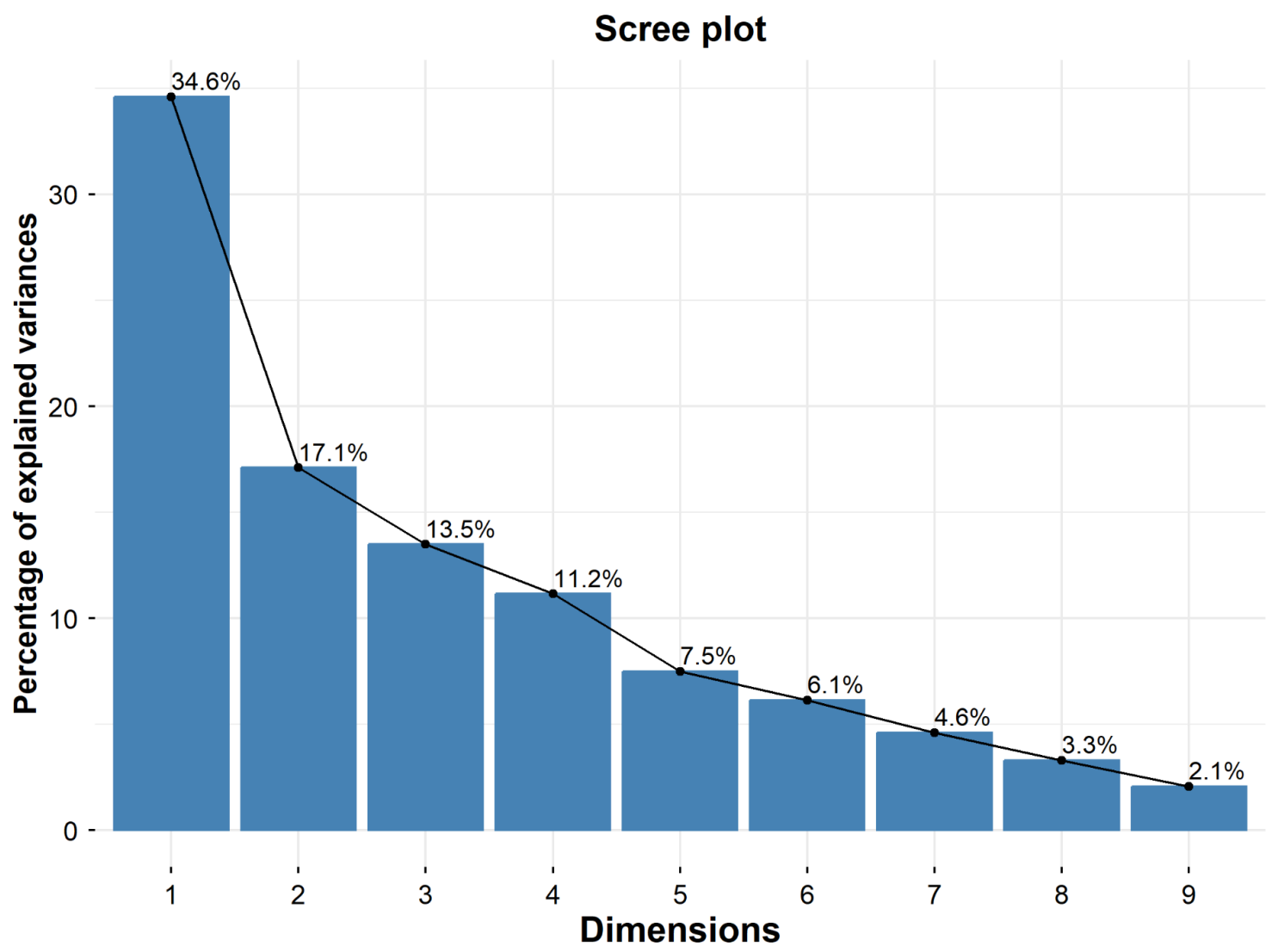


Figure 2

Scree plot of eigenvalues from principal component analysis showing the retention of four components with eigenvalues greater than one.

