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Understanding the Smallholder Legume-based Mixed Farming System: Application of the Whole-Farm Household Modeling in Uganda

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ABSTRACT

Smallholder farming remains an important and major source of livelihood for many rural poor globally. Worldwide, over 500 million smallholder farms account for 84% of all farms, which operate around 24% of all agricultural land. However, most smallholders are resource-constrained and obtain low productivity on often increasingly degraded lands. Legumes play a crucial role in socio-economic and rural development in the low-input –low-output smallholder agriculture systems since they provide food, income and fix nitrogen into soils. Development and research actors often neglect that smallholder and their farming systems are heterogeneous in terms of resource endowments and socio-economic characteristics, and blanket recommendations add no value. Against this backdrop, this study explores and comprehends the relationship between smallholder farms, farmers, and their environment(s) to understand the complexities and boundaries and provide targeted recommendations for farm improvement in northern Uganda. Notably, previous and current government agricultural programs in Uganda (such as the National Agricultural Advisory Services, Operation Wealth Creation, and the Parish Development Model), have mostly taken standard 'one-size-fits-all' approaches to agricultural development, and in turn, no significant poverty reduction and rural development has been registered.

This dissertation aims to describe and analyse smallholder pigeon pea (*Cajanus cajan* [L.] Millspaugh) based mixed farming systems and provide targeted recommendations for pro-poor smallholder development in northern Uganda. We adapt the farming systems analytical approach to provide a detailed description of the farmer, the farm, and its environment. Specifically, we assessed the role and determinants of membership in farmer groups on pigeon pea yield and technical efficiency, developed a smallholder typology based on resource endowment, socio-economic and environmental variables, assessed smallholder preferences for pigeon pea across the identified farm types, and simulated farm improvement alternatives using the FarmDESIGN multi-objective model. The study uses mixed methods approaches and is based on empirical field research conducted in rural northern Uganda in 2019 and 2020. We conducted a baseline study to develop a hypothesis about the farming system, followed by a quantitative survey of 257 randomly selected pigeon pea-producing smallholder households, a detailed characterization with two model farms for multi-objective optimization, and a soil-fertility assessment.

Results show that smallholder farmers who were members of farmer groups had better access to credit, markets, extension, and price information, compared to non-members. However, the success of farmer groups in northern Uganda is largely limited by access-related factors such as poor road infrastructure, and low access to credit, price, and market information. The results further show that both members and non-members were technically inefficient in the production of pigeon pea. Using multivariate statistical approaches, six distinct pigeon pea farm types were generated, in which 54% of the smallholders were low-resourced, with below-average land size, livestock units, and low household income. Smallholders preferred pigeon pea because it is highly nutritious and cheaper compared to other locally available protein sources, it fixes nitrogen, it is relatively easy to harvest and provides more biomass compared to other crops. We identified trade-offs and complementarities; for example, improving soil organic matter through the use of crop residues as mulch instead of using them as livestock fodder, given the low soil organic matter balance of most soils. Our results underline the need for strengthened collective public and private action efforts to enhance smallholders' access to credit, market information and extension services, for increased and improved social learning and better economies of scale. Additionally, smallholders highlight the need for improved pigeon pea varieties that are pest and drought-resistant and easy to intercrop, especially with cereals. Further, pigeon pea breeding efforts should not solely focus on yield improvement, but

must address the needs expressed by smallholders. Smallholders across farm types can also target improved livestock feeding which could further improve farm-yard manure and subsequent crop productivity. Results from the FarmDESIGN model confirm the need for program targeting for the low and high resourced farm types to address the specific needs of smallholder farmers. Overall, agricultural programs should be more targeted to the different smallholder types given their different contexts, needs and capacities.

Kleinbäuerliche gemischte Leguminosenanbausysteme in Uganda: Anwendung eines Whole-Farm-Household Modells

Kleinbäuerliche Landwirtschaft stellt nach wie vor die Lebensgrundlage für viele arme Menschen in ländlichen Gebieten weltweit dar. Global gibt es über 500 Millionen kleinbäuerliche Betriebe, die 84 % aller landwirtschaftlichen Betriebe ausmachen und etwa 24 % der gesamten landwirtschaftlichen Nutzfläche bewirtschaften. Die Mehrheit der kleinbäuerlichen Betriebe verfügen nur über sehr begrenzte Produktionsressourcen und erzielen – oft auf zunehmend degradierten Böden - nur eine geringe Produktivität. Der Anbau von Hülsenfrüchten spielt häufig eine wichtige Rolle in der kleinbäuerlichen Landwirtschaft. Obwohl der Anbau von Hülsenfrüchten für die Nahrungsmittelversorgung und die Einkommen von kleinbäuerlichen Betrieben oft sehr wichtig ist und Stickstoff in den Böden binden kann, wird der Anbau von Hülsenfrüchten in der Entwicklungspraxis und -forschung häufig marginalisiert. Zudem werden kleinbäuerliche Betriebe zumeist nach einzelnen Anbausystemen gruppiert, und dabei die sehr heterogene Ressourcenausstattung und die unterschiedlichen sozioökonomischen Hintergründe der Betriebe vernachlässigt. In Uganda verfolgen Landwirtschaftsprogramme der Regierung (wie die National Agricultural Advisory Services, die Operation Wealth Creation und das Parish Development Model) weitgehend pauschalen Handlungsempfehlungen, ohne dass es in den letzten Jahrzehnten zu einer nennenswerten Armutsbekämpfung und Entwicklung im ländlichen Raum gekommen wäre.

Diese Dissertation untersucht die Beziehungen zwischen kleinbäuerlichen Betrieben und ihrem sozioökonomischen und naturräumlichen Umfeld im Norden Ugandas. Das Ziel dieser Dissertation ist es, insbesondere kleinbäuerliche Betriebe, die Straucherbsen (Cajanus cajan [L.] Millspaugh) in verschiedenen Regionen im Norden Ugandas anbauen, detailliert zu beschreiben und zu analysieren und daraus gezielte Empfehlungen für eine armutsorientierte kleinbäuerliche Entwicklung zu entwickeln. So wird der Einfluss der Mitgliedschaft in Bauernorganisationen auf die Erträge und die technische Effizienz von kleinbäuerlichen Betrieben analysiert, eine Typologie der kleinbäuerlichen Betriebe auf der Grundlage von Ressourcenausstattung, sozioökonomischen Faktoren und Umweltvariablen entwickelt, die Präferenzen der kleinbäuerlichen Betriebe beim Anbau von Straucherbsen bewertet und mit Hilfe des FarmDESIGN Whole-Farm-Household Modells Alternativen zur Verbesserung des Produktion simuliert. Die Studie basiert auf empirischer Feldforschung die in den Jahren 2019 und 2020 im ländlichen Norden Ugandas durchgeführt wurde. Die Datenerhebung nutzt den *mixed methods* Ansatz. Zunächst wurde eine Grundlagenstudie durchgeführt, auf deren Basis eine Hypothese entwickelt wurde. Danach folgte eine quantitative Umfrage unter 257 zufällig ausgewählten Straucherbsen-produzierenden kleinbäuerlichen Betrieben, sowie eine detaillierte Charakterisierung von Modellbetrieben zur Mehrzieloptimierung und der Bewertung der Bodenfruchtbarkeit.

Die Ergebnisse zeigen, dass kleinbäuerliche Betriebe, die Mitglieder von Bauernorganisationen sind, im Vergleich zu Nichtmitgliedern einen besseren Zugang zu Krediten, Märkten, Beratung und Preisinformationen haben. Der Erfolg von Bauernorganisationen im Norden Ugandas wird jedoch weitgehend durch eine schlechte Infrastruktur und einen geringen Zugang zu Krediten, Preis- und

Marktinformationen eingeschränkt. Die Ergebnisse zeigen außerdem, dass sowohl Mitglieder als auch Nicht-Mitglieder bei der Produktion von Straucherbsen technisch ineffizient waren. Mithilfe multivariater statistischer Verfahren wurden sechs verschiedene Straucherbsen-Betriebstypen ermittelt. Der Hauptgrund von kleinbäuerlichen Betrieben, Straucherbsen anzubauen, besteht darin, dass sie im Vergleich zu anderen lokal verfügbaren Proteinquellen sehr nahrhaft und billig sind, Stickstoff binden, relativ leicht zu ernten sind und im Vergleich zu anderen Pflanzen mehr Biomasse liefern. Die Studie zeigt zahlreiche Komplementaritäten der Produktionsfaktoren, zum Beispiel die Verbesserung der organischen Substanz des Bodens durch die Verwendung von Straucherbsen-Housernterückständen als Mulch. Unsere Ergebnisse unterstreichen die Notwendigkeit verstärkter öffentlicher und privater Maßnahmen, um den Zugang von kleinbäuerlichen Betrieben zu Krediten, Marktinformationen und Beratungsdiensten zu verbessern, das soziale Lernen zu verstärken und die Skalenerträge zu steigern. Darüber hinaus haben kleinbäuerliche Betriebe einen Bedarf an verbesserten Straucherbsensorten, die schädlings- und trockenheitsresistenter sind und sich dennoch mit anderen Kulturen, insbesondere mit Getreide, als Mischkultur kombinieren lassen. Die Neuzüchtungen sollten sich nicht nur auf die Maximierung der Erträge konzentrieren, sondern vielmehr auf die von den Kleinbauern geäußerten Bedürfnisse eingehen. Die Ergebnisse des FarmDESIGN-Modells bestätigen die Notwendigkeit einer gezielten Ausrichtung der landwirtschaftlichen Entwicklungsprogramme auf die unterschiedlichen Rahmenbedingungen, Bedürfnisse und Kapazitäten von kleinbäuerlichen Betrieben.

DEDICATION

To my children: Maria Faustina N and Joseph Lutaaya,

My husband: Mr. Mugagga Ssenkungu

&

My parents: Mr. James Muwonge (RIP) & Mother Teo Nabatanzi

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LIST OF ACRONYMS AND ABBREVIATIONS

ANOVA	Analysis of Variance
A2N	Africa 2000 Network
BNF	Biological Nitrogen Fixation
CAPI	Computer Assisted Personal Interview
CGIAR	Consultative Group on International Agricultural Research
DC	Detailed characterization
DEED	Describe, Explain, Explore and (re) Design
DRC	Democratic Republic of Congo
DSSAT	Decision Support System for Agro-technology Transfer
FAO	Food and Agricultural Organization
FGs	Farmer Groups
FSA	Farming Systems Analysis
GDP	Gross Domestic Product
GHG	Greenhouse gases
HSD	Honest Significance Difference
KIIs	Key Informant Interviews
MAAIF	Ministry of Agriculture, Animal Industry and Fisheries
MEA	Modern Extractive Agriculture
NAADS	National Agricultural Advisory Services
NDP	National Development Plan
NGOs	Non-Governmental Organizations
NPA	National Planning Authority
NUFS	Northern Uganda Farming System
NUSAF	Northern Uganda Social Action Fund
PCA	Principal Component Analysis
SDGs	Sustainable Development Goals
SPF	Stochastic Production Frontier

SSA	Sub-Saharan Africa
SPF	Stochastic Production Frontier
SOM	Soil Organic Matter
TE	Technical Efficiency
TLU	Tropical Livestock Unit
UBoS	Uganda Bureau of Statistics
UNCST	Uganda National Council for Science and Technology
UPE	Uganda Primary Education
USE	Uganda Secondary Education
VSLAs	Village Savings and Credit Associations
ZARDI	Zonal Agriculture Research and Development Institute
ZEF	Center for Development Research

Understanding the Smallholder Legume-based Mixed Farming System: Application of the Whole-Farm Household Modeling in Uganda

1. GENERAL BACKGROUND

1.1 Introduction

Smallholder farming remains the most important and major source of livelihood for many rural poor people. Worldwide, there are over 500 million smallholder farms accounting for 84% of all farms, that operate on 24% of all agricultural land (Lowder et al., 2016, 2021). Given the break-neck population growth, the need to produce more food is top on the development agenda. On the other side, the limits of intensive agriculture and its ecological costs as well as the impacts of climate change are becoming more and more evident. About 30% of the global food is produced by smallholder farmers who own less than 2 ha of land (Herrero et al., 2017; Ricciardi et al., 2018). Beyond providing livelihoods, smallholder farming is important for sustaining landscapes, agro-biodiversity, social stability, and cultural values. However, most smallholders worldwide are facing a 'development deadlock', operating with low input-output cycles, often on increasingly degraded lands (Garrity et al., 2012). Worldwide, questions remain on the role and future of smallholder farming. How far can smallholders sustainably produce (more and better) food and 'farm their way out of poverty' without further impacting the environment? In this context, legumes play a crucial role in sustainable and pro-poor development perspectives (Duchene et al., 2017). Upon this backdrop, this study aims to understand the role of pigeon pea as an important legume grown in the smallholder mixed farming system in northern Uganda.

Uganda's agricultural sector contributes about 24% to the Gross Domestic Product (GDP) (NPA 2020), and provides employment to over 80% of the rural population (UBoS 2014). Over 95% of the smallholders own less than 2 ha of land (NPA 2020), a typical characteristic of small-scale production systems in sub-Saharan Africa (SSA). Smallholders are challenged by climate change, land fragmentation and soil degradation, with about 39% of the arable land in Uganda being degraded (Kaweesa et al. 2018). In this context, mixed farming systems are socio-economically and environmentally more sustainable than monoculture farming (Nord et al. 2020). In smallholder farming, monocultures can be economically risky as farmers face low resilience to price and production fluctuations. It often leads to loss of (agro-) biodiversity, inefficient and seasonal use of resources, pest and disease outbreaks and to larger vulnerability to climatic variability than mixed farming (Martens et al., 2015). In the last decades, worldwide much focus has been put on smallholder agriculture diversification. Further, intercropping and rotations of legumes can provide feasible pathways to increase productivity, resilience and sustainability of smallholder farmers (Martens et al. 2015).

1.2 Understanding smallholder systems using the Farming Systems Approach (FSA)

Farming systems refers to are heterogeneous in many aspects; in terms of resource capacities, farmer characteristics and aims for farming (Vanlauwe et al., 2019). The FSA approach comprehends the differences with regard to agro-ecology and socio-economic farm characteristics and takes resource capacities at farm, local, regional, national and international level into consideration. Farming systems are complex and dynamic, with socio-economic, ecological, institutional and cultural components that are inter-related, however, often researched in disciplinary isolation (Garrity et al., 2012). Therefore, interdisciplinary and systems thinking are crucial approaches for understanding farming systems analysis, diagnosis and for recommending practicable alternatives that could lead to sustainable development. This study adapts the FSA framework as described by Garrity et al. (2012) to comprehend the complexity, diversity and characteristics of smallholder legume-based mixed farming system in northern Uganda (Figure 1.1).

The study aims to comprehend the relationship between farms, farmers, and their socio-economic and ecological environment(s), as conceptualized in Figure 1.1. The three components (farm, the farmer and environment) form a farming system with information flows and interaction across boundaries, and require interdisciplinary approaches to understand their complexity. Dixon et al. (2015) define farming systems as a population of farm households, generally of mixed types and sizes, with similar configuration of resources, livelihoods, consumption, and opportunities. A farm system represents individual farm households comprising cropping and livestock systems that transform land, capital and labor into products for consumption or sale (Giller, 2013).

The use of the hierarchical approach to understanding and defining farming systems is appropriate for understanding the scale, whereby from individual farm systems, we define the hundreds and millions of households that form the farming system (Giller, 2013). The FSA challenges the notion of blanket 'one-size-fit-all' approaches to agriculture development that has dominated research and practice before. Adapting the FSA, this study contributes to the understanding and improvement of the northern Uganda farming system, starting with understanding the individual farm systems 'farm households' at village level. To understand trade-offs, synergies and boundaries, we employ the bio-economic whole-farm FarmDESIGN model developed by the Farming Systems and Ecology Group at Wageningen University Research (Groot et al., 2012; Jones et al., 2003).

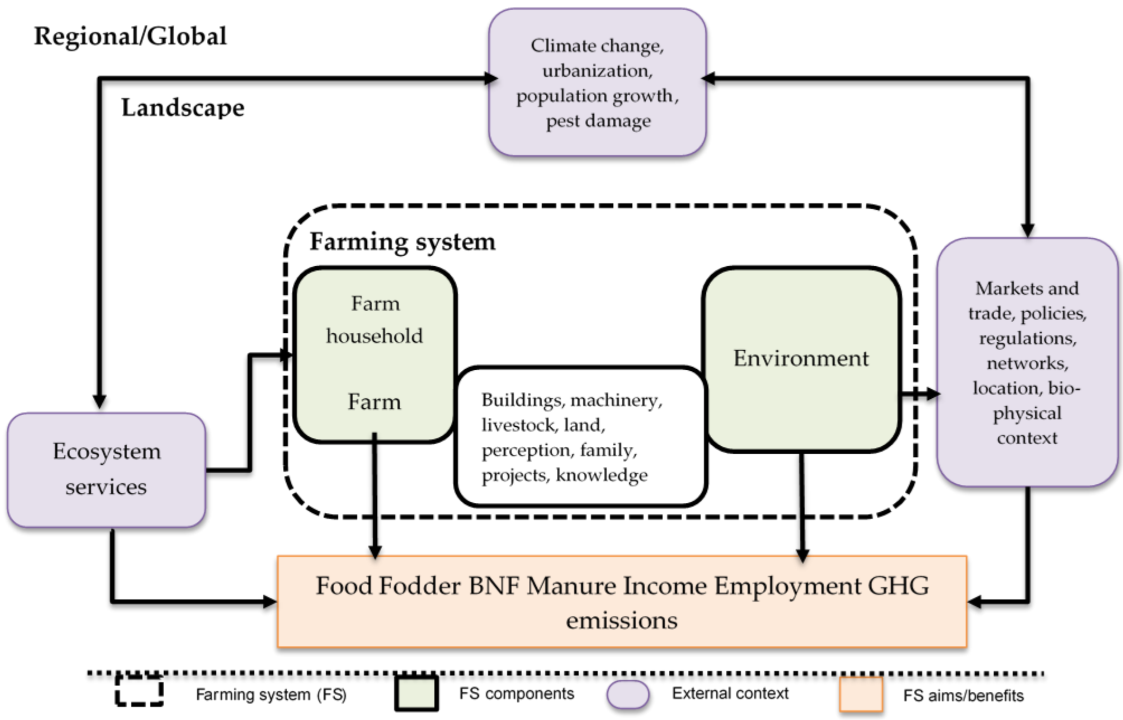

Figure 1.1: Conceptual framework for Farming Systems Analyses (FSA). Adapted and modified from (Darnhofer et al. 2012; Garrity et al. 2012; Dixon et al. 2015). The dashed lines delineate the farm system 'farm household' from the landscape and the regional scale, where we find millions of farm households. BNF is Biological Nitrogen Fixation, and GHG is Green House Gas.

1.2.1 The Farm Household

The farm household is the most important and central part of the smallholder farming system. Considering the farm household characteristics is pertinent for understanding the capacity and resources available to the farmer. Smallholder farm households primarily depend on the farms for provisional (food, income, fodder, manure, etc.), regulatory (e.g. climate regulation), and cultural ecosystem services (Dixon et al., 2015). The extent of ecosystem service provision is partly a function of the resource endowments of the farm households. Such endowments include land, livestock, capital, and infrastructure, and are influenced by external factors such as current market prices, social networks, and political structures (Figure 1.1). The quantity and quality of resource endowments owned by farm households determines the productivity of the farm. In smallholder farm households, family members normally provide farm labor, with women taking up much, if not most, of the labor (Doss & Quisumbing, 2020). In northern Uganda, farm households are predominantly oriented towards subsistence, with high resource limitations, and several institutional challenges such poor infrastructure and limited access to technical information.

1.2.2 The Farm and its Environment in northern Uganda

The farm provides direct and indirect benefits to the households. The most common crops grown are seasonal cereals and legumes that provide food, fodder, straw and other crop residues. Small ruminants such as goats and sheep and poultry are kept to supplement the household's need for meat, milk, eggs and manure, and source of extra cash in scarcity (Herrero et al., 2013, 2021). Farmers practice intercropping and crop rotation on most of the plots, as well as fallowing to replenish their soils (Kermah et al., 2017).

The farming system in northern Uganda, like elsewhere in SSA, are highly variable in terms of production, income, soil-fertility and labor availability (Ojiem et al., 2014). Soils are generally infertile, sandy and often nutrient depleted (Isabirye et al., 2004). Smallholders use crop residues and manure to improve soil fertility. Labor input is mainly limited by the number of active household members (especially women), also affected by the youths abandoning agriculture for better off-farm activities. Such day-to-day constraints limit smallholders' uptake of agricultural innovations and their ability to increase production. Further, the use of home-saved seed is common in northern Uganda, and only occasionally supplemented by hybrid seeds (Obuo et al., 2004), which also contributes to the low crop yields.

1.3 Sustainable Intensification with Legumes

The Sustainable Development Goals (SDGs) are unlikely to be achieved by most countries in SSA, with about six years until 2030. SDG Goals 1 and 2 aim to end poverty and hunger for all by 2030, respectively (UN 2015). In contrast, food insecurity and population size are currently increasing in SSA (Giller, 2020). Uganda, like many SSA countries, face further challenges of political, institutional and economic instability, which further limit smallholders' development capacities (Bekunda et al., 2022). Sustainable Intensification (SI) broadly includes the complex social dimensions of sustainability, including food security and nutrition (Kim et al., 2019). The goal of SI is to enable smallholders to improve their farm productivity without compromising the environment (S. Snapp, Rogé, et al., 2018). In many regions in SSA, like in northern Uganda, legumes traditionally provide multiple socio-economic and ecological benefits and are part and parcel of attaining SI (Nassary et al., 2020; Silberg et al., 2017).

Pigeon pea (*Cajanus cajan* [L.] Millspaugh) is a semi-perennial, multi-purpose legume that provides plant-based protein, and grains provide up to 38% protein content (Nassary et al., 2020), fodder and firewood for smallholders in northern Uganda. It is particularly important for the poor smallholder households in the tropics and sub-tropics including Asia and Africa (Fuller et al., 2019). Pigeon pea is an affordable organic alternative for soil fertility improvement (Nord et al. 2020), as it can reduce the amount of inorganic fertilizers by up to 50% without compromising soil productivity (Chimonyo et al., 2019). Pigeon pea is an annual short-lived perennial shrub, measuring 1-4 m in height, a variable habit (Fuller et al., 2019). Most of the pigeon pea produced in northern Uganda is for domestic consumption, with negligible surplus sold on local and regional markets in south Sudan and the Democratic Republic of Congo (DRC) (Obuo et al., 2004).

Notwithstanding the actual and potential benefits from pigeon pea, it is still an 'orphan crop' with relatively little to no attention from development agencies and agriculture research and practice (FAO, 2021; Tadele, 2019). Agricultural research in SSA tends to focus on a few major annual cereal crops, like maize, sorghum and rice, and major cash crops like coffee, while legumes often 'fall through the cracks'. For example, the Consultative Group for International Agricultural Research (CGIAR) Tropical Legumes Program (Phase TL I, II and III) aimed to promote legumes in Uganda and other SSA countries, though the main focus was on common beans, soy beans and cowpeas (Ojiewo et al., 2020; Varshney et al., 2019). Breeding of pigeon pea toward smallholder preferred traits is infrequent, leading to few hybrid varieties (Khoury et al., 2014). The few pigeon pea breeding programs that previously existed have focused on drought resistance (Kaoneka et al., 2016). Understanding pigeon pea growing smallholders' needs and preferences is critical for tailoring future breeding and extension and to improve usage by and actual benefit for smallholders (Grabowski et al. 2019; Hendre et al. 2019).

1.4 Scope of the Dissertation

While there are many studies on smallholder farming systems and their characteristics in SSA, examination of legume-based smallholder farming systems in general, and pigeon pea in particular, in a marginalized post-conflict region, is lacking. In view of the above, this dissertation aims to describe pigeon pea-based farming systems in northern Uganda, to understand their complexities and boundaries and provide recommendations for better performance through a model framework. The study employs interdisciplinary approaches and is based on empirical field work conducted in northern Uganda in 2019 and 2020. Both qualitative and quantitative data collection approaches were employed; a baseline study to develop a hypothesis was followed by a cross-sectional survey with pigeon pea growing smallholders. A detailed characterization of selected farm types and soil-fertility assessments were conducted in October 2020.

Qualitative data was collected from experts from the Zonal Agricultural Research and Development Institute (ZARDI) in Ngetta and extension agents in Lira, Pader, and Kitgum districts in September 2019. This information helped in the development of a questionnaire for the subsequent household survey. Survey data allowed an understanding of the role of membership in farmer groups on pigeon pea yield and technical efficiency. Further, we used the survey for clustering of smallholders into a typology, and a better description of the farming system in detail. The survey was carried out between October and November 2019 with 257 smallholders in the three districts of Lira, Pader and Kitgum in northern Uganda who had grown pigeon pea for at least two consecutive years. The identification of the interviewees was random, following a multi-stage sampling strategy using the district, sub-county, parish, and village level as the strata. To triangulate survey data, we held Key Informant Interviews (KIIs) with researchers at ZARDI in Ngetta, Lira district.

We hypothesize that the pigeon pea-based farming system in northern Uganda is a mixed subsistence system, smallholders produce both crops and animal products mainly for domestic consumption. We therefore aimed to understand the interaction of the farming system components as described in section 1.2, and to provide targeted recommendations for improved farm performance and ultimate sustainable intensification.

The first study (see Chapter two) analyzed the role of membership of smallholders in farmers' groups on pigeon pea yield and technical efficiency. The second study (see Chapter three) developed a smallholder typology and identified the factors leading to such diversity in the farming system. This allowed a selection of representative farms for a detailed characterization survey conducted in October 2020 for bio-economic modeling (see Chapter four). The aim of the detailed characterization was to provide a basis for a complete farming system diagnosis and exploration using the FarmDESIGN whole-farm bio-economic model. Additionally, we collected soil samples on 18 pigeon pea farm plots in Lira, Pader and Kitgum in October 2020, which were later analyzed in the plant and soil laboratory of Makerere University in Kampala.

1.4.1 Main Objective

The study aimed to describe and analyse the smallholder pigeon pea-mixed farming system northern Uganda and provide targeted recommendations for better and improved farm performance and ultimate livelihood, food security and sustainable intensification.

Specific Objectives:

a) to assess the role of membership of pigeon pea growing smallholders in farmer groups on pigeon pea yield and technical efficiency, and the factors that influence farmer- group membership;
b) to develop a typology of pigeon pea growing smallholders and factors driving such diversity;
c) to assess smallholders' preferences of pigeon pea across the identified farm types;
d) to simulate farm improvement alternatives using a whole-farm bio-economic model (FarmDESIGN) by maximizing farm profit, labor, and minimize soil organic matter and N balance for better and targeted farm performance.

1.4.2 Ethical Consideration and Approval

This study received ethical approvals from the ethical review board of the Center for Development Research (ZEF), University of Bonn. The research protocols were also approved by the Uganda National Council of Science and Technology (UNCST) (Code SS 5196), through the research ethics committee of the Makerere University School of Social Sciences. Before each interview, informed consent was sought from the respondents.

1.5 Description of the Study Area

1.5.1 Study Districts

This dissertation is based on empirical field research carried out in the three districts of Lira, Pader and Kitgum in northern Uganda in 2019 and 2020. Over 90% of the population in northern Uganda depends on smallholder agriculture (UBoS 2018). The civil war in northern Uganda that lasted about 20 years (between 1986 and 2006) led to substantial marginalization and impoverishment of the region, with villages and land abandoned and/or lost, infrastructure destroyed, and public services like schooling and health care nearly non-existent. Since 2006, northern Uganda is gradually recovering from the effects of the civil war with relatively more security and stability. Yet, northern Uganda still has by far the highest poverty rate in the country with over 30% of the population living below the poverty line (Okello et al., 2019).

Northern Uganda is predominately semi-arid, with uni-modal rainfall (usually April to October), and a long dry period (usually November to March). Farming is rain fed and characterized by a combination of annual and perennial crops, as well as livestock rearing (Kaizzi 2014). The study districts are located in the “Annual cropping and cattle Northern System” (see Figure 1.2), also known as the Acholi-Lango sub-system (Kaizzi, 2014).

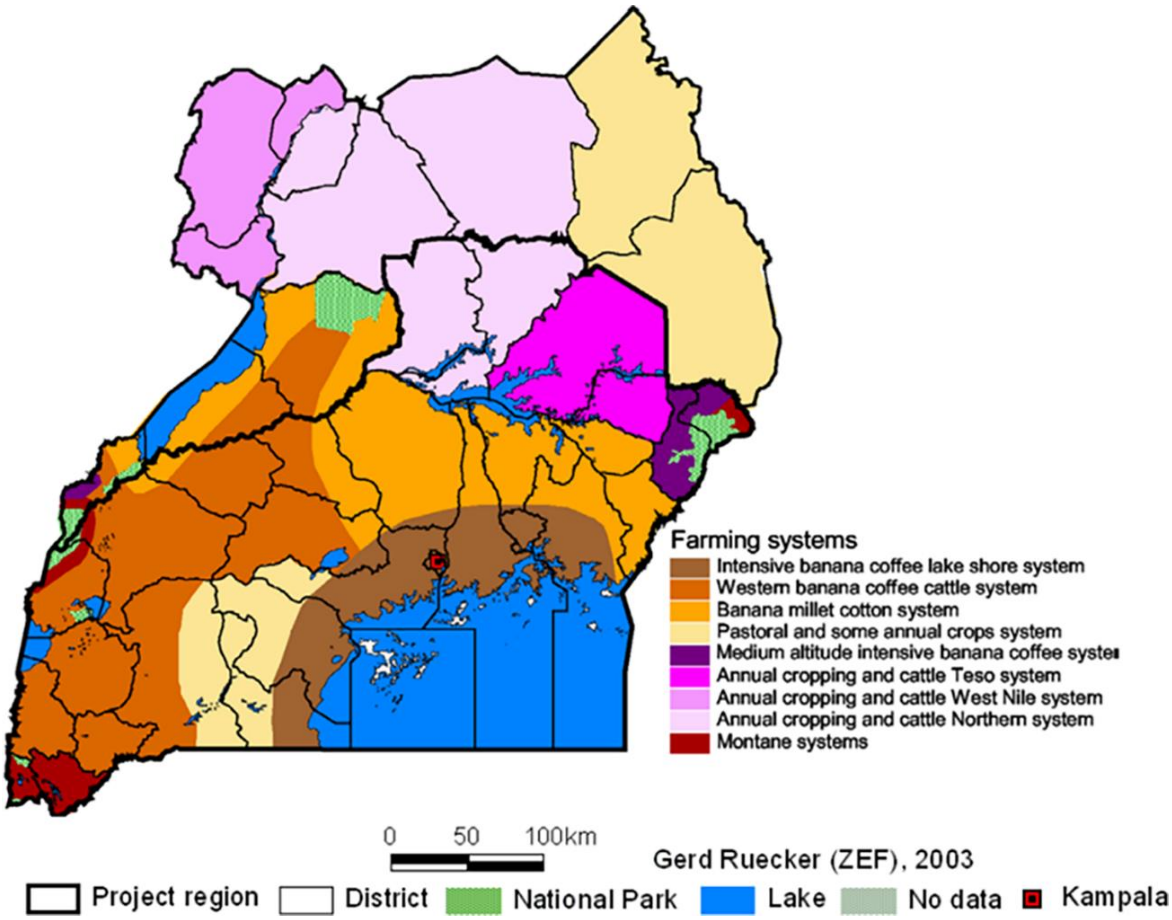

Figure 1.2: The farming systems of Uganda the study area is the "Annual cropping and cattle Northern System", also known as the Acholi-Lango sub-system (Kaizzi, 2014) (https://www.yieldgap.org/uganda).

Finger millet is the most important cereal crop grown in northern Uganda, followed by sorghum and maize (UBoS 2020). Pigeon pea, cowpea, beans, and soybeans are the main legumes, normally intercropped with cereals. Main cash crops are cotton, tobacco and sunflower. To some extent, smallholders practice agroforestry, with shear and macadamia-nut trees for additional livelihood benefits. Table 1.1 shows the key characteristics of the three study districts.

Table 1.1: Characteristics of Lira, Pader and Kitgum districts, northern Uganda

Parameter	Unit	Lira	Pader	Kitgum	Reference
District area	km^2	1,322	3,363	4,042	www.Ubos.org
Population	People	408,043	178,004	204,048	www.ubos.org (Census, 2014)
Altitude (av.)	m	1,074	1,197	1,050	www.climatedata.org
Temperature (av.)	^0C	25.2	25.3	25.3	www.climatedata.org
Rainfall (av.)	mm/yr	2,215	1,842	1,547	www.climatedata.org
Soil fertility	low, high	Low	low	Low	(C. S. Wortmann & Eledu, 1999; Yost & Eswaran, 1990)
pH		5.8	6.1	6.2	(Stoorvogel and Smaling 1993)

1.5.2 Socio-economic and livelihood characteristics of smallholders in northern Uganda

Smallholder farming in northern Uganda exhibits generally low input-output cycles, low mechanization, and ineffective farm management practices. The hand-hoe remains the main farming tool, with a few high-resourced smallholders owning or hiring ox-ploughs. Farming is labor-intensive with labor mostly provided by women (sowing, weeding, harvesting, and threshing), while men do the land opening and provide labor for cash-based crops. The ownership, control and access to production resources is different between men and women. Women are normally in charge of producing legumes, including pigeon pea.

Female-headed households are generally more prone to poverty compared to their male-headed cohorts. Small ruminants (goats, sheep) and poultry (ducks and chicken) are commonly kept. However, much of the larger livestock was lost during the civil war and later through cattle rustling by Karamojongs (Rockmore, 2020). A few high-resourced households keep cattle and oxen. Livestock provides manure, milk and eggs, income, draught power, and prestige. Non-farm income opportunities are minimal compounded by low education level and poor infrastructure (Shikuku, 2019). Additional cash income is generated through charcoal selling, local brewery, small trading, pottery, and tailoring for women.

In light of the many challenges faced by smallholders in northern Uganda, there has been increased involvement of both governmental and non-governmental organizations (NGOs) in various development initiatives and projects since the end of the civil war in 2006. For example, the Northern Uganda Social Action Fund (NUSAF), supported by the World Bank, aims to "empower communities in Northern Uganda by enhancing their capacity to systematically identify, prioritize, and plan for their needs and implement sustainable development initiatives" (World Bank, 2016). The Promoting Rural Development in Uganda (PRUDEV) program, supported by the GIZ, aims to "improve the agricultural-based development of the rural economy in northern Uganda" (www.giz.de/en/worldwide/59817.thml). Their efforts are crucial, however, not much has been achieved since smallholders are considered as a homogeneous group without detailed and up-to-date knowledge on their mixed farming system diversity and needs. Therefore, the severity and complexity of challenges for smallholders in northern Uganda demands for more context-specific empirical research to allow for better targeted and practical recommendations.

1.6 Structure of the Dissertation

The dissertation starts with a general introduction and motivation for the study, providing a conceptual framework and characteristics of the study districts. Chapter two assesses the role of membership of smallholders in farmer groups on pigeon pea yield and technical efficiency in the northern Uganda farming system. We applied the Stochastic Production Frontier (SPF) model and complementary models to assess the influence of membership in farmer groups on pigeon pea yield and technical efficiency. Chapter three develops a smallholder typology based on smallholder characteristics and resource endowments using multivariate statistical approaches. We further assessed smallholders' preferences for pigeon pea across the identified six farm types, gender and the three study districts using Likert scale analysis. Chapter four simulates representative farms utilizing a bio-economic model FarmDESIGN and designates the current farm performance parameters (Groot et al. 2012). Chapter five provides a summary of the key findings and draws general conclusions and recommendations. It also raises questions for future research needs.

2. FARMER GROUPS, YIELD AND TECHNICAL EFFICIENCY: EVIDENCE FROM PIGEON PEA SMALLHOLDERS[1]

ABSTRACT

Membership in farmer groups can enormously contribute to agricultural development. However, little is known about the importance of farmer groups in Uganda, specifically for pigeon pea smallholders in northern Uganda. We surveyed 257 pigeon pea-producing smallholders in three districts in northern Uganda to examine factors that motivate membership in farmer groups and its influence on pigeon pea yield and technical efficiency. We applied the Stochastic Production Frontier model (SPF) and complementary models to assess the determinants of membership in farmer groups and its impact on pigeon pea yield and technical efficiency. Technical efficiency is defined as the degree to which smallholders use the minimum feasible farm inputs to produce a given level of pigeon pea yield. Results show that farmer group members were generally older and more experienced, and had better access to extension services (76%) and credit (43%) compared to non-members. Age of the smallholder, access to agricultural training, extension services, and the distance travelled to market centres were statistically significant, thus increasing the likelihood of seeking group membership. Technical efficiency was low and quite similar, at 63% and 59% for members and non-members, respectively, implying that both groups did not use the available farm inputs very efficiently. Our results confirm that membership in any farmer group boosts smallholder's access to extension, agricultural training services and formal credit. However, the results also show that written extension materials and oral trainings are mostly in English, which is not spoken by most people in the districts, and that farmer group services are provided in centralized ways, making it difficult or impossible for smallholders in remote villages to benefit from them. For northern Uganda, the study provides recommendations for improving the human, financial and physical capacities of extension agents and the extension system to support sustainable intensification and rural development.

2.1 Introduction

It is widely acknowledged that membership in farmer groups (FGs) can improve smallholder livelihoods, for example by contributing to better access to markets, supply of production inputs as well increased bargaining power (Wossen et al. 2017; Wouterse and Faye 2020). In Uganda, like in many other sub-Saharan African (SSA) countries,

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collective action through FGs is often implemented and supported by both governmental and non-governmental organizations (NGOs) at different administrative levels (Ekepu et al., 2017; Meier zu Selhausen, 2016). However, despite all collective action efforts, smallholders in Uganda continue to be challenged by poverty, low crop yields, decreasing soil fertility, low mechanization, high pest and disease pressure as well as increasing impacts of climate change (Vanlauwe et al., 2019). Relatedly, Uganda's population is increasing and projected to exceed 100 million people by 2050 (Vollset et al., 2020), implying an increasing demand for food (Uganda Bureau of Statistics, 2020; World Bank, 2016).

FGs are fundamental instruments for smallholder agricultural transformation in developing countries (Ingutia, 2021; Lowder et al., 2021). The motivation of smallholders to become members in FGs is determined by several interwoven socio-economic and institutional factors and individual perceptions of their expected benefits against the costs (Bizikova et al., 2020). Such perceptions can be manifold, from expected better access to (often subsidized) farm inputs, extension, credit, and price information, to socio-economic and political pressure and power (Abdul-Rahaman and Abdulai 2018; Francesconi and Wouterse 2021).

Ainembabazi et al. (2017) illustrated that membership of smallholders in FGs can be an important mechanism for improving the farm productivity of smallholders in East Africa's Great Lakes Region through improved technical efficiency (TE) in input use. Further, Abdul-Rahaman and Abdulai (2018) identified collective action mediated by FGs in Ghana as an important strategy to increase TE and improve rice yield of smallholders. For smallholders in Zimbabwe, Mujeyi et al. (2020) reported an increase in social capital and information exchange as a result of participation in FGs. To the best of our knowledge, there is no scientific empirical evidence to show the role of farmer groups in the pigeon pea mixed farming systems in northern Uganda.

Understanding the Smallholder Legume-based Mixed Farming System: Application of the Whole-Farm Household Modeling in Uganda

This chapter examines the factors that influence the smallholder's membership decisions and the influence membership on pigeon pea yield and TE in northern Uganda. We define TE as the degree to which smallholders use the minimum feasible farm inputs (such as land, seed, labour and pesticides), to produce a maximum pigeon pea yield. We use propensity score matching (PSM) to account for selection bias due to non-random decisions by smallholder to join FGs. The study denotes "farmer groups" as either formal or informal village-level smallholders individuals organized around shared objectives with the purpose of supporting their collective and individual interests (Bizikova et al., 2020).

2.2 Farmer Groups in northern Uganda

Northern Uganda is predominantly agrarian-based (MAAIF 2010, 2017), with over 70% of the population directly dependent on subsistence agriculture (UBoS, 2020). After 20 years (1986-2006) of civil war in northern Uganda (Manor, 2007), multiple governmental and NGO development programs aimed to improve smallholder livelihoods and increase agricultural productivity in the region (Wallace 2016). The support of smallholders' collective efforts at village level was, and remains a central component in many of these programs (MAAIF 2010).

In 2001, the Ugandan government launched the National Agricultural Advisory Services (NAADS), as a semi-autonomous body under the Ministry of Agriculture, Animal Industry and Fisheries (MAAIF), with an objective of promoting smallholder agriculture through farm input provision via FGs (Wallace 2016; MAAIF 2017). The expectation was that FGs formed 'bottom-up' at the village level would lead to the formation of farmers' associations at higher administrative levels (Kampmann & Kirui, 2021). FGs focussed on a few selected crops and livestock enterprises that were seen to have competitive advantages (Wallace, 2016). Some FGs engaged in collective bulking and marketing, especially for cereals, and provided price and market information to their members. NAADS to some extent supported FGs by providing advisory and technical services and farm inputs (AfranaaKwapong & Nkonya, 2015). Smallholder's entry and FG membership is non-random, and some smallholders are members in more than one FG depending on their needs, resources, and location. The membership of a smallholder in an FG is usually formalized with an annual fee and a requirement to participate in the FGs meetings regularly. For many groups in northern Uganda, the membership fees are around US$ 3 per person per year, including entry and registration fees.

The effectiveness of FGs in northern Uganda in the last 20 years was largely dependent on the quantity and quality of advisory services and the provision of farm-input by NAADS (UBoS 2020). However, the ‘success’ of NAADS was and is still contested (AfranaaKwapong & Nkonya, 2015). Apart from the comparatively low numbers of extension agents, challenges like low level of participation from smallholders and poor group governance continue to persist (AfranaaKwapong & Nkonya, 2015; Wallace, 2016). NGOs, for example the Africa 2000 Network (A2N), Plan International, TechnoServe and ZOA-Uganda, also supported FGs in northern Uganda since the end of the civil war (Ekepu et al., 2017). Most FGs focus on cash crops like cotton, sesame, sunflower, and maize. Legumes such as pigeon pea were rarely in the portfolio, despite their great importance for smallholders’ livelihoods. As of 2020, there are 162 FGs in Lira district, and 72 each in Pader and Kitgum districts, respectively, with group memberships ranging between 10 and 50 smallholders (https://www.thefarmersguideug.com/).

2.3 Conceptual Framework

In this section, I present the conceptual framework used to analyse the factors that motivate or demotivate pigeon pea growing smallholders in northern Uganda to be a member in any FG and thereafter specify the general Stochastic Production Frontier (SPF) model as shown in Figure 2.1. We hypothesize that the membership of pigeon pea growing smallholders in FGs is influenced by the following factors: access to credit, training, extension and that group membership increases yield and TE.

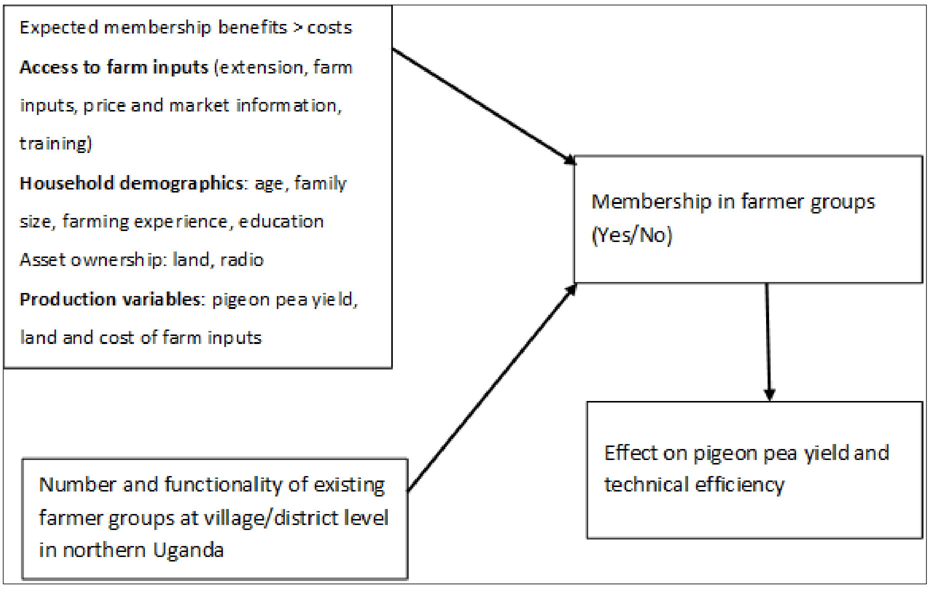

Figure 2.1: Schematic representation of factors influencing smallholders' decision to seek FG membership in northern Uganda. The arrows show the relationship between the dependent and independent variables. Authors' own illustration

We account for potential selection bias, since group membership is a non-random decision. Previous research by Ekepu et al. (2017) found that gender and access to extension significantly influences membership in farmer associations in Soroti District, Uganda. Similarly, Mwaura (2014) reported that membership of smallholders in FGs throughout Uganda had positive impacts on their banana and cassava yields, but negative effects on yields of sweet potatoes, beans and maize.

The decision for group membership is binary (Figure 2.1). We include smallholder's access to inputs, credit, training and extension, and plot-level variables for the estimation of factors influencing their memberships. Smallholders' age, experience, and education as well as household family size (as a proxy for family labour) were included building on previous work by Ainembabazi et al. (2017); Nakazi et al. (2017); Agole et al. (2021). Access to extension, price and market information, and agricultural training were included as dummy variables (1=yes, 0=no), and radio ownership included as a dummy variable (Abdul-Rahaman and Abdulai 2020).