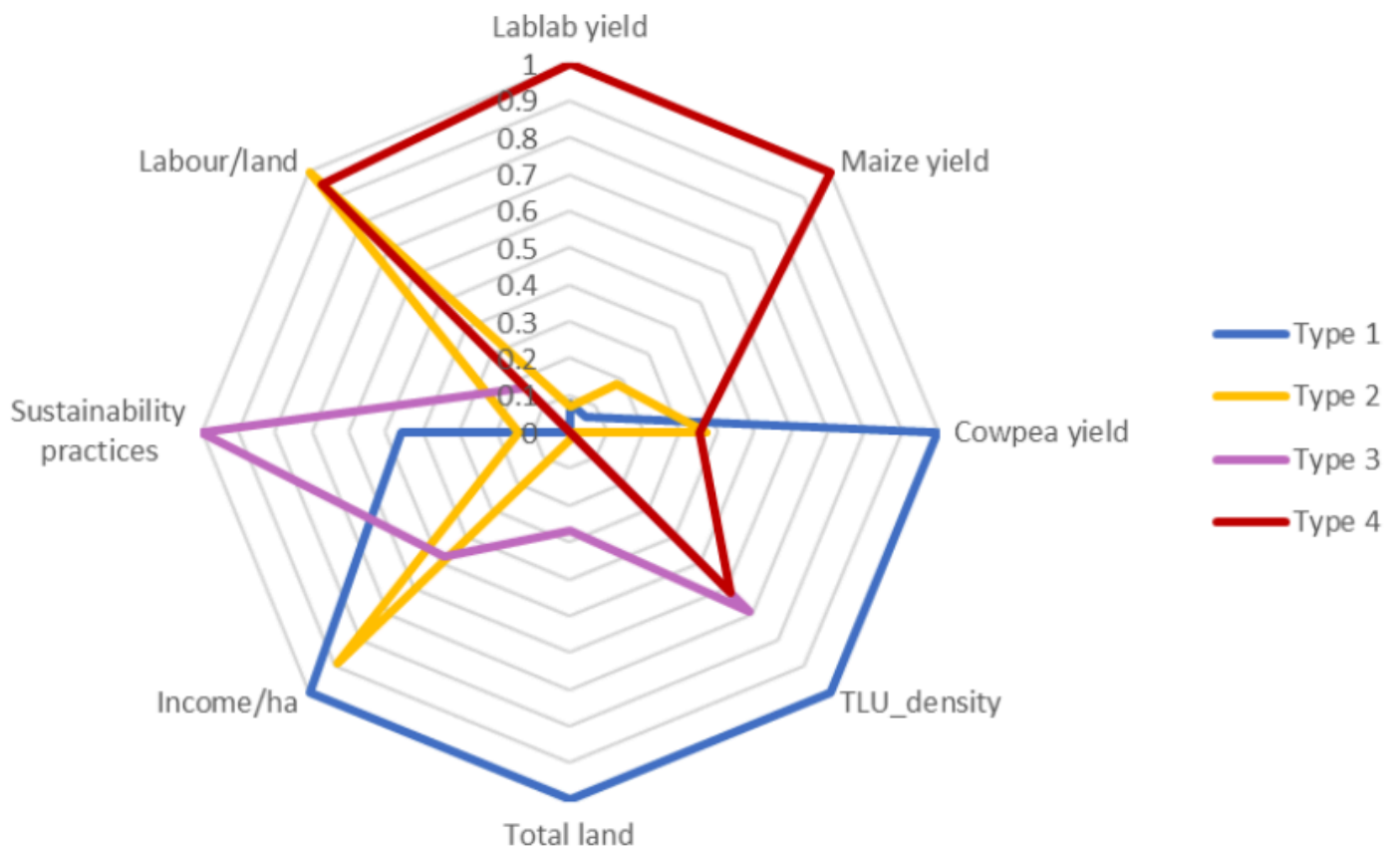


Figure 3

Radar plot showing standardized resource and production characteristics across farm types.

Supplementary Files

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- [TableS1.docx](#)