2.3.1 The Binary Probit Model

Since group membership is binary, it is better explained with binary outcome models (Verbeek, 2004), such as the probit model. Therefore, the ordinary least squares (OLS) model was not sufficient in modelling factors influencing FG membership (Maddala, 1986). Given the non-randomness of the decision to be member in an FG (Figure 2.1), several factors influence this decision. Following Abdul-Rahaman and Abdulai (2018), we take the probability to be member in a FG as the difference between the benefits of membership G_B^*, and the expected losses G_L^*. Group membership increases if expected benefits exceed costs involved, i.e. $G_i^* = G_B^*$ - G_L^* > 0. However, what is observed is group membership, with G_i^* being a latent variable that is unobservable. G_i^* as a function of observable characteristics in a latent variable structure as;

$$G_i^* = \gamma Z_i + \omega_i + G_i = 1[\ G_i^* > 0] \qquad 2.1$$

Where G_i is a group membership indicator, taking 1 if a smallholder is a member in a FG, and 0 otherwise. γ is the error term with 0 mean and variance σ^2, and Z_i is a vector of observable smallholder farm and household characteristics believed to influence the decision for membership in FGs. Therefore, the likelihood of membership in any FG is specified as below;

$$Pr\ (G_i\ = 1) = Pr\ Pr\ (G_i^* > 0)\ = Pr\ Pr\ (\omega_i\ > -Z_i\,\gamma)\ = 1 - F(-Z_i\,\gamma) \qquad 2.2$$

Where F is the cumulative distribution function for ω_i .

2.3.2 The Stochastic Production Frontier Model

We hypothesize that the pigeon pea yield of a smallholder increases if he or she is a member of an FG. We therefore used the Stochastic Production Frontier Model (SPF) to estimate how membership affects yield. The model is specified as follows:

$$Y_{ij} = f(X, G_B\,) + \varepsilon_i,\ \varepsilon_i = v_{ij} - u_{ij} \qquad 2.3$$

Where Y_{ij} is the yield of the ith smallholder, X is a vector of inputs and explanatory variables, and G_B is a dummy variable that captures the effect of group participation. v_{ij} is a two-sided error term and u_{ij} denotes the one-sided error term capturing efficiency. The subscript j refers to G_B for smallholders who are members in the jth group and G_L for non-members. Due to the non-random nature of joining FGs, it is likely that selection bias arises due to observed and unobserved smallholder traits. We address the bias when estimating the SPF model to obtain unbiased and consistent yield and TE estimates (Bravo-Ureta et al., 2012). Smallholders face technical inefficiencies because of differing production opportunities given their varying resource endowments in terms of capital, infrastructure and other physical and environmental characteristics (O'Donnell et al., 2008). We determine separate frontiers across FG members and non-members to account for TE differences across the two groups.

2.3.3 Accounting for selection bias in the stochastic production frontier model

Greene (2011) and Lai (2015) acknowledge sample selection bias in the SPF model and used different approaches to estimate TE. For instance, Solis et al. (2006) applied the Switching Regression Approach (SRA) to SPF to analyze TE levels for smallholders in El-Salvador and Honduras under two different levels of soil conservation practices. They found potential selection bias for high and low level adopters and separate SPFs, and consequently, selection bias were corrected for in each group. Likewise Mayen et al. (2010) addressed self-selection in FGs by using PSM to compare organic and conventional farms in the United States. They report minor differences between organic and conventional farms when TE was measured against the appropriate agricultural technology. However, they only corrected for biases stemming from observed variables and nothing for the unobserved covariates.

We use the Cobb-Douglas (CD) function to estimate the propensity scores. PSM is often used to evaluate the impacts of a binary treatment variable (Ruben & Fort, 2012). Subsequently, we correct for selection bias for both the observed and unobserved factors for the estimation of production function and TE. We follow Greene (2010) to deal with bias from unobserved factors, for example, smallholder's motivation and managerial ability. The model is an improvement to Heckman's self-selection specification for the linear regression model and assumes that the unobserved characteristics in the selection equation are correlated with the noise in the SPF model (Bravo-Ureta et al., 2012). The model is specified as:

Sample selection model:

$$G_i = 1[Z_i \gamma + \omega_i > 0], \omega_i \sim N[0,1] \qquad 2.4$$

SPF:

$$y_i = \beta' x_i + \varepsilon_i, \varepsilon_i \sim N[0, \sigma_\varepsilon^2] \qquad 2.5$$

$$(y_i, x_i) \text{ observed only when } G_i = 1 \qquad 2.6$$

Error structure;

$$\varepsilon_i = v_{ij} - u_{ij},$$
$$u_i = |\sigma_u U_i| = \sigma_u |U_i|, \text{ where } U_i \sim N[o, 1]$$
$$v_i = \sigma_v V_i \text{, where } V_i \sim \text{N}[0,1] \qquad 2.7$$
$$\omega_i, v_i N_2 [(0,1), (1, \rho\sigma_v, \sigma_v^2)]$$

Where; G_i is a binary dependent variable taking on 1 for FG membership and 0 for non-membership, y is the output (pigeon pea yield), Z is a vector of covariates in the sample selection model and x is a vector of inputs for the production frontier model. The parameters to be estimated are γ and β whereas the error structure correspond to the errors in the SPF model. The parameter ρ indicate the presence or absence of selection bias associated with the unobserved variables (W. Greene, 2010). Therefore, we first estimate the sample selection SPF model for group members and repeat for non-members, in which case the dependent variable G_i in the selection equation is reversed, i.e., G_i equals 1 for the non-participants and 0 for the group participants (W. Greene, 2010).

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2.4 Materials and Methods

2.4.1 Description of the Study Area

Data were collected in Lira, Pader and Kitgum districts in northern Uganda between September and December 2019. The districts were selected as they are hotspots for pigeon pea production in Uganda (Hillocks et al., 2000). The region is characterized by a semi-arid climate, unimodal rainfall and rain-fed subsistence agriculture (Kaweesa et al. 2018; Shikuku 2019). It is the poorest region of Uganda, with 33% of the population living below the poverty line (World Bank, 2016). Food insecurity is widespread, also due to the effects of the two decades of civil war between 1986 and 2006 (Chapman et al. 2009; Kaweesa et al. 2018). Similarly, Wallace (2016) reported that 59% of the households in northern Uganda consumed only one meal per day. Smallholders keep some livestock (goats, sheep, cattle and chicken) for additional income, domestic use, draught power and manure (Kristjanson et al., 2012; Samberg et al., 2016). The population density of Lira, Pader and Kitgum districts is 301, 54 and 51 people/ km^2, respectively (Uganda Bureau of Statistics, 2020).

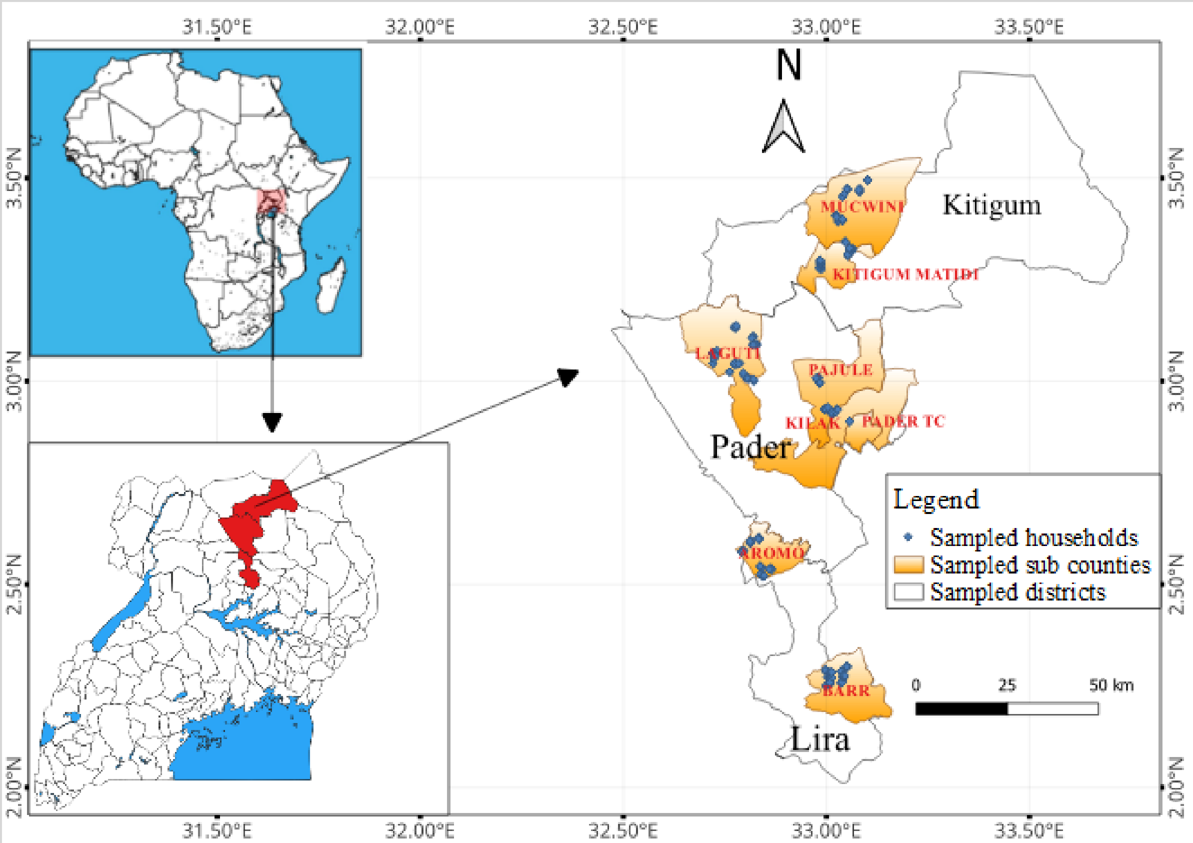

Figure 2.2: Map of Uganda showing the sampled districts in northern region and the selected households

Northern Uganda is prone to climate change compared to other parts of the country (Akongo et al., 2017). The soil type are ferralsols and nutrient-depleted (Apanovich & Lenssen, 2018), with a high demand for P and K (Yost & Eswaran, 1990). The complexity of challenges faced by smallholders in northern Uganda calls for context-specific empirical research to contribute to better livelihoods and more food security.

2.4.2 Sampling and Data Analysis

A baseline study including interviews with agricultural extension workers and researchers at the Zonal Agricultural Research and Development Institute in Ngetta guided selection of the study districts. Three districts were purposively selected following a multi-stage approach from district to villages, and based on pigeon pea production statistics for northern Uganda. In the second sampling stage, two sub-counties were selected per district, and in each sub-county, three villages were selected following a simple random sampling. Finally, the study was conducted in 18 villages in the three districts.

We employed a quantitative approach that involved use of a pre-tested semi-structured questionnaire to interview 257 pigeon pea smallholders using a Computer Assisted Personal Interview (CAPI) Kobo-collect toolbox (Gravlee, 2002). The questionnaire included sections on smallholder household characteristics, pigeon pea production, marketing and consumption attributes, farm endowments, as well as challenges and opportunities regarding pigeon pea production. The interviews were held in either Langi or Acholi language, and took between 30 to 40 minutes each. All sampled smallholders had grown pigeon pea for at least two consecutive years. Data was analysed using STATA statistical package version 15.1 (StataCorp, 2017). Mean and standard deviation were used for descriptive statistics, and the probit, CD function, and PSM techniques to assess FG membership, yield, TE and its determinants respectively.

2.4.3 Specification of the Empirical Model

Membership in FGs is usually non-random; we therefore use a PSM approach to cater for selection bias. Dehejia and Wahba (2002) and Caliendo and Kopeinig (2005) show that the PSM estimator provided low bias especially using cross-sectional datasets, like in our case. Caliendo and Kopeinig (2005) illustrates the several matching criteria used in PSM; including nearest neighbor matching (NNM), caliper matching, kernel matching, stratification and interval matching. For this study, we employed both the NNM and kernel matching algorithm (Caliendo and Kopeinig 2005; Abdul-Rahaman and Abdulai 2018).

The SPF model was estimated with correction for selection bias after the matching procedure. We first model smallholders' membership decisions using the probit model, which is described by a criterion function and expressed as a function of exogenous smallholder factors that influence FG membership:

$$G_i = \gamma_0 + \sum_{j=1}^{13} \gamma Z_{ij} + \omega_i \qquad 2.8$$

Where G_i is the binary variable assigned to a value of 1 for members, and 0 for non-members, γ is a vector of unknown parameters to be estimated, and ω is the error term distributed as N (0,σ^2). Z represents the variables; age of the smallholder, education level, farming experience, family size, distance of the farm to the nearest market center, total land owned, access factors (credit, agricultural training, extension) and whether the smallholder lives in Lira, Pader or Kitgum districts.

When smallholders join FGs, the chances of accessing extension services and credit normally increase (Abdul-Rahaman and Abdulai 2018). This is related to endogeneity, which is addressed by employing a two-stage control function approach as outlined in Wooldridge (2015). Radio ownership is used as a proxy variable for access to information on prices and market opportunities, which we first estimated separately in the probit model following Ainembabazi et al. (2017). We assumed that smallholders who owned a radio have better access to information compared to those without one. The proxy indicator was expected to influence access to information on prices and market opportunities but not affect group membership.

In the second stage, the observed predicted residuals of access to price and market information were incorporated into the group membership probit model. This approach has often been used in research on collective action, for example by Abdul-Rahaman and Abdulai (2018) in Ghana, who used distance to credit sources and the status of farm roads as control variables to credit and extension access, respectively.

Lastly, we evaluated the two most commonly used functional forms in efficiency studies; the CD and Translog (TL) models (Becker & Ichino, 2002; Bravo-Ureta et al., 2020). We used a log likelihood ratio test to reject the TL model in favor of the CD model at 5% level of significance. The CD model is specified as below:

$$In(Y_i) = \beta_o + \sum_{j=1}^{5} \beta_j lnX_{ji} + \sum_{k=1}^{8} \delta_k D_{ki} + v_i - u_{i,} \qquad if\ G_i = 1 \qquad 2.9$$

Where Y_i denotes pigeon pea yield, i, X_{ji} is the quantity of the jth input; D are the dummy variables; β and δ are unknown parameters to be estimated; *v* and *u* are the elements of the error term, ε. The dependent variable in the CD model is pigeon pea yield for the harvests of 2019 in kilogram (kg). The covariates are production function inputs, namely pigeon pea yield-dependent variable (YIELD), acreage (HECT), proportion of seed bought (SEED) and pesticides (PESTIC). To determine the effects on TE, we employed alternative models; the logit, probit, and complementary log-log regression for the second estimation stage (Abdulai & Abdulai, 2017).

2.5 Results

2.5.1 Descriptive Statistics

From the 257 sampled smallholders, 61% were members of an FG (Table 2.1). FG members were older (43 years compared to 40 years), but smallholders in the two groups had the same level education (5 years), comparable years of farming experience (22 years for FG members compared to 21 for non-members) and the same household size (about seven members in both groups).

FG members allocated less land for pigeon pea production (0.7 ha) than non-members (0.9 ha). However, FG members harvested slightly higher average yields (336 kg ha^{-1}) than non-members (311 kg ha^{-1}). Likewise, the use of pesticides was similar for both groups, with average costs of US$ 2.3 and 2.2 per season for members and non-members, respectively.

Table 2.1: Descriptive statistics for overall sample, FG members and non-members in Lira, Pader and Kitgum districts, northern Uganda

Variable	Code	Description	Pooled sample (n=257)	Mean (SD) Members (n=158)	Mean (SD) Non-members (n= (n=99)
Group Membership		1= Group member, 0= non-member	-	0.61	0.39
Age	AGE	Age of smallholder in years	41.5 (13.4)	43 (13.1)	40 (13.8)
Education level	EDU	Complete years in school	5.3 (3.4)	5.2 (3.4)	5.3 (3.3)
Family size	FSIZE	Household size (number)	6.96 (2.8)	6.9 (2.8)	6.9 (2.9)
Farming experience	FEXP	Number of years in farming	21.5 (13.6)	22 (13.3)	20.6 (14.2)
Access to;					
Extension access	EXT	1=access to extension services, 0= no	0.7 (0.5)	0.76 (0.43)	0.59 (0.49)
Radio ownership	RADIO	1=household owned a radio, 0= no	0.5 (0.5)	0.5 (0.4)	0.5 (0.5)
Credit	CRDT	1=have access to credit, 0= no	0.4 (0.5)	0.46 (0.5)	0.38 (0.49)
Agricultural training	TRNG	1=received agricultural training, 0=no	0.5 (0.5)	0.5 (0.5)	0.48 (0.5)
Price and market information	PRICE	1= have access to price and market information, 0= no	0.374 (0.485)	0.41 (0.039)	0.32 (0.047)
Land owned	LAND	Total land owned in hectares	2.6 (2.8)	2.7 (2.8)	2.5 (2.8)
Pigeon pea variety planted	VARIETY	1= planted improved variety, 0= no	0.05 ((0.2)	0.06 (0.24)	0.03 (0.17)
Distance to nearest market centre	DIST	Distance to market centre in kilometer	1.4 (2.2)	1.3 (2.1)	1.59 (2.4)
Lira	LIRA	1 = location is lira district, 0 = no	0.32 (0.5)	0.31 (0.5)	0.33 (0.5)
Pader	PADE	1 = location is Pader district, 0 = no	0.35 (0.5)	0.33 (0.5)	0.42 (0.5)
Kitgum	KITG	1 = location is Kitgum district, 0 = no	0.33 (0.5)	0.35 (0.5)	0.25 (0.4)
Variables for the SPF model					
Pigeon pea yield	YIELD	Total yield of pigeon pea harvested in 2019 (in kg ha^{-1})	326 (341)	336 (272)	311 (334)
Pigeon pea acreage	HECT	Land used for pigeon pea for 2019 (in ha)	0.8 (1.1)	0.7 (0.9)	0.9 (1.3)
Proportion of pigeon pea seed bought (input)	SEED	Proportion of seed bought during for 2019 (percentage)	24.1 (41.5)	24 (41)	23.6 (42)
Pesticide expense	PESTIC	Cost of pesticides/chemicals used for 2019 (in USD)	2.3 (3.99)	2.3 (4.15)	2.2 (3.75)
Perception of soil fertility status for legume plots	SFERT	1= fertile, 0= not fertile	0.96 (0.2)	0.97 (0.16)	0.93 (0.26)

Note: SD is Standard Deviation, reference period is 2019 (harvest from September to December). 1 USD = 3679 Uganda shilling (Bank of Uganda, November-2019)

2.5.2 Factors Influencing Smallholder`s Decisions for FG Membership

Table 2.2: Results of the probit model for factors influencing FG membership for smallholders in Lira, Pader and Kitgum districts

	1	2
	Probit	Marginal effects
Variable	Coefficients (SE)	Coefficients (SE)
AGE	0.089**	0.034**
	(0.039)	(0.015)
EDU	-0.019	-0.007
	(0.029)	(0.011)
FEXP	-0.003	-0.001
	(0.013)	(0.005)
FSIZE	-0.048	-0.018
	(0.033)	(0.013)
TRNG	-83.34**	-0.102**
	(33.33)	(0.045)
EXT	83.83**	.337**
	(33.32)	(0.260)
PRICE	0.310*	0.116
	(0.182)	(0.066)
CRDT	0.227	0.085
	(0.179)	(0.067)
DIST	-0.078**	-0.029**
	(0.039)	(0.015)
VARIETY	0.173	0.064
	(0.426)	(0.152)
RADIO	0.055	0.021
	(0.180)	(0.068)
LAND	0.013	0.005
	(0.012)	(0.005)
LIRA	-0.230	-0.088
	(0.228)	(0.088)
Residual for PRICE	920.6**	348.85**
	(368.3)	(139.41)
Constant	-480.3**	
	(191.5)	
Log likelihood	-156.57	
LR chi2 (15)	29.48	
Prob >$\chi 2$	0.0140	
Number of observations	257	

Note: **, and * represent significance at 5% and 1% levels respectively, Standard Error in parentheses

To assess factors that influenced membership in FGs, we use a probit model and its coefficients (1) and marginal effects (2) estimates are presented in (Table 2.2). The log-likelihood $\chi 2$ was 29.5 with 15 degrees of freedom, and prob > $\chi 2$ was 0.014 showing that the model was statistically significant.

Age of the household head (AGE), access to agricultural training (TRNG), extension services (EXT), and distance to the nearest market centre (DIST) significantly correlated with FG membership, meaning that a unit increase in farmers' age increased the probability that the smallholder participates in an FG by 3.4%. The probability of smallholder membership in FGs increased significantly with access to credit (CRDT) by 8.5%. However, the distance to the nearest market centre (DIST) significantly decreased the likelihood of membership in FGs, suggesting that smallholders in remote villages are rarely members in FGs, possibly due to poor infrastructure and less governmental and NGO engagement, and limited information access. Formal education (EDU) did not influence the decision for membership in FGs.

2.5.3 Estimates of the Stochastic Production Frontier

Results of the SPF model are presented in Table 2.3 for both the conventional and the sample selection models. The pooled sample estimates represent FG members and non-members with and without selection correction. Whereas the conventional model accounted for only observable characteristics, the sample selection model corrected for both observable and unobservable biases. The dependent variable is pigeon pea yield (YIELD) for 2019 and the explanatory variables in the production function and inefficiency determinants. The log-likelihood ratio test led to rejection of the null hypothesis of homogenous technology for group members and non-members at 5% for the conventional and sample selection models, matched *(LR = 22.78, $\chi 2$ = 0.030, df = 11).*

The null hypothesis test of no TE (*lambda = 0*) was rejected in all cases for FG members and non-members, indicating that TE contributed to pigeon pea yield differences between the two groups. The evidence for selection bias on the unobserved attributes justified why we use the sample selection model for members and non-members and the TE estimates as scores from the conventional SPF model were biased and inconsistent (Bravo-Ureta et al. 2012; Abdul-Rahaman and Abdulai 2018).

Table 2.3: Estimates of the SPF model for the conventional and sample selection models for factors influencing FG membership in northern Uganda

Variable	Conventional SPF model			Sample selection SPF model	
	pooled sample	Members	Non-members	Members	Non-members
	Coefficients (SE)	Coefficients (SE)	Coefficients (SE)	Coefficients (SE)	Coefficients (SE)
HECT	1.816 (3.084)	4.755 (4.572)	1.127 (3.941)	3.678 (4.686)	11.12**(4.651)
SEED	-0.149 (0.197)	0.261 (0.254)	-0.623**(0.304)	0.159 (0.265)	-0.152 (0.341)
PESTIC	0.0002 (0.001)	0.001 (0.001)	0.001 (0.001)	0.001 (0.001)	0.003 (0.002)
SFERT	-95.139** (40.64)	84.559 (64.243)	73.075 (49.034)	85.741 (65.622)	23.775 (53.669)
VARIETY	-104.207** (42.77)	-123.233***(48.05)	9.611 (82.083)	-79.465** (47.651)	-1.341 (102.77)
PADE	127.009*** (22.057)	92.143***(25.518)	89.626***(31.509)	95.356***(26.401)	18.529 (36.507)
LIRA	120.579***(26.7)	72.814**(32.259)	113.580***(42.896)	79.659***(32.828)	5.913 (50.399)
FEXP	-3.839 (6.422)	0.878 (1.755)	-6.901 (6.914)	-0.540 (2.086)	-2.307 (57.88)
AGE	-1.793 (2.493)	-1.384 (1.899)	-3.416 (3.062)	0.343 (2.014)	-3.993 (34.368)
EDU	7.394 (19.227)	16.979** (7.564)	-1.764 (6.818)	12.813**(7.169)	-
FG membership	17.179 (17.711)	-	-	-	-
Constant	-34.025 (46.342)	15.212 (68.699)	0.927 (51.255)	11.074 (71.004)	33.18 (56.076)
Log likelihood	-1611.66	-985.78	-614.84	-996.09	-617.837
Prob > chi2	0.000	0.0062	0.0024	0.0013	0.013
Sigma_u	8.369 (140.895)	10.377 (14.436)	14.969 (19.689)	1.777 (10.319)	12.779 (35.848)
Sigma_v	128.052 ***(5.989)	145.194***(9.002)	120.173***(8.585)	127.189***(7.133)	132.359***(11.81)
Lambda	0.654 (139.535)	0.0715 (16.823)	0.125 (21.416)	0.014 (12.559)	0.097 (37.839)
rho				-	-
No. observations	257	158	99	158	99

Note: **, and *** represent significance at 5% and 1% levels respectively. SE is Standard Error

The partial production elasticities measure the percentage contribution of each input to percentage change in yield. These were positive for FG members, apart from use of improved pigeon pea varieties. The reported partial elasticities for members and non-members in the sample selection model were lower compared to those in the conventional model, suggesting that sample selection bias overestimated the elasticities (Villano et al., 2015). For FG members, the elasticities of location and education were positive and significant, illustrating the positive impact on pigeon pea yield. FG members (treated group) consistently had higher TE compared to non-members (untreated group) as illustrated in Figure 2.2.

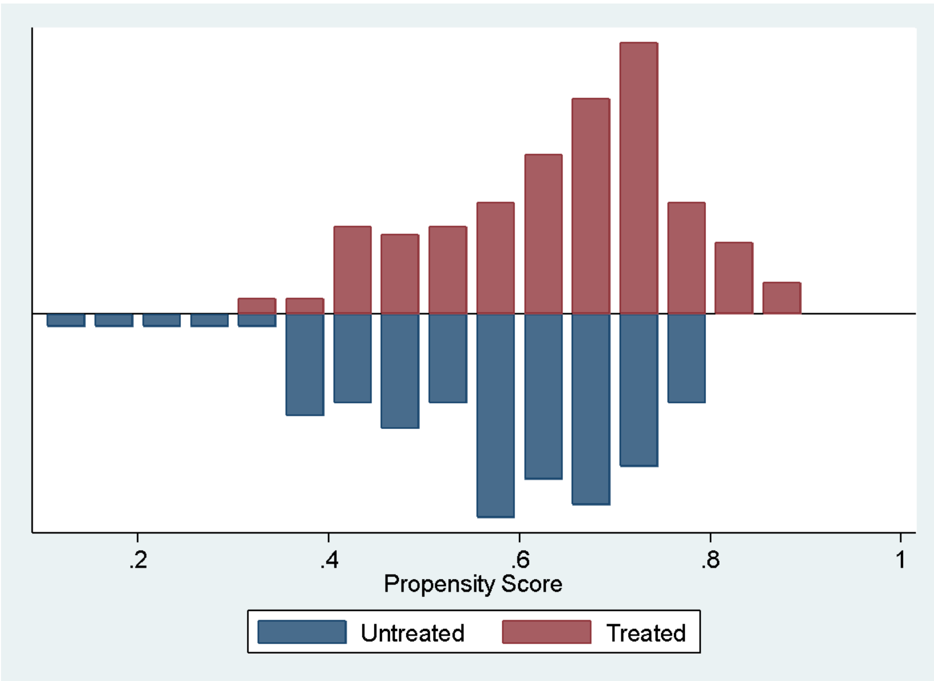

Figure 2.2: Distribution of propensity scores for FG members (treated) and non-members (untreated) in the common support region.

2.5.4 Measuring Technical Efficiency

For determinants of TE, we used alternative models, i.e., logit, probit and complementary log-log regression for the second estimation stage and later tested for the appropriate functional form (Abdulai and Abdulai, 2017). The average TE for group members was 63% compared to 59% for non-members. None of the two groups produced pigeon pea at the maximum (where TE = 1 or 100%), due to several factors. Our results point to factors such as low access to extension, low access to price and market information, distance to nearest market, and the low formal educational level of the smallholders (Table 2.4).

Table 2.4: Determinants of TE in the probit model, logit model and cloglog model

Variable	1 Probit model	2 Logit model	3 Cloglog model
	Coefficient (SE)	Coefficient (SE)	Coefficient (SE)
AGE	0.005	0.008	0.005
	(0.012)	(0.019)	(0.011)
EDU	-0.022	-0.034	-0.023
	(0.029)	(0.048)	(0.029)
FSIZE	0.004	0.006	0.006
	(0.03)	(0.051)	(0.030)
CRDT	0.119	0.172	0.170
	(0.183)	(0.307)	(0.178)
TRNG	0.046	0.099	0.008
	(0.184)	(0.309)	(0.179)
EXT	-0.893***	-1.477***	-0.886***
	(0.211)	(0.368)	(0.195)
SEED	-0.004**	-0.007**	-0.005**
	(0.002)	(0.004)	(0.002)
PRICE	-0.299*	-0.506**	-0.283
	(0.179)	(0.300)	(0.179)
LAND	-0.008	-0.014	-0.007
	(0.012)	(0.021)	(0.013)
DIST	0.092**	0.150**	0.096**
	(0.045)	(0.075)	(0.044)
Constant	1.142**	1.881	0.726
	(0.448)	(0.744)	(0.443)
Log likelihood	-147.81	-148.13	-147.04
LR chi2	27.72	27.08	29.27
Prob > chi2	0.0036	0.0045	0.0021
No. of observation	257	257	257

Note: **, and *** represent significance at 5% and 1% levels respectively. SE is Standard Error

2.6 Discussion

In this study, we use the binary probit model and complementary models to determine the factors that influence smallholders’ membership to FGs and TE for pigeon pea production in northern Uganda, respectively. We used a cross-sectional survey with 257 pigeon pea smallholders in Lira, Pader and Kitgum districts of northern Uganda, out of which 61% were members in any FG. As hypothesized, we found several factors that influence smallholders' FG membership. Specifically, access-related factors like access to agricultural training, extensions services, and price and market information significantly influenced smallholders' likelihood for group membership (Table 2.2).

2.6.1 Reasons for Joining FGs and Influencing Factors

Overall, about 37% of the smallholders had access to agricultural credit (Table 2.1). Smallholders reported their main sources of credit as Village Savings and Credit Associations (VSLAs), locally known as *bol li cup*. Similarly, FG members had better access to agricultural credit (46%) than non-members (38%) (Table 2.1). Further, 45% of the smallholders reported borrowing and saving as their main motivation for membership in FGs (Figure 2.3). This points to the importance of access to credit for smallholders. Credit is required for the purchase of farm inputs such as mineral fertilizers, improved seed, synthetic herbicides and pesticides. Similar results were reported by Wossen et al. (2017) and Olagunju et al. (2021) for smallholders in Nigeria. The access to credit from commercial banks is very limited for smallholder in northern Uganda. Commercial banks are usually located only in the few cities (trading cetres) in the region, far from smallholders' reach, and smallholders often lack collateral requirements, such as formal land titles, to borrow from these banks (Akudugu, 2016). Therefore, approaches to improve the borrowing and saving structures for smallholders in northern Uganda can enhance credit access for improving sustainable intensification and smallholders livelihoods.

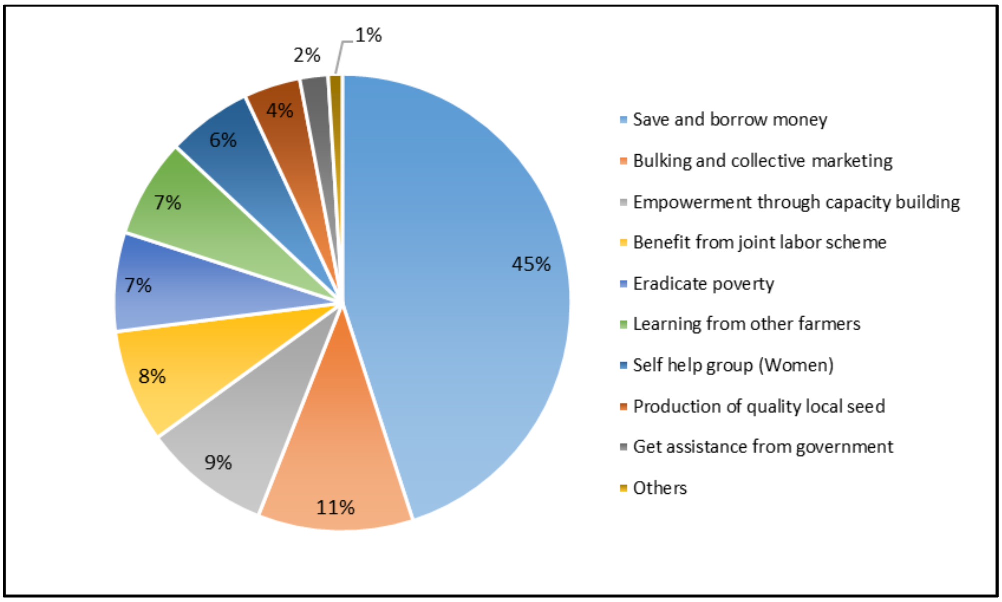

Figure 2.3: Motivation for smallholders to be members in FGs in northern Uganda

We found that FGs accumulate funds through membership fees of about US$ 3 per year as entry and registration fees. For example, the *Jingkomi Local Seed Business Group* in Kitgum district has about 100 members, of which over 70% are women, with a goal of improving access to credit to smallholders through low-interest loans and flexible repayment terms.

About 11% of the FG members joined a FG to benefit from bulking and collective market services. Agricultural marketing in northern Uganda is massively challenged by the poor and dilapidated road infrastructure. Northern Uganda is majorly rural, often with hard-to-reach villages with poor road connectivity (UBoS 2020). Public and private transport rarely exist and the few existing roads are often impassable, and seasonally flooded (Akongo et al., 2017). This implies limited access to markets where smallholders can sell their produce and buy agricultural inputs. As a proxy for market access, the distance to the nearest market centre (DIST) was positive and significant in influencing smallholders' membership in FGs. Smallholders who live in remote village are less likely to become FGs members than compared to those living closer to towns, since most of the FG meetings and activities are located at the parish or sub-county offices.

Similarly, we show that overall, only 37% of all smallholder had access to price and market information (PRICE), which further limit produce marketing. Bizikova et al. (2020) illustrated how FG membership improved smallholders' market access and income in rural regions across SSA. Strategies to improve market access through road rehabilitation, and setting up grain aggregation centres are hence recommended.

About 9% of the smallholders joined FGs to tap into training and extension opportunities (Figure 2.3). Agricultural extension is majorly offered by the few government agents (often through NAADS). The results showed that an increase in access to extension increased the likelihood of membership by 34%. Earlier results from Ghana illustrate a similar significant and positive effect of extension access (EXT) to smallholders' membership (Ma and Abdulai 2016). However, despite Ugandan governments' efforts to (re-)establish a wide agricultural extension system in northern Uganda after the civil war, there are only about 5-8 extension agents per 100,000 farmers in northern Uganda, a low ratio compared to other regions of the country (AfranaaKwapong & Nkonya, 2015). Even so, in many rural parts of SSA, training and information provided by extension agents often fails to meet smallholders' needs, as reported for insistence from Ethiopia by Leta et al. (2020). Overall, not only increasing the number of extension agents in remote areas, but also making their services more demand driven and applied to the actual problems of smallholders, can be a step toward vitalizing the role of FGs in northern Uganda.

The average formal education level in the study three districts was 5.3 years of school attendance, which is lower than the overall Ugandan standard. This is most likely a consequence of the 20-year long civil war that contributed to low school enrolment rates (Ssentanda & Asiimwe, 2020). Similarly, our results show that education level did not significantly influence membership in FGs (Tables 2.2). Government efforts to improve formal education attendance via the Universal Primary Education (UPE) and Universal Secondary Education (USE) programs, launched in 1997 and 2007, respectively, have not benefited the northern Uganda region (Uganda Bureau of Statistics, 2020;

World Bank, 2016). The 20-year long civil war prevented many children (who are now adults) to go to school, and left many educational facilities vandalized; many girls were forced into early marriage and motherhood (Baines & Gauvin, 2014). In contrast, Mojo et al. (2017) and Olagunju et al. (2021) found that formal education of smallholders significantly increased their likelihood to become members in farmer cooperatives in Ethiopia and Nigeria, respectively. To overcome challenges of low formal education, the provision of agricultural-related training services not only in English but in Langi and Acholi languages could help in increasing smallholder's membership in FGs and generally the effectiveness of the FG services in northern Uganda.

2.6.2 Options to Improve Technical Efficiency and Pigeon pea Yield

The average TE for FG members was 63% compared to 59% for non-members, an indication that in general pigeon pea smallholders were not producing very efficiently (Figure 2.2). This implies that both FG members and non-members could potentially increase pigeon pea production by 37% and 41%, respectively. In contrast, Okello et al. (2019) reported a mean TE of 78% for rice farmers in northern Uganda. Among the factors affecting TE, education level, access to extension, and proportion of seed bought significantly influenced efficiency. This confirms the notion that smallholders can rarely maximize their efficiency since they constantly face multiple production-related constraints.

Important to note is that FG members and non-members often live close to each other in the same villages, implying likely spill over effects between the two groups. Pigeon pea yield (YIELD) was generally low, with 336 kg ha^{-1} and 311 kg ha^{-1} for members and non-members, respectively (Table 2.1). About 24% of the smallholders bought hybrid pigeon pea seeds at least occasionally, and majority (76%) used home-saved local pigeon pea varieties, locally known as *Apio-Elina, Apena,* and *Adong*. Local varieties are relatively low yielding and often prone to pests and diseases (Kaoneka et al. 2016; Manyasa et al. 2009). Similarly, Milne et al. (2015) in Tanzania found that 78% of the smallholders used mainly local pigeon pea varieties. Smallholders expressed their desire to plant improved and hybrid pigeon pea varieties, but cannot afford the high costs of about US$ 2 per kg of these seeds. The high prices of hybrid seed in rural northern Uganda can be attributed to the remoteness of the region, its poor road network and the low number of agro-dealers (Atube et al., 2021; Sikora et al., 2019). Consequently, the involvement of the extension system and more private market players could help reduce the costs for the smallholders.

There are a multitude of NGOs and other civil society organisations that are active in northern Uganda since the end of the civil war focussing on the post-war rehabilitation of the region. Such organizations provide training and agricultural support to smallholders, in addition to the governmental NAADS and OWC. However, smallholders reported that they particularly benefit from the work of some NGOs, such as TechnoServe and World Vision that have supported FGs in northern Uganda since 2010. Shikuku (2019) found that smallholder extension training in FGs in northern Uganda can lead to substantial positive changes in farm management and crop yield, and that smallholders who receive agricultural training can act as agents to train FG non-members, leading to knowledge diffusion through social learning and change. Further, respondents reported that they received training through 'demonstration-plots' and farmer field schools. For example, pigeon pea mother-trials hosted at the Zonal Agricultural Research and Development Institute (ZARDI) in Lira district in 2019 showcased a range of agricultural innovations such as land preparation, row planting and intercropping. With such trainings, smallholders are better equipped with Good Agronomic Practices (GAPs) pertinent for sustainable intensification.

Smallholders in Lira district had a 9% lower likelihood for FG membership, compared to those in Pader and Kitgum districts (Table 2.2). This is perhaps due to the greater 'remoteness' of many villages of Lira district, and hence a lower coverage of FG services compared to Pader and Kitgum districts. The distance between the homesteads of the smallholders and the FG meeting and service locations, in most cases in parish and sub-county offices, plays a critical role. For rural Ghana, Abdul-Rahaman and Abdulai

(2018) showed that the distance and travel time between the homesteads of smallholders and the FG offices and centres and played a critical role in FG membership. To enhance FG membership and to increase the accessibility and adaptability of FG services in northern Uganda, we recommend decentralization of FG meeting locations and services to nearby localities such as for village.

2.7 Conclusions

This study contributes to understanding smallholder FGs as important components of agricultural transformation and rural development in northern Uganda. FGs are important for smallholders to increase access to credit, extension and training services, collective marketing and market information. Northern Uganda is particularly challenged by numerous historic, socio-economic and environmental problems, not least by the legacies of the 20-year long civil war.

Our results show that membership in FGs is largely limited by access-related factors, further exacerbated by low formal educational levels, poor transport infrastructure, small land sizes, and minimal access to production inputs. We further show, that both members and non-members of FGs do not achieve technical efficiency in pigeon pea production. This implies that FGs are not a panacea as their impact on production efficiency is limited and that also smallholders who are FG members continue to face major production and marketing challenges. The main motivation for smallholders to seek FG membership are borrowing and saving services. This underlines the high demand of smallholders in rural northern Uganda for formal credit structures which needs to be reflected in agricultural transformation and development programmes and policies.

We further recommend strengthening FGs by putting more efforts into the education and motivation of extension agents and providing them with better incentives and means to work in remote areas together with - and for - smallholders. We also recommend that written and oral agricultural training services should not only be delivered in English which is often not well spoken and/or understood by smallholders, but in Langi and Acholi languages. That would particularly support most marginalized smallholders with little formal education in remote areas. In addition, FG services need to be more decentralized and adapted to the village level, given the poor transport infrastructure, long travel distances and cultural heterogeneity in northern Uganda.

Understanding the Smallholder Legume-based Mixed Farming System: Application of the Whole-Farm Household Modeling in Uganda

3. A SMALLHOLDER TYPOLOGY AND PREFERENCES FOR PIGEON PEA IN MIXED FARMING SYSTEM IN NOTHERN UGANDA[2]

ABSTRACT

Pigeon pea *(Cajanus cajan)* is very important for food and nutrition security of smallholders in northern Uganda, and elsewhere in rural sub-Sahara Africa, but remains an under-researched 'orphan crop'. Development practice and science often work with broad categories (like "smallholders" or "maize farmers") but reality shows that smallholders are heterogeneous with varying perceptions, needs and resource capacities. Against this backdrop, we clustered smallholders in the mixed farming system in three study districts in northern Uganda and assessed their preferences for pigeon pea. We used cross-sectional data from 257 pigeon pea producing smallholders, corroborated with key informant interviews. Using multivariate statistical analysis, we generated six clusters that explained 63% of the total variance. Three farm types (LEX-Low resourced and experienced, LUN-Low resourced and inexperienced, and LED-Low resourced and educated) represented 28, 9, and 17% of the farms, respectively. These farms were resource-constrained with low farm size, low livestock units, low formal education attained and low pigeon pea sales. Three other types (MEX-Medium resourced and experienced, HEX-High resourced and experienced, HED-High resourced and educated) represented 18, 18 and 10% of the sample were highly resourced given their above-average level of resource endowment. Pigeon pea was mainly produced for subsistence, especially by the low-resourced farm types. Across farm types, smallholders preferred pigeon pea because of its ability to fix nitrogen (94%), pigeon pea is relatively easy to harvest (90%) and provides more biomass (89%) compared to other crops. This typology allows for tailored pro-poor agricultural policies to address particular necessities of specific smallholder farmer types, such as focused agricultural training to the illiterate and formal credit for the poorer farmer groups. Understanding varied smallholders' needs and preferences can facilitate investments into improving pigeon pea traits that are particularly effective, sustainable and appropriate for smallholders.

3.1 Introduction

Over 80% of the people in sub-Saharan Africa (SSA) derive their livelihoods from smallholder agriculture (Dixon et al., 2015). They produce between 50 to 70% of the global food, yet often remain food insecure themselves (Giller et al. 2021). Many smallholders find themselves in a 'development deadlock' where their resources are

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degraded and they lack the necessary resources for sustainable intensification and transformation (Hussein, 2017). The low yield is often further at risk due to soil degradation and climate change (Garrity et al., 2012). Agriculture in SSA is dominated by seasonal cereal crops (Glover et al. 2010; Snapp et al. 2018), sometimes intercropped with legumes (Myaka et al., 2006). In many parts of SSA, legumes are essential components of smallholder farming systems and livelihoods (Snapp et al. 2019). Most legumes, however, are below the radar of development discourses and policies, and continue to remain under-researched and underutilized ‘orphan crops’ (Duncan et al., 2018).

Pigeon pea (*Cajanus cajan* [L.] Millspaugh) is a multi-purpose legume, cultivated on 6.97 million hectares worldwide, with a global yield of 5.05 million tons (FAO, 2020). Pigeon pea is mainly grown by smallholders in semi-arid regions in SSA, Asia, and central America (Pazhamala et al., 2017; Walker et al., 2015). It is a semi-perennial legume, harvestable after between 6 to 8 months. It can fix nitrogen between 40 to 250 kg/ha^{-1} and reduce soil erosion due to its taproot properties (Grabowski et al., 2019; Mhlanga et al., 2015). In Uganda, pigeon pea plays an important role for smallholder’s food and nutrition security, especially in the semi-arid and resource-constrained northern region (Hendre et al., 2019; Tadele, 2019). It is an inexpensive and reliable source of proteins (‘poor man’s meat’), carbohydrates, minerals and vitamins (Akporhonor et al., 2006), and further provides fodder and residues that are used as feed, mulch and fuel wood (Snapp et al. 2019).

Previous governmental policies and programs in Uganda have provided mainly blanket approaches towards smallholder agriculture and rural development (NPA 2020). Such approaches do not acknowledge and incorporate the stark heterogeneity among smallholders, their differing capacities, needs and resources. As a result, such policies and programs have remained largely ineffective and without substantially benefiting smallholders equally, particularly the poorest (Dixon et al., 2015; Tittonell et al., 2020). Understanding farming systems diversity and related characteristics and needs can support the development of agricultural policies and programs that fit different farm types and needs to develop more resilient and sustainable farming systems (Dixon et al., 2015).

There are many approaches to studying smallholder heterogeneity. Some studies suggest focusing on key elements that determine comparative advantages of different smallholder livelihoods, considering, for example, the agricultural potential, market access, and population density (Alvarez et al., 2018; Omamo et al., 2006). Research in Ghana (Kuivanen et al., 2016; Michalscheck et al., 2018), Ethiopia (Kebede et al., 2019; Mutyasira, 2020), and South Africa (Makate et al. 2018) focused on linkages between smallholder diversity and technology adoption, livelihood strategies and poverty dynamics.

In Uganda, Kansiime et al. (2018) studied the diversity of smallholders in the West Nile Zone and identified three clusters based on resource use efficiency. Mulinde et al. (2019) identified three and two clusters for coffee producing smallholders in eastern and central Uganda, respectively. Sebatta et al. (2019) classified coffee and banana producing smallholders around Mount Elgon in eastern Uganda, and identified four clusters based on different crop intensification pathways. Bongers et al. (2015) identified five clusters for coffee producing smallholders in eastern and southern Uganda, based on differences in land size, and relative contributions of coffee, banana and off-farm labour to total household income. To our knowledge, no typology has been developed for pigeon pea producing smallholders in northern Uganda, based on resource endowment and environmental parameters.

Despite previous studies on understanding smallholder heterogeneity, a scientific inquiry into the factors leading to smallholder diversity in northern Uganda is lacking. This study comprehends the heterogeneity of pigeon pea smallholders based on their socio-economic characteristics and resource endowment in northern Uganda. The specific objectives were two-fold; i) to characterize pigeon pea smallholders and understand the factors that lead to smallholder diversity in northern Uganda, and ii) to assess pigeon pea smallholders' preferences with regard to production, marketing and consumption attributes across identified farm types, and provide targeted recommendations to the needs of each farmer type.

3.2 Materials and Methods

3.2.1 Study Area

The study covered northern Uganda's three districts (Lira, Pader and Kitgum). The case study districts were selected as they constitute the pigeon pea bread-basket of the country (Hillocks et al., 2000). The region is characterized by semi-arid climate and rain-fed subsistence agriculture (Shikuku et al., 2019). Northern Uganda is more prone to climate change than other parts of the country (Akongo et al., 2017). According to the World Bank (2016), northern Uganda is the poorest part of the country, with 33% of the population living below the poverty line.

Food insecurity is rampant in northern Uganda, worsened by the armed conflict between 1986 and 2006 (Chapman et al., 2009). About 59% of the households in northern Uganda consume only one meal per day (Wallace 2016). The dominant cereal crops are maize, rice, sorghum and finger millet (Kaweesa et al. 2018). Pigeon pea is the most important legume (Manyasa et al., 2009). Smallholders keep some livestock (goats, sheep, cattle and chicken) for additional income, food, manure, draught power and for prestige (Bongers et al., 2015). The population density of Lira, Pader and Kitgum districts is 301, 54 and 51 people/ km^2, respectively (UBoS 2020).

The dominant soil type are ferralsols, highly depleted in nutrients (Bekunda et al., 2022), as well as alisols and plinthosols (Isabirye et al., 2004). In general, soil fertility is low, with a surface texture of sandy to coarse loamy, a low Cation Exchange Capacity (CEC) and a high demand for P and K (Yost & Eswaran, 1990). Thus, the severity and complexity of challenges for smallholders in northern Uganda demand for more context-specific empirical research to provide tailored recommendations.

3.2.2 Sampling and Data Collection

A baseline study including interviews with agricultural extension workers and researchers at the Zonal Agricultural Research and Development Institute in Lira district guided the identification of the study districts. Three districts were purposively selected following a multi-stage approach (from district to sub-county, parish and villages as the smallest administrative unit), and pigeon pea production statistics per district. In the second sampling stage, two sub-counties were selected per district, and in each sub-county, 3 villages were selected following a simple random sampling, a total number of 18 study villages.

The study employed a quantitative approach that involved the use of a pre-tested semi-structured questionnaire to interview 257 pigeon pea smallholders using a Computer Assisted Personal Interview (CAPI) Kobo-collect toolbox (Gravlee, 2002). The questionnaire included sections on household characteristics, pigeon pea production, marketing and consumption attributes, farm endowments, as well as challenges and opportunities regarding pigeon pea production. The interviews were held in the local Langi and Acholi languages, and took between 30 to 40 minutes. All sampled smallholders had grown pigeon pea for at least two consecutive years.

3.2.3 Multivariate Statistical Analysis

We undertook three steps to build the typology: Exploratory Analysis (EA), Principal Component Analysis (PCA) and Cluster Analysis (CA). We used a Likert scale to assess smallholder preferences.

Exploratory Analysis. We selected structural and functional variables for the construction of the typology. Variables were related to household characteristics, resource endowments and pigeon pea production-related attributes (Appendix*, Table S3.1*). Household characteristics included family size, farming experience, age, education and years of experiences in growing pigeon pea of the household heads or their spouse. Resource endowment variables included land used, the proportion of land dedicated to crop and livestock production, as well as the value of farm assets and livestock. Smallholder farmers in northern Uganda own rudimentary including; hoes, pangas, axes, winnower, shovels, knapsack sprayers and wheelbarrows.

To assess livestock ownership and its monetary value, we converted livestock into a uni-dimensional Tropical Livestock Unit (TLU) index of wealth in kilograms of live weight following Jahnke (1982). The index measures both wealth and manure available to the farm (Bongers et al., 2015). Each TLU is taken as an animal having a live weight of 250 kg (Jahnke, 1982). Household income variables included both average monthly farm and off-farm income and the monetary value of farm assets. Pigeon pea related attributes included acreage, yield and the proportion sold in 2019.

We used box-plots to visualize the data spread (accounting for outliers within variables) (see Figure 3.1). During data cleaning and diagnostics, one outlier farm was deleted, hence 256 smallholder farms remained for analysis. The data set permitted the identification of primary patterns and variabilities. PCA was conducted on 16 variables using the orthogonal varimax approach (Dray & Dufour, 2007). Prior to using the PCA, we measured the suitability of the variables using the Kaiser-Meyer-Olkin (KMO) test of sampling adequacy (Kaiser, 1974). Both the overall and individual variables' sampling adequacy was above the 0.5 threshold (Below et al., 2012; Lagerkvist et al., 2015).

Principal Component Analysis. We used PCA to reduce the dimensionality of the data by applying the ade4 package in R version 4.1.0 (Jolliffe, 2005; R Core Team, 2021). We used Bartlett's test to check if the observed correlation matrix diverged significantly from the identity matrix (Kumar et al., 2019). Bartlett's K-square was 63,225 (df=16, $P<0.001$), suggesting a rejection of the null hypothesis and implying, that the correlations between selected variables were significantly different from 0 and large enough for the PCA. The decision rule for Principal Component (PC) selection also followed an Eigen value >1, and selected PCs with a cumulative variance >60% (Rousseeuw, 1987), we selected six PCs that explained 63% of the total variance (Appendix*, Table S3.1*).

Cluster Analysis. We employed the new orthogonal data projection derived from the PCA. We constructed a dendrogram of an ascendant hierarchical classification, using Ward's criterion (Ward, 1963), to measure cluster dissimilarity and to minimize the total within-cluster variance. A dendrogram is a graphical representation of the hierarchy of farm types (Schonlau, 2002). The selected farm types had a minimum of 24 and a maximum of 72 pigeon pea smallholder farms. All variables were then subjected to a one-way analysis of variance (ANOVA) to identify significant associations and/or differences between variables and farm types. This was followed by a Tukey's HSD (honest significant difference) for post-hoc mean separation in R software.

Likert scale measurement of smallholder preferences for pigeon pea. Preferences for pigeon pea were measured regarding pigeon pea production, marketing and consumption attributes across the generated farm types. The attribute list (see *Figure 3.3*) was developed from literature research and corroborated with the interviews in the pre-test. We used a 5-point Likert scale (1=strongly disagree, 2= disagree, 3= neutral, 4=agree and 5=strongly agree) following Likert (1932) and Wakita et al. (2012). Internal reliability estimates were obtained using Cronbach's α coefficient, with an overall value of 0.75, which is acceptable according to Bryman (2016). The alpha coefficients for each attribute were also above 0.5, which is acceptable. We visualized the perception using diverging stacked bar charts with the likert package in R software (https://www.github.com/jbryer/likert).

3.2.4 Results

3.2.5 Descriptive Statistics

The descriptive statistics are presented in Table 3.1. The average age of the respondents is 42 years, with an average farming experience of 21 years. Livestock ownership is on average 3.4 TLUs with the highest value of 3.9 TLUs in Kitgum district. On average, smallholders devote 64% of their land to crop production, 11% to livestock production and about 25% is left under fallow. Pigeon pea yield is on average 380 $kgha^{-1}$ (408 $kgha^{-1}$ in Lira, 408 $kgha^{-1}$ in Pader, and 341 $kgha^{-1}$ in Kitgum district).

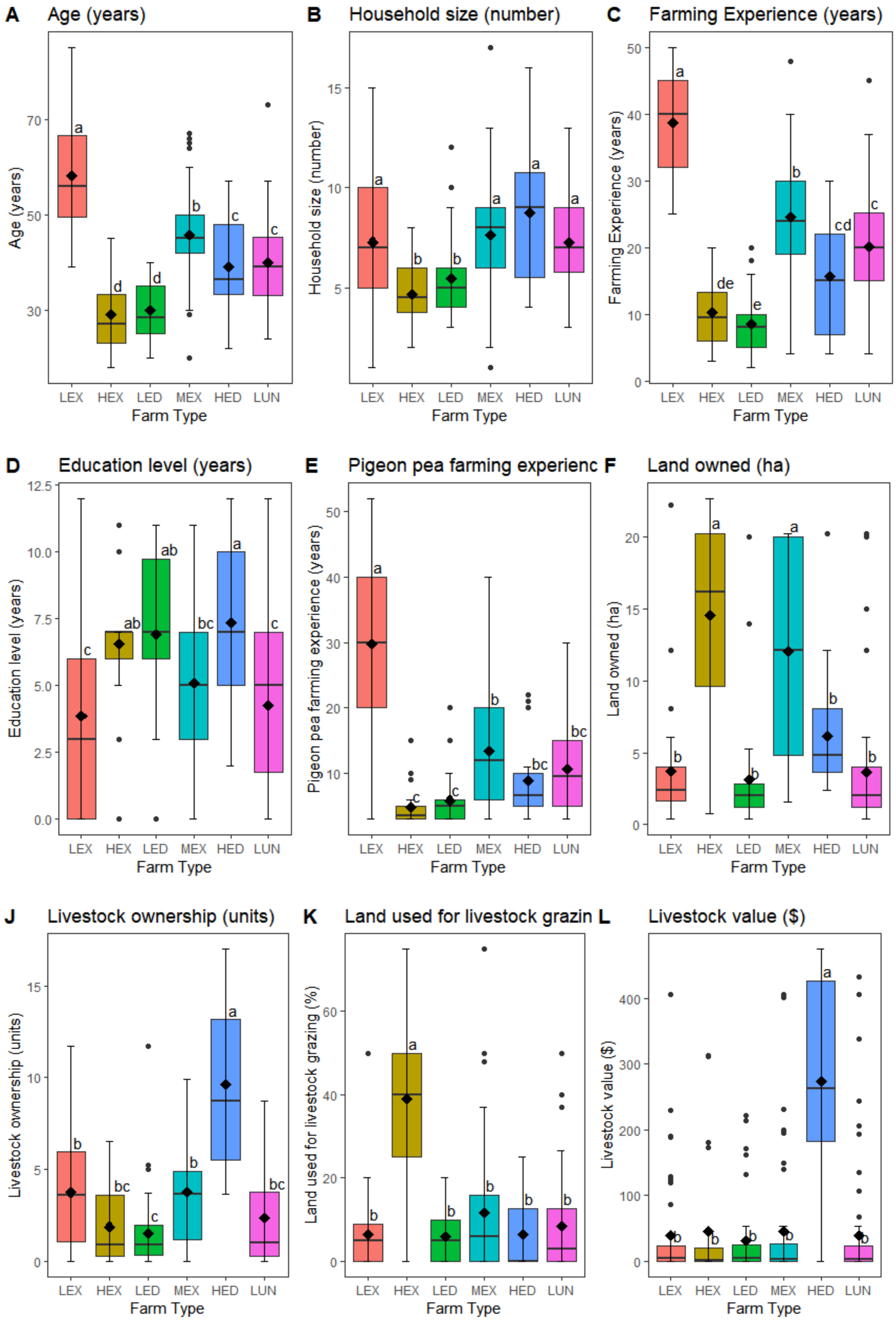
Table 3.1. Descriptive statistics of selec ted variables in Lira, Pader and Kitgum districts, northern Uganda

Variables	Pooled sample	Lira	Pader	Kitgum
	Mean (SD), n=257	Mean (SD), n=83	Mean (SD), n=94	Mean (SD), n=80
Age	41.6 (13.4)	40.8 (15.1)	42 (12.6)	41.7 (12.4)
Family size	6.9 (2.8)	6.1 (2.7)	7.4 (2.9)	7.3 (2.8)
Education level	5.3 (3.4)	5.6 (2.9)	4.5 (3.4)	5.9 (3.5)
Farming experience	21 (12.6)	20.9 (14.1)	22.4 (11.9)	19.7 (11.9)
Average monthly off-farm income	21.6 (21.17)	19.28 (19.97)	22.61 (22.02)	22.83 (21.44)
Land owned	2.55 (2.67)	2.99 (3.39)	2.51 (2.43)	2.02 (1.98)
Value of farm assets	29.22 (29.02)	26.23 (28.48)	31.69 (29.56)	29.42 (29.02)
Proportion of land: crop production	63.8 (20.9)	66.6 (20.9)	63.6 (18.7)	61 (23.1)
Proportion of land: livestock production	10.9 (15.2)	17 (18.9)	8.9 (12.4)	6.9 (11.9)
Livestock value	63.3 (117.65)	63.29 (107.77)	66.42 (118.43)	62.49 (127.54)
TLU	3.4 (3.6)	2.5 (2.4)	3.7 (3.9)	3.9 (3.9)
Pigeon pea acreage	0.57 (0.57)	0.38 (0.69)	0.65 (0.49)	0.69 (0.45)
Proportion of pigeon pea sold	28.8 (29)	19.9 (22.9)	21.8 (26.7)	46.5 (30.4)
Quantity of pigeon pea produced per ha	380.3 (264.4)	385.8 (249.3)	407.7 (268.6)	341 (275.3)
Intercropped pigeon pea	0.78	0.53	0.93	0.87
Number of years for growing pigeon pea	13 (12.9)	14.8 (13.6)	13.8 (12)	10.6 (9.3)

Source: Survey data 2019. Means and standard deviation (SD) presented. Note: Tropical Livestock Unit (TLU) conversion: cattle=1, goats, sheep and pigs=0.1, donkeys=0.5, Oxen=1.42, chicken, turkeys, ducks and guinea fowls=0.01, rabbits=0.02 (Jahnke, 1982).

3.2.6 Typology

We generated six farm types; LEX (Low resourced and experienced), HEX (High resourced and experienced), LED (Low resourced and educated), MEX (Medium resourced and experienced), HED (High resourced and educated), LUN (Low resourced and inexperienced), respectively. Mean and standard deviation are used to describe and compare farm types (Figure 3.1). The farm types represent 47, 24, 42, 45, 26 and 72 smallholder farmers, respectively (Table 3.2). The correlations between farm types and variables are presented in Appendix Table S3.


A
Age (years)
Age (years)
Farm Type
LEX HEX LED MEX HED LUN
B
Household size (number)
Household size (number)
Farm Type
LEX HEX LED MEX HED LUN
C
Farming Experience (years)
Farming Experience (years)
Farm Type
LEX HEX LED MEX HED LUN
D
Education level (years)
Education level (years)
Farm Type
LEX HEX LED MEX HED LUN
E
Pigeon pea farming experienc
Pigeon pea farming experience (years)
Farm Type
LEX HEX LED MEX HED LUN
F
Land owned (ha)
Land owned (ha)
Farm Type
LEX HEX LED MEX HED LUN
J
Livestock ownership (units)
Livestock ownership (units)
Farm Type
LEX HEX LED MEX HED LUN
K
Land used for livestock grazin
Land used for livestock grazing (%)
Farm Type
LEX HEX LED MEX HED LUN
L
Livestock value ($)
Livestock value ($)
Farm Type
LEX HEX LED MEX HED LUN

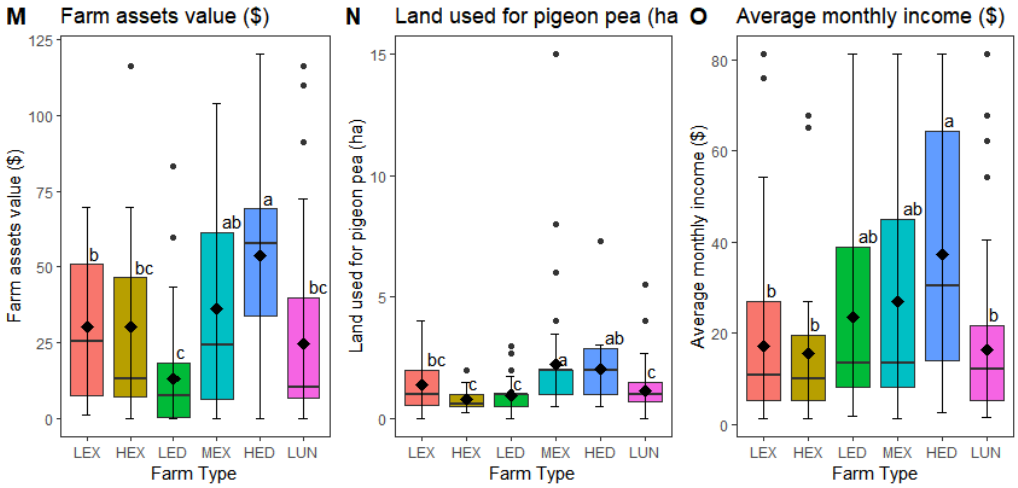


Figure 3.1: Farm features for the six farm types identified using hierarchical clustering analysis (n=256). The black diamond dots represent the mean and outlier values (black circles). Farm types sizes were; LEX (Low resourced and experienced-47), HEX (High resourced and experienced-24), LED (Low resourced and educated-42), MEX (Medium resourced and experienced-45), HED (High resourced and educated-26), LUN (Low resourced and inexperienced-72), respectively. Error bars represent (estimated marginal) means +/- standard error. Means not sharing any letter are statistically significant by the Tukey-test at 5% level of significance.

Table 3.2: Description of the six farm types of pigeon-pea smallholder farmers obtained from hierarchical cluster analysis.

Resource category	Farm type	Description
Low	LUN Low resourced and inexperienced, (n=24, 9%)	Smallholders were young, about 38 years on average, with low levels of education, and only about 3 years of schooling. They had small family sizes, about 7 persons per household. They owned about 1 ha of land on average, of which they dedicated 73% to crop production, about 11% to livestock and 16% under fallow. The average monthly income is $ 10.98 and the average monetary value of farm assets was $ 15.2. Smallholders in this cluster further owned limited livestock, on average 1 TLU, with an average of $ 10.7 livestock monetary value. They produced 327 $kgha^{-1}$ of pigeon pea and allocated about 0.38 ha to its production. They had about 17 years of farming experience.
Low	LED Low resourced and educated, youngest, (n= 42, 17%)	Smallholders here were the youngest, 30 years on average with 8 years of formal schooling, far more formally educated than LUN smallholders. However, they had the lowest farming experience of 9 years, and had grown pigeon pea for an average of 5 years. They owned 1.6 ha land on average, of which they used 74% for crop production, 10% for livestock and 16% left under fallow (Table S4). They owned 2.2 TLU on average and produced 364 kg/ha^{-1} of pigeon pea, of which 40% was sold. Family size was about 5 persons per household with an average monthly income of $ 26.56 and low livestock value of $ 35.35.
Low	LEX Low resourced and experienced, older smallholders (n= 72, 28%)	The smallholders in this farm type were the oldest group with an average age of 58 years and 44.5 years of farming experience. However, they had on average only 4 years of formal education and were resource-constrained, with 2.5 TLU and an average of $ 23.77 livestock monetary value. They only sold 13% of their pigeon pea production. They owned on average 2.9 ha of land, with 55% dedicated to crop production, 12% for livestock and 33% under fallow. Family size was about 5 persons per household.
Medium	MEX, Medium resourced and experienced, (n= 47, 18%)	Smallholders in this farm type were 48 years on average and had 29 years of farming experience. They had an average of 4 years of formal schooling and large family sizes, with about 8 persons. They owned about 1.3 ha, of which 70% were used for crop production, 6% for livestock and 23% left under fallow. They owned about 4 TLUs with a value of $ 37.98. Pigeon pea production was 402 kg/ha^{-1}, of which 25% was sold. They had a high monetary value of the farm assets, with $ 34.6.
High	HEX, High resourced and experienced, (n= 45, 18%)	Smallholders in this farm type were on average 39 years old and relatively well educated with 6 years of formal school attendance. They owned 6.4 ha of land of which 44% was used for crop production, 21% for livestock, and left 35% under fallow. Farming experience was on average 19 years, with 10 years of growing pigeon pea. They produced about 375 $kgha^{-1}$ of pigeon pea and sold 27% of the harvest. They owned 3.3 TLUs with a high livestock value of $ 77.1. Their family size was about 7 persons per household.
High	HED High resourced and educated, (n =26, 10%)	Smallholders in this farm type were 43 years old on average, with 7 years of formal schooling. They owned on average 2.4 ha of land with 49% of it allocated to crop production, 8% for livestock production and 43% under fallow. They harvested 478 kg/ha^{-1} of pigeon pea of which the sold large parts with 50%. They owned 10 TLUs, and had the highest livestock value ($ 324) of all farm types. They also had the highest average monthly income ($ 32.77) and the largest family size, with about 10 persons per household. The farming experience was on average 18 years, which is low compared to farm types LEX and HED.

1 USD = 3695 Uganda Shilling, Bank of Uganda rate for November 2019

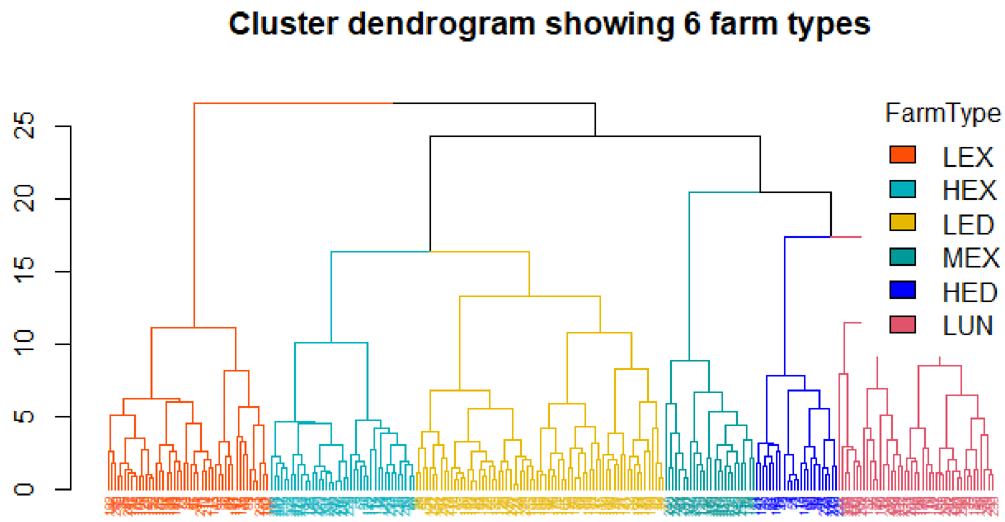


Figure 3.2: Representation of the six farm types constructed resulting from hierarchical clustering using the Ward's method. Farm types and their size were; LEX (Low resourced and experienced-47), HEX (High resourced and experienced-24), LED (Low resourced and educated-42), MEX (Medium resourced and experienced-45), HED (High resourced and educated-26), LUN (Low resourced and inexperienced-72), respectively.

3.2.7 Preferences

About 92% of the smallholders of the LUN farm type perceived that pigeon pea was more drought resistant than other crops, compared to 91% of the LEX and 84% of the LED smallholders (Figure 3.3). Regarding harvest attributes, 96% the MEX smallholders perceived that pigeon pea was easy to harvest, compared to 98% HEX and 96% HED smallholders. Further, 64% of the LEX smallholders preferred pigeon pea because it provided multiple benefits, such as grain, fodder and residues, compared to 47% LUN and 58% LED smallholders. This is also expressed by the statement of a male smallholder from Pader district:

"Pigeon pea has several benefits; best food crop, sticks used for cooking and the grain provides a small income for household necessities like soap, paraffin and school necessities for our children." (Male smallholder, Pader district, 30/11/2019)

Across all farm types, 94% of the smallholders grow pigeon pea because of its nitrogen fixing ability, because it is easier to harvest (90%) and provides more biomass (89%) compared to other crops. Smallholders reported that they weed pigeon pea only once or twice a year compared to thrice or more for cereals and/or other legumes such as beans and cowpeas. Women take up most of the work and responsibility for pigeon pea. This includes ploughing, sowing, weeding and harvesting. This is also reiterated by a male smallholder from Kitgum district:

"Pigeon pea and other legumes are mostly grown by women because it requires less labour and effort for all the farm activities. The sale of surplus grain enables us to buy and hire oxen, afford household necessities, pay school fees and have additional income to support other enterprises." (Male smallholder, Kitgum district, 7/12/2019)

Similarly, a female smallholder from Lira district reported:

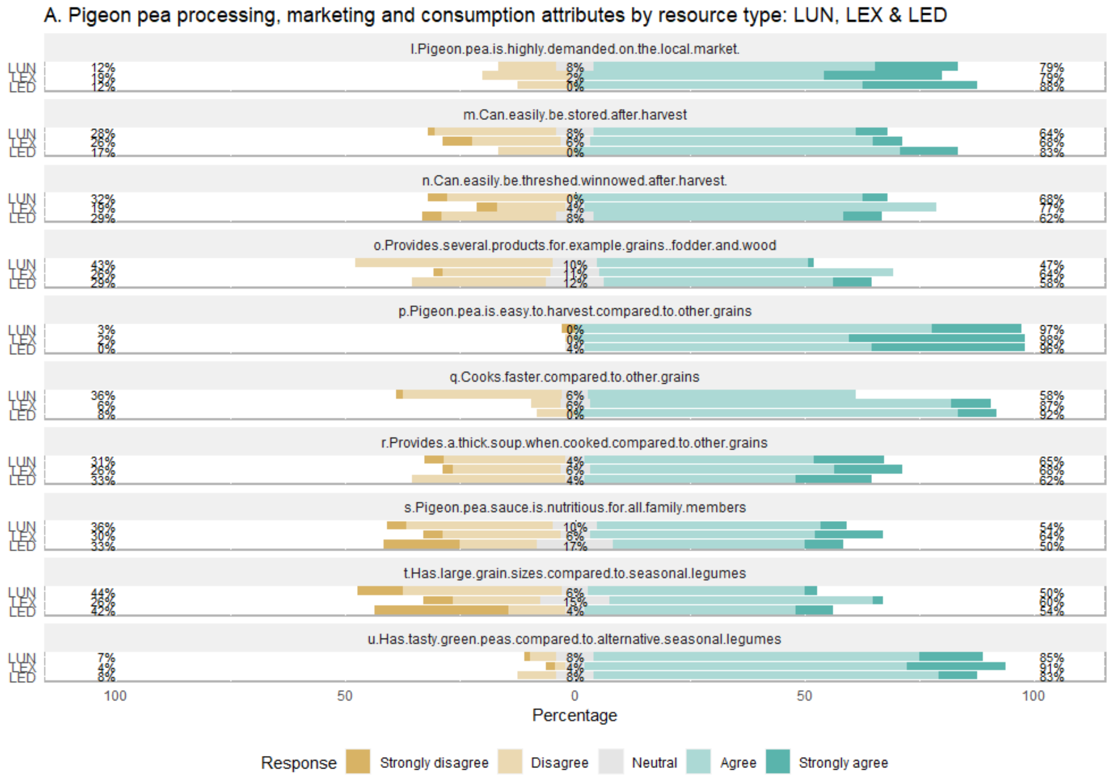
"Men usually take the [pigeon pea] *harvests to local markets because they can move around and are the household heads. However, for harvesting; women are mostly involved because men have a lot of other work during the harvest season." (Female smallholder, Lira district, 25/11/2019).*

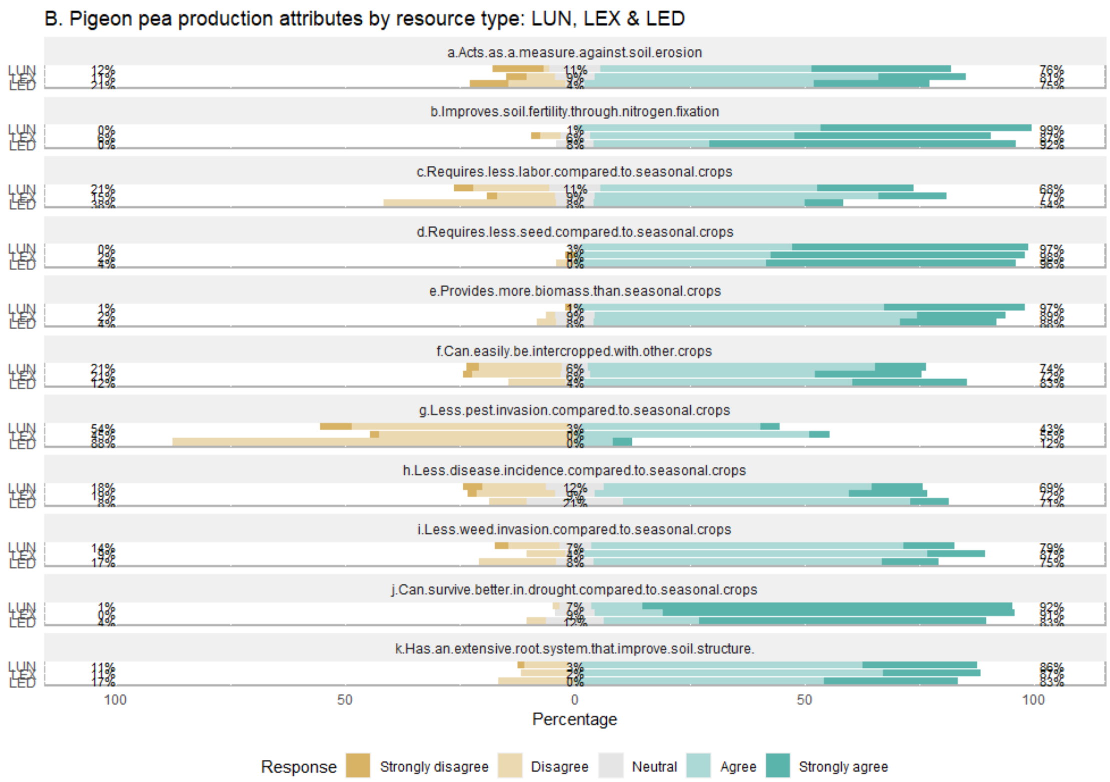
Further, smallholders grow pigeon pea because of its easy to intercrop especially with cereals and legumes that are short term. . This enhances soil fertility and subsequent yields.

A female smallholder from Lira district stated that:

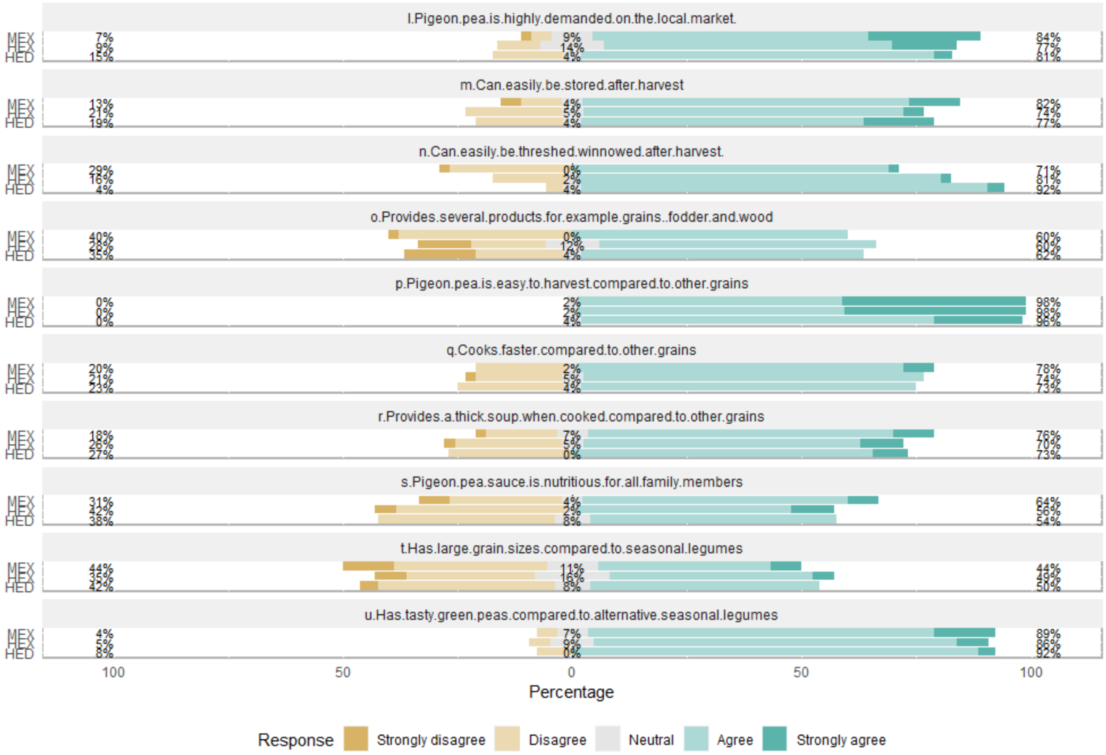
"Pigeon pea plots are intercropped with cereals for example millet and sorghum, and other legumes, and it is also sometimes rotated on an annual basis depending on our needs and labour availability." (Female smallholder, Lira district, 21/11/2019)

Smallholders reported to cut pigeon pea stems and store them until threshing. In that form, the shelf life of the pigeon pea grain is improved as the grain is safe from weevils and other infestations. Generally, pigeon pea is characterised to be a low labour crop.


A. Pigeon pea processing, marketing and consumption attributes by resource type: LUN, LEX & LED
l.Pigeon.pea.is.highly.demanded.on.the.local.market.
m.Can.easily.be.stored.after.harvest
n.Can.easily.be.threshed.winnowed.after.harvest.
o.Provides.several.products.for.example.grains..fodder.and.wood
p.Pigeon.pea.is.easy.to.harvest.compared.to.other.grains
q.Cooks.faster.compared.to.other.grains
r.Provides.a.thick.soup.when.cooked.compared.to.other.grains
s.Pigeon.pea.sauce.is.nutritious.for.all.family.members
t.Has.large.grain.sizes.compared.to.seasonal.legumes
u.Has.tasty.green.peas.compared.to.alternative.seasonal.legumes
LUN
LEX
LED
100
50
0
50
100
Percentage
Response
Strongly disagree
Disagree
Neutral
Agree
Strongly agree


B. Pigeon pea production attributes by resource type: LUN, LEX & LED
a.Acts.as.a.measure.against.soil.erosion
b.Improves.soil.fertility.through.nitrogen.fixation
c.Requires.less.labor.compared.to.seasonal.crops
d.Requires.less.seed.compared.to.seasonal.crops
e.Provides.more.biomass.than.seasonal.crops
f.Can.easily.be.intercropped.with.other.crops
g.Less.pest.invasion.compared.to.seasonal.crops
h.Less.disease.incidence.compared.to.seasonal.crops
i.Less.weed.invasion.compared.to.seasonal.crops
j.Can.survive.better.in.drought.compared.to.seasonal.crops
k.Has.an.extensive.root.system.that.improve.soil.structure.
LUN
LEX
LED
100
50
0
50
100
Percentage
Response
Strongly disagree
Disagree
Neutral
Agree
Strongly agree

C. Pigeon pea processing, marketing and consumption attributes by resource type: MEX, HEX & HED



D. Pigeon pea production attributes by resource type: MEX, HEX & HED

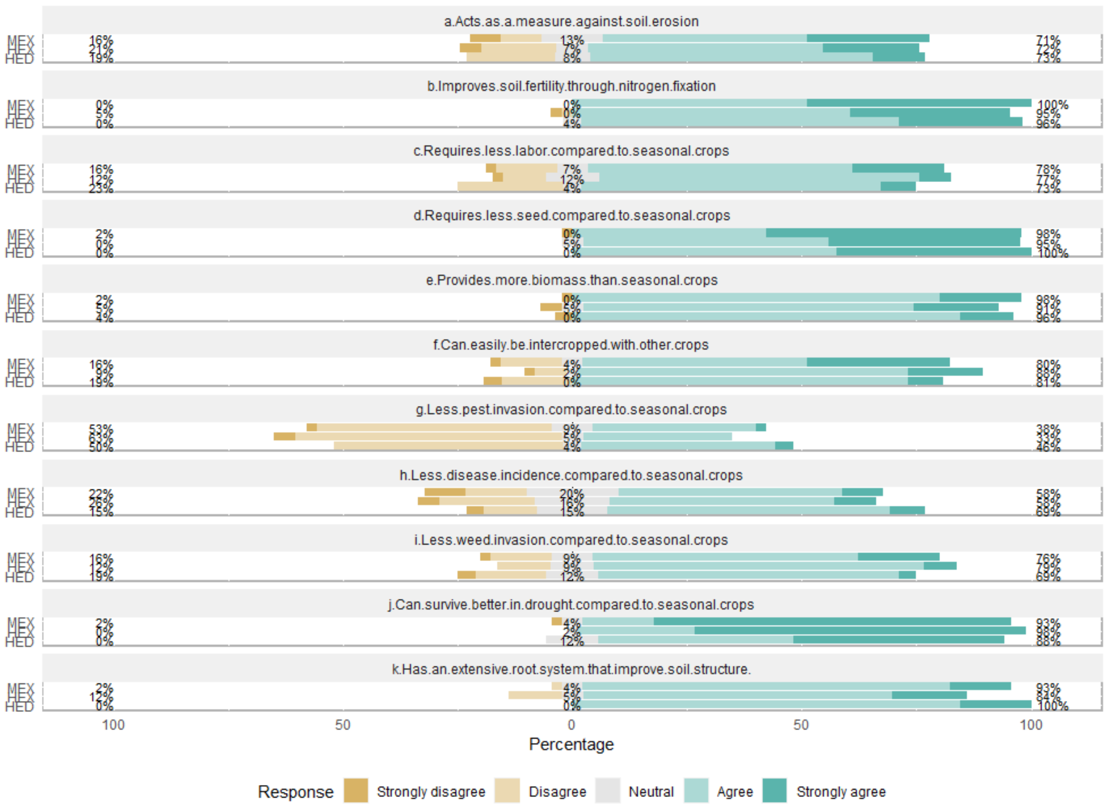


Figure 3.3: Smallholder preferences for selected pigeon pea attributes. Likert type rate used is 1=strongly disagree, 2=disagree, 3=neutral, 4=agree and 5=strongly agree. The percentage on the left side indicate the share of respondents answering with 1 or 2 on the Likert scale. The percentage in the middle indicate the share of respondents answering with 3 (neutral). The percentage on the right side indicate the share of respondents answering with 4 or 5. A and B are attributes for the low resourced farm types, while C and D represent attributes for the medium and high resourced smallholder farmers respectively.

Majority of the female smallholders (65%) (*Supplementary Material Figure S2*) mentioned that their pigeon pea production was highly infested by pests, compared to 55% of the male smallholders. The latter mostly spray pigeon pea with insecticides (most often *Cypermethrin*), while women rather engage in the physical labour of pest hand-picking. Smallholders in Lira and Pader districts mostly plant the pigeon pea variety *Apio Elina*, harvestable after 6 months (mainly planted in March and harvested around August/September). In Kitgum district smallholders mostly plant the pigeon pea variety *Agogi,* which is harvestable after 8 months (mainly planted in April and harvesting around December/January). Depending on the need for fresh peas, sometimes harvest were heaped for later threshing. Threshed pigeon pea is stored for several months; either to wait for better market prices, or to consume it later and/or a proportion kept for next season planting.

3.3 Discussion

Using multivariate analysis, we generated six farm types of pigeon pea growing smallholders in northern Uganda. We found significant differences for the majority of the variables across farm types at $P < 0.05$ (Figure 3.1). In addition, we found varying preferences regarding the production, marketing and consumption attributes of pigeon pea across farm types, gender and districts (Figure 3.3).

3.3.1 Farm household characteristics and resource endowment heterogeneity

Our findings strongly mirror the aging trend of smallholders in northern Uganda. This is partly due to the orientation of younger people ‘out of agriculture’, their migration to the cities and central and southern Uganda in search of work as well as to the effects of the civil war (Rockmore, 2020). Generally, the average age of smallholders was above 30 years across all farm types and districts. LEX (58 years) and MEX (48 years) had older smallholders compared to HED (43 years) and HEX (39 years), and age is statistically significant across farm types. Many youths do not continue with agriculture but migrate for work to urban centres; a development which is observed in many rural areas in Africa (see for example Makate et al. 2018). Rietveld et al. (2020) reported differences between male and female youths in central Uganda in terms of migration, with male migrating majorly for work, and female for both work and marriage.

In northern Uganda, male youths are often engaged in small businesses in near-by small towns, normally in very precarious and part-time arrangements. On the other hand, the old generation of smallholders continue to work on the farms and are normally more experienced, which is also evidenced from our findings. Youths in northern Uganda are more risk-averse than older farmers due to their limited experience and are less likely to adopt new crop types as also reported in Albania (Granzhdani, 2013). The migration of youths and their shift away from agriculture severely reduces household labour endowment and the sustenance of smallholder farms.

Overall, formal education of the respondents is low, with an average of 5 years of schooling. This mirrors the low educational level in northern Uganda compared to other regions of the country (UBoS 2020), which can be explained by structural challenges and the long-term impacts of the civil war. Formal education is statistically significantly across the six farm types, with LED having the highest (8 years of education). This confirms findings by Occelli et al. (2021) who illustrated that formal education combined with local knowledge has a multiplier effect for agricultural development among smallholders in Ethiopia. Likewise, Granzhdani (2013) reported higher rates of agricultural technology adoption by formally educated smallholders compared to formally less educated ones.

Additionally, formal education has been found to improve access to information and non-farm employment opportunities, implying better household incomes for such households. The cash income of the sampled smallholders is generally low. This can be explained by the low integration into produce markets and the subsistence orientation, also due to the remoteness of the sampled villages. We further find positive relations between sold crop quantities and income of smallholders in rural SSA (see for insistence Chikowo et al. 2014). Yet, a continuous cash income is important and a major determinant for food self-sufficiency in rural SSA (Giller, 2020). Apart from farming, smallholders reported to generate additional income from selling *Ajon/Malwa*, a local brew homemade from dry millet in northern Uganda, as well as sell of charcoal and firewood. Female smallholders also engage in tailoring and road-side selling of fruits, vegetables and grain. Thus, we suggest that the provision of more and better targeted formal educational programs could encourage both formal employment and agricultural development across different smallholder types.

Further, we find that all smallholders own some livestock. However, ownership of livestock is significantly different across the farm types. The high-resourced smallholders rather kept high value livestock such as cattle and oxen, compared to low-resourced types who owned mostly poultry and small ruminants like goats and sheep. This is also reflected in the monetary value of livestock with HED and HEX ($ 324 and $ 77, respectively). Livestock acts as a contingency safety net and 'life-saving' income source in case of crop failure, health challenges, or other socio-economic crises, and can be sold when there is a quick requisite for money. However, in the last decades there has been a decline in livestock numbers in northern Uganda due to the severe impacts of the civil war and cattle rustling (Akongo et al., 2016). Rockmore (2020) showed that livestock keeping in northern Uganda was more risky during the civil war than farming, and many smallholders lost or sold their livestock. This is mirrored until today in the low livestock numbers recorded in this study. The average TLU is 3.4 units TLU per smallholder. There are, however, strong differences between the farm types. HED (10.22 TLU) and HEX (3.34 TLU) had more livestock units compared to LUN (1.13 TLU) and LEX (2.54 TLU).

Land use patterns also vary significantly between the six farm types. Results show that low-resourced farm types (LUN- 72.7%, LED—74.3%) allocated relatively more land to crop production than high-resourced farm types (HEX—44% and HED—49%). Similarly, Kansiime et al. (2021) found in Kenya that low-resourced smallholders allocated relatively much more land to crop production than high-resourced counterparts.

Smallholders allocated on average about 0.57 ha of land to pigeon pea production. Relatedly, the average pigeon pea yield was 380 kgha^{-1}. This is relatively low productivity – also given comparable yields of hybrid pigeon pea varieties of up to 3,000 kgha^{-1} as reported from Tanzania and Mozambique (Kiwia et al., 2019). The observed below average pigeon pea yield in the study area can be attributed to low soil fertility, arid climate, and low rates of fertilizer application (which are far below those recommended, compounded by poverty and poor market linkages (Chianu et al., 2012). On average, smallholders left 25% of their agricultural land under fallow. Fallowing is another strategy used by resource-constrained smallholders to replenish soil fertility. These findings concur with Mutyasira (2020) in Ethiopia where 22% of smallholders left their land under fallow. Improvement in soil fertility management especially for the low-resourced smallholders through conservation agricultural practices and innovations, can increase crop productivity and higher returns to smallholders.

3.3.2 Preferences for pigeon pea as a multi-purpose legume

Understanding smallholders' preferences are of utmost importance for achieving agricultural development and sustainable intensification. We disaggregated smallholders' preferences for pigeon pea attributes across six farm types, three districts and gender (Figure 3.3 and Appendix Figure 3). Smallholders perceive that pigeon pea is drought-tolerant (89%), has high biomass (91%), with ability to improve soil quality through nitrogen fixation (93%) as the most important production-related attributes of pigeon pea. Similar results are reported from Kenya and the Democratic Republic of Congo (DRC), where smallholders preferred pigeon pea compared to other legumes due to its nitrogen fixing capability and its potential to improve soil fertility (Muoni et al., 2019). It is further reported that the use of pigeon pea fodder increases the intake of low quality feed and improves the live-weight of small ruminants because of its relatively higher nitrogen concentration (Shenkute et al., 2013).

Snapp and Silim (2002) showed that smallholders in Kenya and Malawi prefer pigeon pea varieties that are high-yielding with good inter-cropping ability. About 44% of the respondents perceived that pigeon pea can survive the dry season compared to other legumes and cereals. Given the semi-arid nature of northern Uganda and increasing effects of climate change in the region (Akongo et al., 2017), future research should focus on breeding pigeon pea varieties that are not only high yielding but more drought-tolerant to survive the long dry season in northern Uganda.

Over 70% of the respondents highlighted that pigeon pea is a low-labour crop. Weeding, for example, can be done only once or twice before harvest, which is much less than with other cereals and legumes locally grown. Similarly, Snapp and Silim (2002) showed that smallholders in Kenya and Malawi mentioned the low-labour demand of pigeon pea as its main positive attribute. Much of the labour related to pigeon pea production (such as sowing, weeding and harvesting) is provided by women. This is in line with other studies that show that labour provided by female smallholders is directed towards food crops, while male smallholders focus majorly on cash crops (see for example Iradukunda et al. 2019).

Our findings show that the majority of the smallholders (62% of the low-resourced and 55% of the high-resourced) perceive that pest and disease infestation are the major problems in pigeon pea production. High pest and disease incidence affects not only pigeon pea production but smallholder farming in general. Respondents mentioned infestation by aphids, borers, leaf miners, and caterpillars, locally known as *Acwii, Ongude, Ocoko,* and *Oruru*, as well as fungal diseases (like Fusarium wilt), especially at the flowering stage. Breeding of pest and disease-resistant pigeon pea varieties can improve productivity and subsequent incomes from farming in the region.

Over 80% of the low-resourced smallholders preferred green pigeon peas (fresh) for domestic consumption because they cook faster and are tasty compared to dry pigeon peas and other legumes. This concurs with Fiacre et al. (2018) who showed that smallholders in Benin consider a short cooking time as the most important attribute of pigeon pea. In northern Uganda, the green peas are mostly used to produce a thick soup, termed *Dek Ngor,* that accompany the common staple foods millet, sorghum bread (*Kwon Kal*), mashed sweet potatoes and cassava (*Layata*). The *Dek Ngor* soup is habitually consumed by smallholder families at least once in two days for lunch or dinner depending on the season and the availability of pigeon peas. It is perceived to be nutritious for all age groups. Anitha et al. (2020) reported a positive impact of consuming pigeon pea soup on wasting, stunting, and underweight children and a high acceptability of such diet in Myanmar. Hence, there is a high potential of pigeon pea to contribute to improved food and nutrition security in northern Uganda, especially for the resource-constrained smallholders.

3.4 Conclusions

In this chapter, we generated six distinct farm types of pigeon pea growing smallholders in northern Uganda using multivariate statistical approaches, and assessed smallholder preferences for pigeon pea across farm types, study districts and gender. We argue that smallholder households are very heterogeneous and ‘one-size-fit-all’ approaches to agriculture development are inappropriate. The variability in farm types can be explained by strong differences in their socio-economic background, their resource endowment at household level, farm size and livestock units owned. More than half of the smallholders (54%) were low-resourced with below average land sizes, TLUs and incomes.

Smallholders highly preferred pigeon pea because it is more nutritious than other crops, improves soil quality through nitrogen fixation, and require less labour compared to other crops. However, smallholders face challenges of high incidence of pests and diseases that affects its productivity. Thus, breeding research and extension should focus not solely on highest yields (which are anyway most often only achieved on agricultural research stations), but should also address important pigeon pea attributes expressed by smallholders. Namely, pigeon pea varieties should be developed and disseminated that are pest and drought-resistant and are still able to be intercropped.

We further recommend targeted agricultural-related training and educational programs in northern Uganda to improve agricultural technology uptake across farm types, since the education level is low. Such programs should be tailor-made to the specific needs of the different smallholders, especially the low-resourced ones, and the marginalised groups (female, younger and older ones). This can also encourage youths' participation in agriculture, for example, with the establishment of and training of youth-groups, to make smallholder agriculture more attractive and 'modern'. This can be combined with the provision of 'start-up' micro-credit to youths who want to start their careers in farming with new innovate ideas. Policies should further particularly target smallholder women who are largely involved in the cultivation, processing and to some extent marketing of important food crops that often 'fly under the radar' of development efforts, like pigeon pea.

4. MULTI-OBJECTIVE OPTIMISATION FOR (TARGETED) RECOMMENDATIONS IN THE SMALLHOLDER MIXED FARMING SYSTEM OF NORTHERN UGANDA

ABSTRACT

Legume intensification is part and parcel of the sustainable intensification agenda to achieve resilient and sustainable smallholder farming system. Yet, smallholders are socially and economically diverse, and work in varied biophysical environments facing a multitude of challenges. Against this background, we employ a FarmDESIGN whole farm model to explore the current performance of the farming system in northern Uganda and analyse trade-offs and synergies for targeted farm improvement alternatives. Data were gathered through a detailed characterization and soil fertility assessment with representative low-resource and high-resource farm types following an earlier developed smallholder typology. The objectives were to maximize farm profit and labor surplus, while minimizing soil organic matter and nitrogen losses. Results show that low-resource farm smallholders can trade-off leisure time to improve yield through mulching and crop residue use to improve soil organic matter. For the high-resourced farm smallholders, purchase of inorganic fertilizers can improve crop productivity, thus, ultimately contribute to household food and livelihood security. Moreover, foregoing leisure to engage in on-farm production and off-farm activities can enhance income across all farm types. Smallholders can also aim for better livestock feeding, e.g., through the purchase of concentrates which could further improve the animal-products quality and quantity, thus improving livelihoods and food security. Towards livelihood and food security enhancement, policies should recognize the complementarity of pigeon pea with other crops and livestock as well as the smallholder mixed nature of the farming system (s) at large.

4.1 Introduction

Redesigning resilient and productive farming systems to feed the growing global population sustainably remains one of the biggest challenges humanity is facing (Burke et al., 2022). Globally, smallholders contribute to over 50% of food production, yet, they often operate under precarious conditions with scarce resources. Challenged with poverty, many smallholders produce mainly for subsistence, with decreasing productivity (Giller et al., 2021; Lowder et al., 2021). The limited use of fertilizers, both mineral and organic, due to poverty and lack of awareness, in addition to limited access to improved crop cultivars further limit and lead to crop productivity (Chianu et al., 2012). Thus, alternative options like enhancing biological nitrogen fixation (BNF) are critical for sustainable intensification and farming system diversification. BNF is crucial for fixing atmospheric nitrogen and making the fixed nutrient readily available to the legume crop and other crops in the cropping system (Stagnari et al 2017). In many parts of sub-Sahara Africa (SSA), pigeon pea is part and parcel of such an approach. Pigeon pea (*Cajanus cajan* [L.] Millspaugh) can fix up to 40 kg nitrogen ha^{-1}, and provide grain, fodder and residues used as mulch (Muoni et al., 2019).

Pigeon pea is an important legume in semi-arid northern Uganda, mostly intercropped with cereals and other legumes. Pigeon pea is primarily produced as a food crop for domestic consumption, with the surplus mainly sold to local and regional markets (Iradukunda et al., 2019). Smallholder farmers in northern Uganda are socially and economically very diverse, and work in different biophysical environments (Namuyiga et al., 2022). Such differences often impact on and affect the access to human and material resources leading to the continuation of low agricultural productivity, efficiency and effectiveness, and the perpetuation of smallholder poverty cycles.

The boundaries of farming systems are foremost demarcated by ecological factors. In the case of northern Uganda, these are, for example, ferralsols, which are highly nutrient-depleted soils. The general soil nutrient depletion for Uganda have been reported in the range of 20 – 40 kg N ha^{-1} yr^{-1}, 4 – 7 kg P ha^{-1} yr^{-1} and 17 – 33 kg K ha^{-1} yr^{-1} (Stoorvogel and Smaling 1993). Soil nutrient losses are mostly caused by soil erosion, leaching, crop harvest and volatilization in smallholder farming systems (C. Wortmann & Kaizzi, 2017). Yet, there is little or no use of mineral fertilizers, with averages of about 1.3 kg ha^{-1} compared to 50 kg ha^{-1} or more in neighboring Kenya (Chianu et al., 2012; C. Wortmann & Kaizzi, 2017). Smallholders largely depend on crop residue mulching and farmyard manure (FYM), which contributes to the low soil organic matter (SOM) stock. Researchers have reported SOM addition of only up to 10 ha^{-1} yr^{-1} per year, which is well below the recommended threshold requirements for crop organic matter demand (Zake et al. (2015). Yet, SOM stocks influence the chemical and physical processes and can be used as an important indicator of the soil rooting environments (Okalebo et al., 2002).

Understanding the Smallholder Legume-based Mixed Farming System: Application of the Whole-Farm Household Modeling in Uganda

Vanlauwe et al. (2015) recommend sustainable soil and land management as the prime step to avert soil erosion and to achieve soil nutrient balances in smallholder farming systems. However, most smallholders in northern Uganda are incapacitated in knowing the soil fertility status on their plots since soil testing and analysis are unaffordable and inaccessible (C. Wortmann & Kaizzi, 2017). Legumes in general and pigeon pea in particular, count as a viable and available option in smallholder agriculture to tackle the challenges of declining soil fertility and low crop productivity in many parts of SSA. Intercropping and integrating legumes into low-input farming systems has multiple socio-economic and ecological benefits. It can, for example, fix between 10% and 90% of the nitrogen demand through symbiosis with nitrogen-fixing rhizobia (Kermah et al., 2018).

Income and food security benefits are the primary objectives of many smallholder farmers. For this purpose, farmers have to make rational decisions on which crops to grow, where and when, which animals to rear, how to allocate labor, etc. - all this within often limited available resource envelopes. Since the 1960's, many farm models and tools have been developed, such as MIDAS[3] and utility maximization models to determine trade-offs and synergies in farming systems and to provide alternatives and solutions to such scenarios (Bell et al. 2008; Ditzler et al. 2019).

Whole farm-household models such as the FarmDESIGN model provide a systematic understanding of farming systems and guide decision-making for tailor-made recommendations (Groot et al. 2012). Despite the increasing development and application of such tools worldwide, there are only few case studies in tropical environments (Michalscheck et al. 2018; Ditzler et al. 2019; Ocimati et al. 2020; Paul et al. 2020). With regard to northern Uganda that has been challenged with several social, economic and environmental challenges, re-designing the farming system should

[3] The Integrated Dryland Agricultural System (MIDAS), a bio-economic model of a mixed crop/livestock system that jointly emphasizes the biology and economics of the farming system.

provide better alternatives to meet the increasing demand for food, feed and fiber. We achieve this through the application of the FarmDESIGN model for the earlier developed smallholder farm types (Chapter Three), i.e., high and low resourced. We aimed to explore the trade-offs and synergies (complementarities) to identify targeted and practical alternatives for re-designing the farming system.

4.2 The FarmDESIGN Model and Multi-objective Optimization

FarmDESIGN is a whole farm-household bio-economic model developed for the analysis and redesign of mixed crop–livestock farm systems. It can support complex farming system decisions (Groot et al. 2012). Complemented by a multi-objective optimization algorithm, it gives users an idea of the potential productive, social, economic, and environmental performance of a farm system (Groot et al. 2012). With this algorithm, we generate a large array of optimal alternative solutions. Each solution constitutes a technical possibility to provide the current economic, social and environmental farm performance allowing an exploration of concrete alternative farm configurations for and farm improvement and subsequent sustainable intensification (Michalscheck et al., 2018).

The FarmDESIGN model centers on a 4-step iterative procedure, i.e. *Describe, Explain, Explore, (re-)Design* (DEED) (Giller et al., 2011; Groot et al., 2012) as shown in Figure 4.1. The DEED cycle is informed by a farm typology that provides prior description of the farming system and an understanding of the farm household characteristics (Namuyiga et al., 2022).

4.2.1 The DEED Framework

The *Describe* phase of the DEED framework details the current state and the components of a farm, as well as its constraints and opportunities related to crops and livestock performance. This step helps to understand the current socio-economic and biophysical characteristics of a farm and the farming household. It includes, for example, crop areas (land sizes/allocation), crop types and their products, livestock and their products, buildings and machinery, overall farm economics, and the bio-physical environment. The *Explain* phase of the DEED framework quantifies the current performances of the farm system in regard to annual resource flows and the balances that are clustered into modules (Groot et al. 2012). This phase aims to explain the current state of the farm, using selected indicators and implications for improvement. The resulting material balances, including feed, labor, nutrient and SOM balances, are calculated at an annual basis.

The *Explore* phase adjusts farm management options to specific objectives through multi-objective optimization based on prior selected farm targets. What-if scenarios are simulated to provide Pareto-optimal solutions, i.e., no additional opportunity for farm improvement through a re-allocation of resources. Further, in the *Explore* phase, trade-offs and synergies are explored in a solution space within which solutions are ranked based on Pareto optimality (Groot et al., 2012). Lastly, in the *(re-)Design* phase, practical and feasible configurations are selected and recommendations provided to farmers and other stakeholders. This study illustrates the DEED framework with three FarmDESIGN modules. We also simulate interventions and offer practical recommendations for smallholder farming systems in northern Uganda.

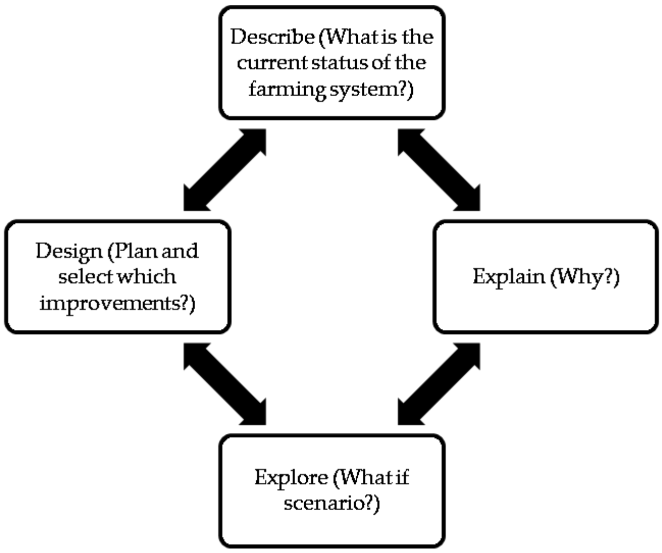


Figure 4.1: Schematic representation of the Describe, Explain, Evaluate, and (re)design (DEED) interactive approach. Adapted and modified from Groot et al. (2012).

4.2.2 The FarmDESIGN Modules

a) ***'Household labor' module:*** Following Ditzler et al. (2019), the farm household labor module is based on the theory of agricultural households (Singh et al. 1986). Farm households maximize utility as a function of cash and labor constraints. Labor balance is calculated as the sum of labor requirements due to crop and livestock management minus the hired labor and the working hours spent by members of the farm household. The household leisure time (hours year^{-1}) is the annual sum of all available time for on-farm and off-farm activities for all household members, T_{tot} (hours year^{-1}) less the hours spent on off-farm labor, L_{OF} (hours year^{-1}) is the labor hours required for farm management, L_{FM} (hours year^{-1}). L_{FM} is calculated as the sum of all labor hours required for crop cultivation, L_C (hours year^{-1}), plus all labor hours required for livestock keeping, L_{LK} (hours year^{-1}), plus the sum of all labor required for general farm activities, L_G (hours year^{-1}), as described in Timler et al. (2020).

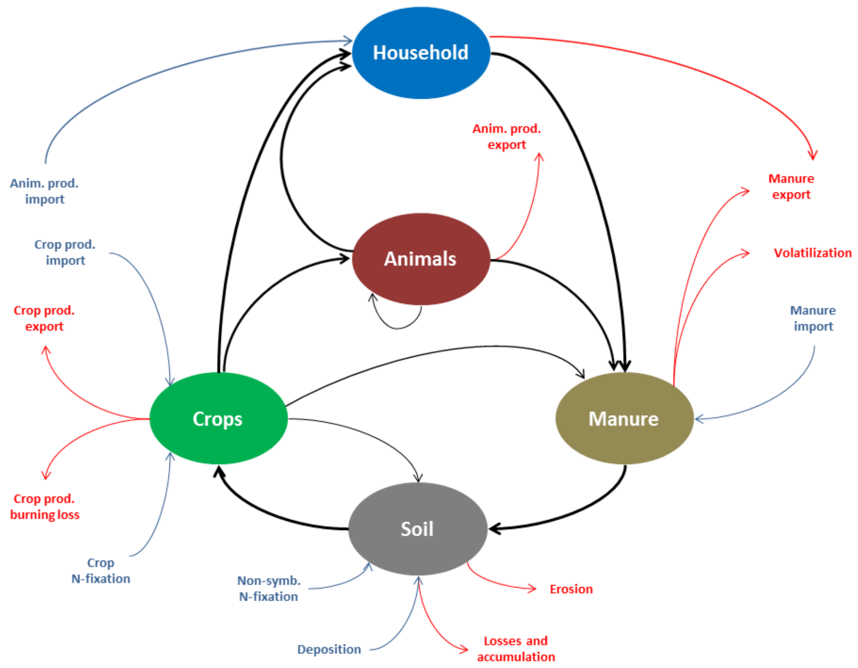


Figure 4.2: Schematic representation of the main components of the FarmDESIGN model. It portrays the resource inputs and outputs (nutrient flows) in the five components of the farming system (household, animals, manure, crops and soil). The black arrows represent flows within the system. blue arrows show resource in-flows from different sources and red arrows show resource out-flows from the system.

b) ***'Farm Household budget'* module:** This module incorporates the economic indicators in FarmDESIGN, both total variable costs and return to labor. These are calculated based on crop and livestock gross margins for each farm minus farm costs, such as labor cost and fixed costs. This module is also based on the theory of agricultural households (Singh et al., 1986). Eq. (1) was modified from Singh et al. (1986) and captures the cash constraints, which we express in United States dollars (USD) per year:

$$P_mX_m = P_a(Q_a - X_a) - P_w(L - H - F) - P_hH - P_vV + E \qquad \text{Eq. (1)}$$

In Eq. (1), variables include,

- X_m is a vector of quantities of market-purchased goods;
- Q_a is the production of an agricultural staple such as a cereal crop (kg);
- X_a is the quantity consumed of the agricultural staple (kg) (so that Q_a - X_a is its marketed surplus);

- L is total labor input into on-farm activities by the family or by hired-in laborers (hours);
- H is the hired-in laborers for on-farm activities (hours), and is the on-family labor part of L;
- F is the total family labor input working on-farm and off-farm (hours);
- V is a vector of variable inputs (for example, fertilizer, pesticides);
- E is any non-labor, non-farm income (USD).

In Eq. (1), parameters include:

- p_m is a vector of prices for the market-purchased goods (such as food) (USD per unit of quantity purchased);
- p_a is the price of the agricultural staple food (USD kg^{-1});
- p_h is the price of hired labor (USD $hour^{-1}$);
- p_w is the market wage for labor (USD $hour^{-1}$);
- p_v is the variable input's market price (USD per unit of quantity purchased).

The decision variables are presented in Appendix (Tables A1 and A2), while parameter values are listed in Table 4.2. In Eq. (1) all decision variables and parameters are non-negative, and the following constraints hold: $(L – H – F) \leq 0$ and $H \leq L$, and if $(L – H – F) < 0$ then labor time of household members is used for off-farm activities or is spent on leisure. We further disaggregate L into three labor categories:

- General farm management (e.g. maintenance, trading, and accounting, L_G);
- Crop management (L_C);
- Livestock management (L_A).

Transaction costs in the labor market may mean that for the same agricultural activity, the purchasing price of labor (hired labor wage paid, p_h) may exceed the selling price of labor (off-farm wage earned, pw), so that $p_h > p_w$, and these are specified as model parameters.

The household free budget reflects the cash constraint from Eq. (1), which relates to the two farm household decisions associated with working time allocation and food choices. Firstly, household members can allocate their income-generating work time to either on- or off-farm activities. This decision will affect the proportion of farm income in the total household income. Secondly, household members can make decisions around how much of their food is sourced from markets and how much is produced on-farm. These decisions affect the cost of supplying food-based nutrients to the household due to differences between the sale and purchase prices of different food items such as cereals and legumes. We capture these two decisions in the '*Household budget'* module with the addition of three variables, i.e., off-farm income, food costs, and other expenditures, which supplement the already existing variable operating profit to make the '*Household budget'* module distinct from the '*Farm profit*' module. The primary indicator of interest calculated in the '*Household budget'* module is the household free budget Eq. (2):

$$B_H = (I_F + I_O) - (C_F + C_E) \qquad \text{Eq (2)}$$

Where,

- B_H is household free budget (USD year^{-1}). In Eq. (1) there is no surplus cash as expenditures equal earnings. This surplus cash of zero is equivalent to B_H implicitly equaling zero, even though not all cash income generated by the household is necessarily spent as some can be saved. In Eq. (2), if B_H exceeds zero the household has surplus cash, and if B_H equals zero the household has spent all its cash income.
- I_F is farm income (USD year^{-1}), and is calculated as the gross value generated from crop and livestock production minus the sum of all variable costs (such as hired labor, fertilizer, seed, and purchased livestock feeds) and fixed costs (such as land and machinery). The variable I_F in Eq. (2) is similar to $P_a(Q_a)-P_hH-P_vV$ using the notation in Eq. (1).

- I_O is off-farm income (USD year^{-1}), and is the sum of all family members' earnings from off-farm activities, including salary, income from working on other farms or other part-time jobs, pensions, and remittances. In Eq. (1) if (L – H – F) < 0, the household earns off- farm income and in our study the household earns off-farm income if $I_O > 0$.
- C_F is food costs (USD year^{-1}), and refers to the value of all food consumed by the household, obtained either from the market or from on-farm production, accounting for differences in sales and purchase prices for food.
- CE is other expenditures (USD year−1), i.e. expenditures not related to agriculture (such as transport fees, and health care), and is the sum of such expenditures incurred by all family members.

c) ***'SOM balance' module;*** this module is calculated as the difference between SOM accumulation and loss. The accumulation originates from roots and stubble that remain on the field after harvest, green manures that are grown as a source of SOM and ploughed under before growing a next crop, feed losses that are dependent on the feeding system and type of feed supplied, and manure either produced on-farm due to excretion by the animals or imported from an external source (Groot et al., 2012). Part of the manure is degraded in the year of excretion and other losses of SOM occur through breakdown of active SOM in the soil and erosion of soil. Rates of SOM degradation are affected by the following environmental variables, as described in Groot et al. (2012).

- Soil moisture availability, quantified as the number of days per year with a soil pF-value lower than 3.5 (W; days). It is assumed that when moisture is insufficient no SOM break-down occurs, due to reductions in water transport, in solute diffusion and in motility and survival of microorganisms (Rodrigo et al., 1997).
- Average temperature (T; °C) during the moist period, following a Van't Hoff function wherein Q10 is a constant representing the increase in OM

degradation for an increase in temperature of 10 °C (Rodrigo et al., 1997), and relative to a reference temperature (TREF; 25 °C under conditions in northern Uganda; Q10 =2) (Kätterer et al. 1998).

- A dimensionless soil texture correction factor that is used to estimate the effect of increased physical protection of OM in soils with higher clay content (Hassink, 1994) (U; 1.2 for sandy soils, 1.0 for loam and 0.8 for clay). Effects of differences in tillage frequency and intensity can be specified by adjusting the structure factor U, thus affecting the degradation rates of all OM fractions.

d) **'Nutrient balance' module**: This module is calculated by subtracting the N exports (manure, crop and animal products) from the sum of N inputs on the farm such as crop and livestock products, manures and fertilizer, deposition, and BNF by legume crops.

4.3 Methodology

4.3.1 Case Study Farms in northern Uganda

The case study farms are located in two study districts, namely Lira (2.2581° N, 32.8874° E) and Kitgum (3.2885° N, 32.8789° E), both in northern Uganda. Lira district is situated in the northern moist farmland whilst Kitgum lies in the northern farm-bush lands with sandy-soil farming systems. In Lira district, the landscape generally consists of gently-rolling plains whilst further north in Kitgum, the landscape consists of rolling and undulating landscapes. The soils of northern Uganda are generally of low fertility with high sand (>60%) and acidic content (C. S. Wortmann & Eledu, 1999) and low levels of SOM (Yost and Eswaran 1990). Northern Uganda receives uni-modal rainfall, the average annual precipitation is about 1,200 mm and the average annual temperature is 25 ^{0}C (C. S. Wortmann & Eledu, 1999; Yost & Eswaran, 1990). The hottest months are December until February, and the rainy season is normally from April to October (Akongo, 2019).

Northern Uganda is characterized as a mixed annual crop-livestock Agro-ecological Zone (AEZ), with smallholders mostly growing cereal food crops supplemented with livestock. Cattle are rather common among high-resourced smallholders, while low-resourced smallholders rather raise small-ruminants like goats, pigs and sheep. Poverty rates are very high, with 33% of the northern Ugandan population classified as extremely poor (World Bank, 2016), and food insecurity is rampant. This is all partly exacerbated by the effects and after-effects of the two decades of civil war between 1986 and 2006 which left northern Uganda particularly marginalized (Chapman et al. 2009; Kaweesa et al. 2018).

Northern Uganda is more prone to climate variability than other parts of the country (Akongo et al., 2017). At the beginning of the rainy season, smallholders usually plough their plots and sometimes apply manure and crop residues from the previous season. High-resourced farms (HRF) often own or hire-in oxen for ploughing, while low-resourced farms (LRF) have to use hand hoes.

4.3.2 Data Collection Strategy

We carried out a baseline survey with 257 smallholders in Lira and Kitgum districts in northern Uganda in September/October 2020. The survey covered representative smallholder farmers from low and high resource endowment farm categories which we constructed in a typology (see Namuyiga et al. 2022). The questionnaire included detailed socio-economic aspects of the farm households such as farm labor allocation, crops, livestock and their products, and farm inputs. From the typology, three representative farms of each of the six farm types were selected for the detailed characterization. For analysis, data from two representative low and high resource farm types were considered to fit the model requirement. Additionally we collected details on crop and livestock from secondary data sources such as Feedipedia-Animal feed resources information systems, e.g. for metabolic energy (ME), dry matter content (DM) and Crude Protein (CP) (g/kg), (https://www.feedipedia.org/node/721).

To assess soil fertility, we collected soil samples from intercropped pigeon pea plots from the 18 representative households in the three farm types. Soil samples were taken with a bucket-auger from two depths of 0-15 cm and 15-30 cm, respectively. Pigeon pea plots were sectioned into three units based on slope position (toe-slope, mid-slope and shoulder-slope). The soil was then quarter sampled to obtain a composite sample of 500 g from the top 15 cm of soil which was later packed. This was then repeated for the two other auger depth positions. Thereafter soils were mixed thoroughly and quarter sampled to obtain a 500 g soil sample from 15-30 cm soil depth. This was packed in a polythene bag, thoroughly labeled and transported to the Plant and Soil Laboratory at Makerere University in Kampala for analysis. This procedure was repeated for each of the other two slope positions in the farm plots, making six soil samples per plot, and a total of 108 soil samples in the study. The soil sampling procedure followed the one suggested by Okalebo et al. (2002).

In the laboratory, soil samples were oven-dried at 40^{o}C, grounded, sieved through 2 mm to remove any debris, and then physically and chemically analyzed following the methods described by Okalebo et al. (2002). Soil pH was measured in a soil/water solution ratio of 1:2.5 as recommended by Anderson and Ingram (1994). Additional environmental data was gathered from the literature, such as deposition levels, N, P, K and dry matter content of crop residues, soil erosion, leaching and ammonization levels as well as livestock feed parameters (Stoorvogel & Smaling, 1990).

4.3.3 Pareto-optimization and Model Configuration

The FarmDESIGN model provides solution spaces that maximize farm profit and SOM, while minimizing labor time and soil nutrient loss. We aimed to provide targeted recommendations for improved farm performance for smallholder farmers in northern Uganda. The multi-objective optimization uses a Pareto-based Differential Evolution algorithm (Storn & Price, 1997), illustrated in Figure 4.3, as used in the FarmDESIGN model described by Groot et al. (2012). Firstly, we evaluated the current performance of the case study farms by assessing the environmental, social and economic indicators calculated by the FarmDESIGN model (see Table 4.2).

We explored the response of the FarmDESIGN model to optimize four parameters, namely *SOM balance, nutrient (N) balance, operating profit, and household labor balance.* We selected the objectives based on our earlier farming system diagnosis and typology of smallholders in northern Uganda (Namuyiga et al., 2022). In addition, our objectives contribute to the three sustainability dimensions, i.e., social, economic and environmental indicators (Goswami et al., 2017), and the overall goal to (better) integrate legumes into mixed farming system in northern Uganda. To create a stable solution space, we ran the optimization for 1,000 iterations for each farm type using a mutation probability and amplitude of 0.85 and 0.15, respectively. Decision variables and constraints set for the optimization are shown in Table 4.2.

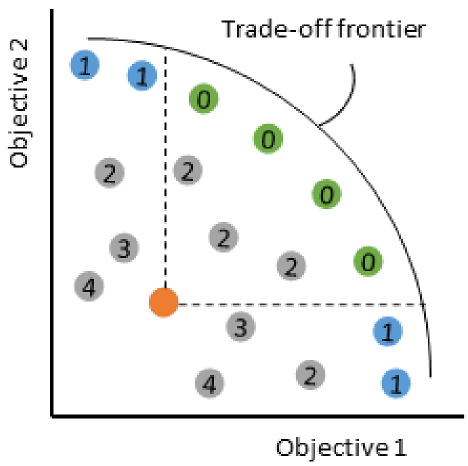


Figure 4.3. Solution space of a Pareto-based optimization in which Objective 1 and 2 are maximized and solutions have different ranks 0-4, modified from (Schreefel et al. 2022). Green circles represent farm configurations outperforming the original farm configuration (orange) on all objectives (rank 0). Blue circles represent farm configurations, which outperform at least one objective (rank 1). Grey circles (ranks 2 4) are farm configurations optimized in different extents towards the objectives.

The model constraints included setting crop areas as decision variables to allow alternative configurations during the optimization process. We also made the land area under pigeon pea production a decision variable since pigeon pea was the focus crop in the study. Intercropping, especially cereals (millet, sorghum and maize), with legumes, is traditionally a common practice in northern Uganda.

The new farm configurations include better alternatives for improved farm performance indicators; such as economic returns, labor use and land use alternatives. These include changes in the decision variables, for example, fertilization of the most profitable crops grown, the addition of livestock on the farm to enhance manure availability, and changes in labor allocation to more profitable enterprises, but also increment in men and women labor allocation to reduce on leisure time.

4.4 Results

Results from the soil analysis are presented in Table 4.1. Results show that the soil pH was slightly acidic (6.0-6.5) and thus generally favorable for farming. There were differences between the two farms especially with organic C, where at the 0-15 cm depth, the LRF had 2.64% and the HRF had 4.66% (Table 4.1).

Table 4.1: Soil parameters for low-resourced and high-resourced farms used in the FarmDESIGN model across the low resourced and high resourced farms

Farm Type	Depth (cm)	Clay (%)	Sand (%)	BD (kg/cm^3)	pH	TN (%)	OC (%)
LRF	0-15	24	61	1450	6.3	0.18	2.64
	15-30	18	68	1200	6.1	0.18	2.39
HRF	0-15	19	73	1320	5.9	0.26	4.66
	15-30	31	60	1520	5.9	0.26	3.40

Note; TN: Total Nitrogen, BD: Bulky Density, OC: Organic carbon, LRF is Low Resource Farm, and HRF is High Resource Farm

The FarmDESIGN model current performance values are presented in Table 4.2 and Figure 4.4. The results indicate better performance alternatives across all objectives for both farm types. We find high SOM losses of between -233 to -245 Kg ha^{-1}year^{-1} and P losses of about -3 Kg ha^{-1}year^{-1} for the HRF and LRF farms respectively. Further, K additions of about 17 Kg ha^{-1}year^{-1} and 12 Kg ha^{-1}year^{-1} for the LRF and HRF types respectively. The social indicators show high labor availability across the two farm types, with 1,916 and 2,273 hours per year for the LRF and HRF farm types respectively. However, we find quite low values for the economic indicators, including operating profit with 52 and 114 USD year^{-1} for LRF and HRF farm types respectively. Cropped land area was 2.9 and 3.8 ha with TLU of 4.7 for the LRF and HRF types respectively.

Table 4.2: Selected original case study farm indicators from the FarmDESIGN: low and high resourced households across Lira, and Kitgum respectively.

Category	Indicator/parameter	Unit	Low-resource Farm (LRF)—Lira district	High-resourced Farm (HRF)---Kitgum district
Environmental	SOM balance	Kg $ha^{-1}year^{-1}$	-232.83	-244.73
	N input	Kg $ha^{-1}year^{-1}$	51.63	47.79
	P losses	Kg $ha^{-1}year^{-1}$	-2.87	-2.66
	K losses	Kg $ha^{-1}year^{-1}$	16.83	11.51
Social (labor)	Total on-farm labor required	Hr $year^{-1}$	1916	2273
	Hired labor	Hr $year^{-1}$	30	50
	Total off-farm labor	Hr $year^{-1}$	320	320
	Leisure time	Hr $year^{-1}$	2904	2547
Economic	Operating Economic profit (+ return to labor)	USD $year^{-1}$	51.65	114.22
	Variable costs with labor	USD $year^{-1}$	1126.94	1202.44
	Cost of hired labor	USD $year^{-1}$	60	63
	Variable costs	USD $year^{-1}$	1066.94	1102.44
	Off-farm income	USD $year^{-1}$	655	655
	Household expenditure	USD $year^{-1}$	437.53	437.53
Farm characteristics	Cropped area	ha	2.9	3.8
	Livestock units	TLUs	4.7	4.7
	Family size	number	9	7

Note: The exchange rate was 1 UGX = USD 3750 (Bank of Uganda rate as at 15th October 2020)

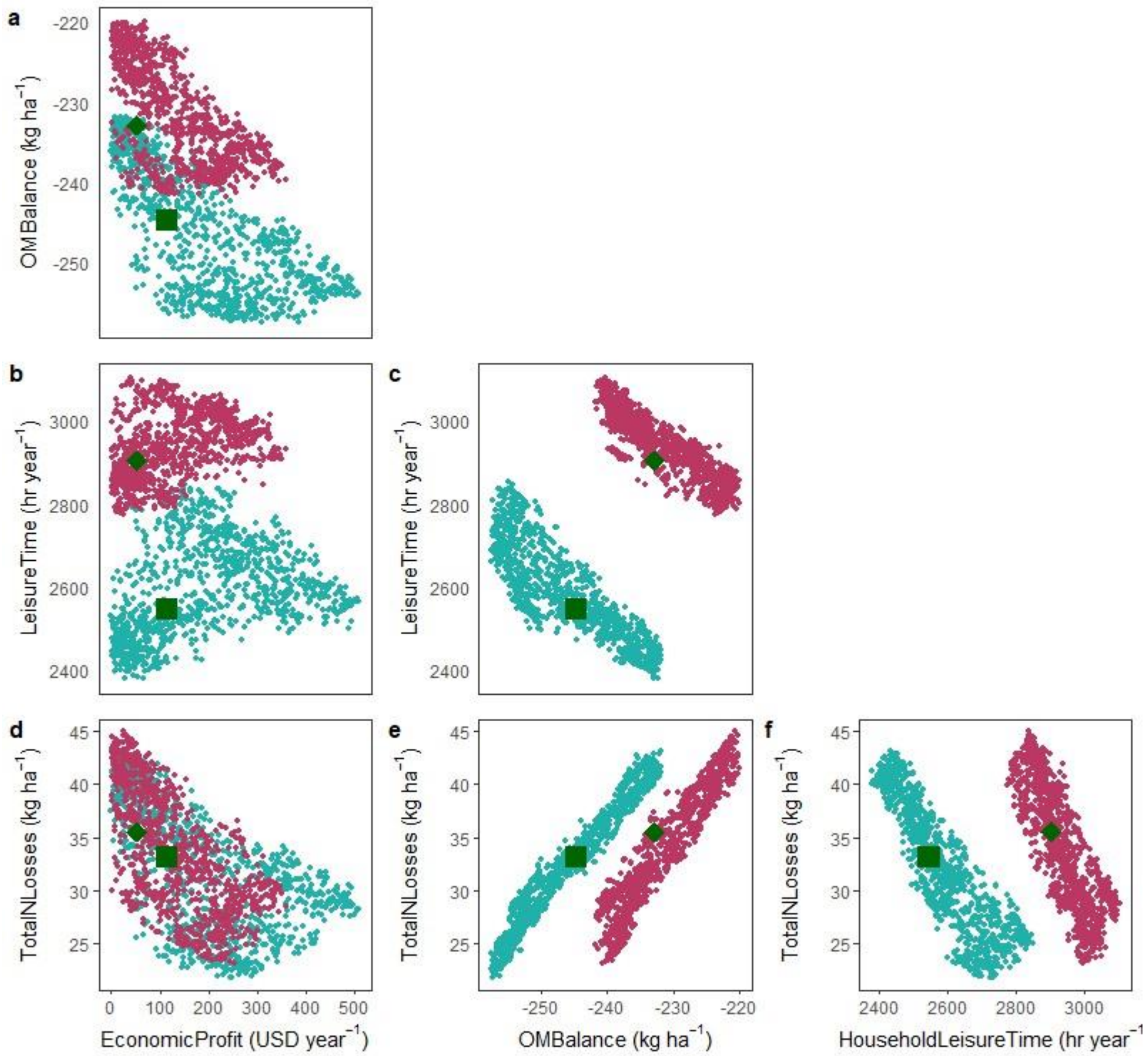


Figure 4.4. Relationship between selected objectives; soil organic matter (SOM) balance, economic profit, nutrient losses and labor balance for low-resource farms (LRF) (light green) and high-resource farms (HRF) (maroon) in Lira and Kitgum districts respectively. Each dot represents an alternative farm configuration, the dark green symbol (square for LRF and diamond for HRF) marks the performance of the original farm configuration.

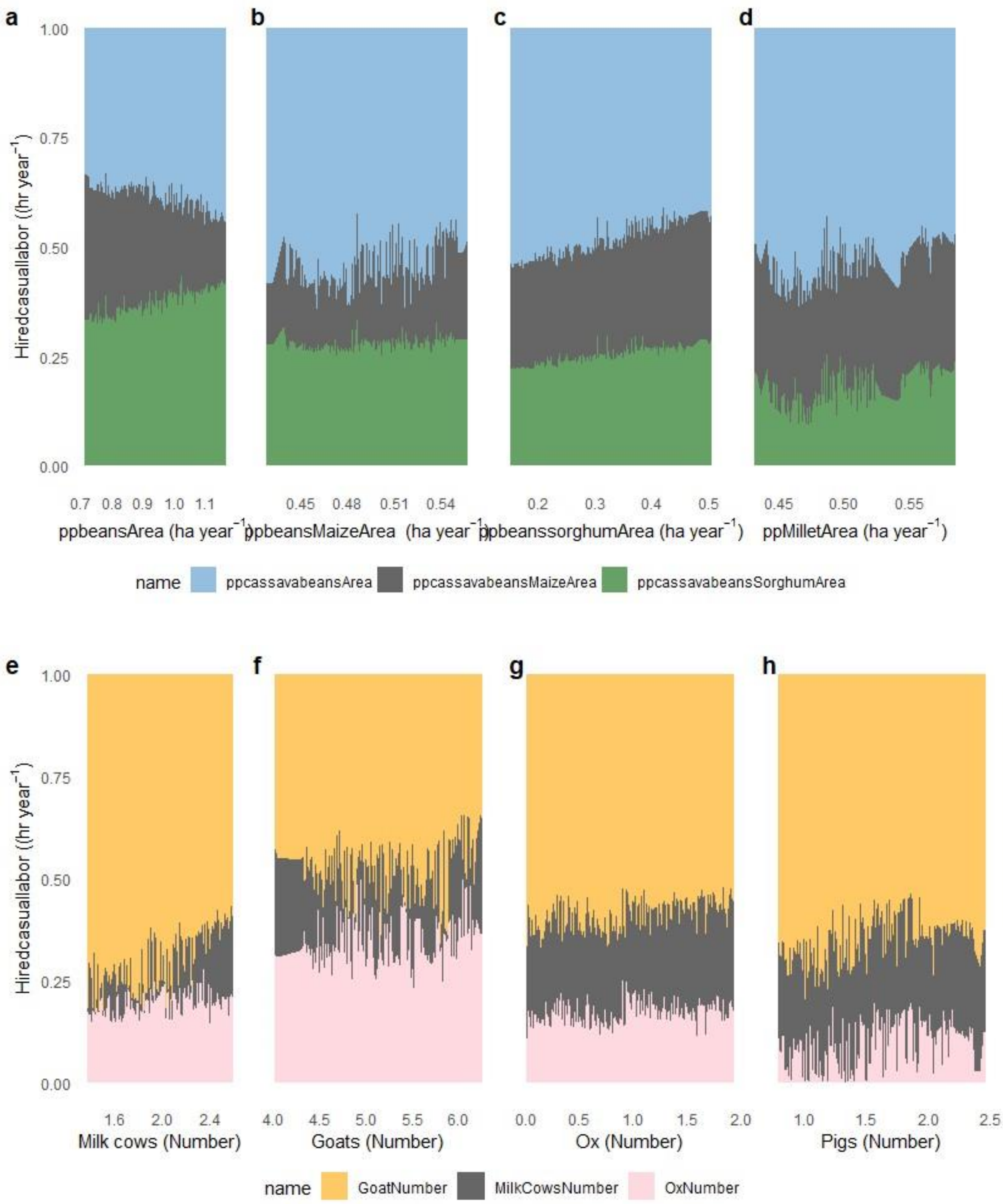


Figure 4.5. Modeled allocation of labor resources; (a-d) for crops (a-d) and for livestock management (e-h) in each alternative farm configuration generated to meet the objectives for the LRF farm in Lira district.

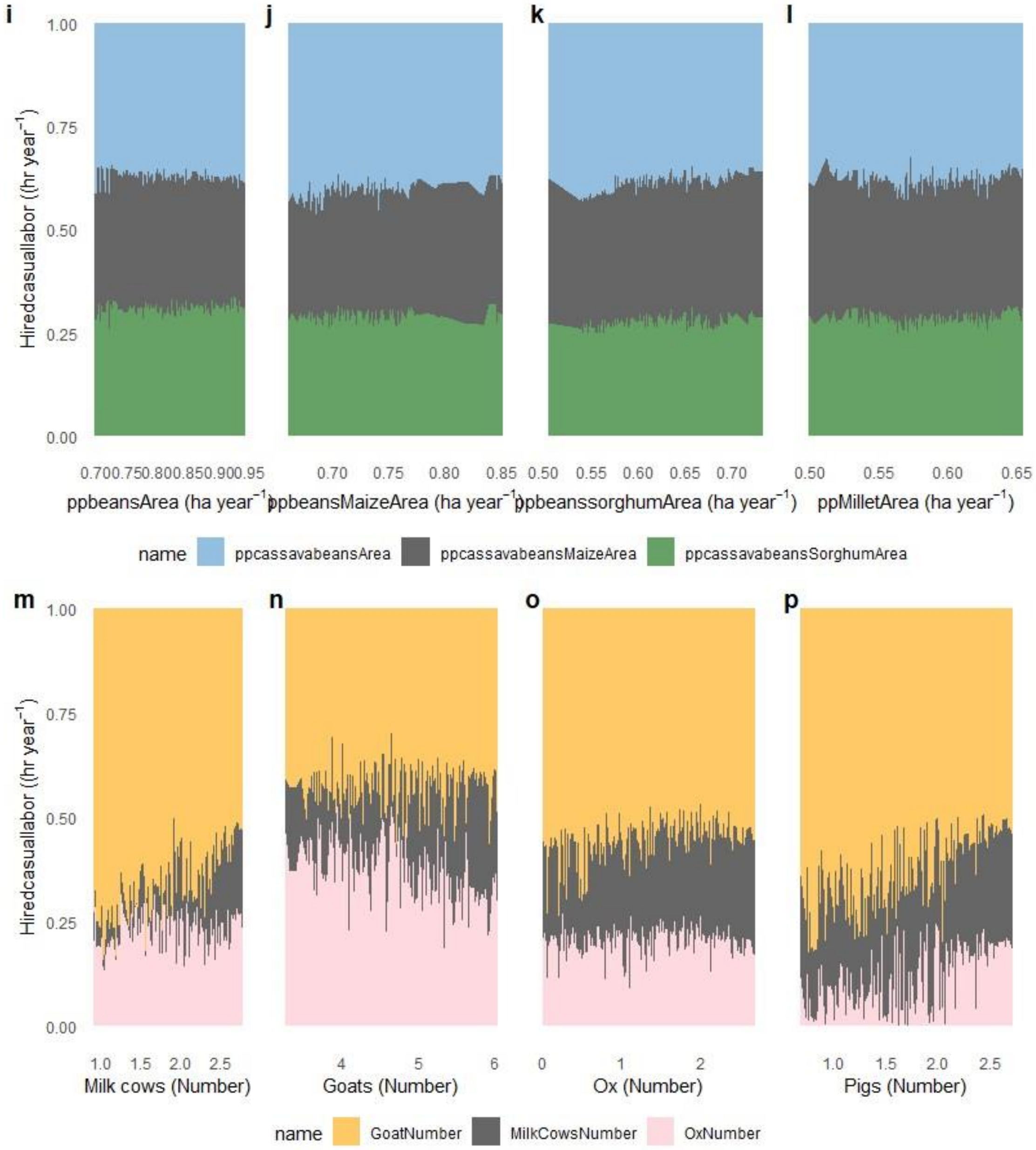


Figure 4.6. Modeled allocation of labor resources for crop growing (i-l) and livestoc management (m-p) in each alternative farm configuration generated to meet the selecte objectives HRF farm type in Kitgum district

Using the extended FarmDESIGN modules, we found better social, economic and environmental alternatives for the two smallholder mixed farms in northern Uganda. The modules were soil OM and nutrient balance, labor balance, and household economic profit. Figure 4.4 portray the relationship, trade-offs, and synergies between selected objectives for optimization. The current farm performance shows that both households have almost the same level of SOM and household economic profit, which are currently low and sometimes negative. However, the HRF has a wider window of opportunity for improvement of the two objectives. If households improve profitability from the current performance level, for instance through higher farm diversification and subsequent crop and animal product harvests and sales, they can afford mineral and organic fertilizers to enhance SOM.

4.5 Discussion

This study used the FarmDESIGN model in the context of the smallholder farming system in two districts of northern Uganda. FarmDESIGN provided improvement in overall farm performance in terms of SOM and N balance for improved crop productivity, labor availability and household profitability by comparing the current farm performance with potentially achievable alternative farm performances to lead to livelihood improvement (Figure 4.4).

Smallholders aim to improve crop productivity within the available resource endowment albeit the prevailing economic and environmental constraints. Crop productivity of smallholder farming in northern Uganda is generally low. This has direct negative impacts on household incomes, food security and natural resource degradation. To improve farm performance, smallholders need to diversify both crop and livestock enterprises, which requires more investment into farming. For example milk and crop product sales could enhance household incomes if re-invested into agricultural related activities. However, the operating economic profit remains low at 51.7 and 114.22 USD year^{-1} for LRF and HRF respectively (see Table 4.2). This is partly due to the high operational and variable costs especially for labor hire and farm input purchase. Such high costs greatly reduce the operating economic profit in addition to reduction in overly what remains at the end of each agricultural season.

We also found a wider window of opportunity for both case study farm types to improve their operating profit attributed to milk sales for the HRF and crop product sales for the LRF (Figure 4.4), since milk is a high value product compared to crop products. Regarding animal related costs, purchase of improved feedstuff such as fodder and concentrates for enhanced milk production is one alternative that can be adopted by households in northern Uganda. Similar results have been reported for smallholders in Kenya who face related production dilemma (Timler et al., 2020). Another inexpensive option is the use of fodder from pigeon pea which can enhance the nutritive live weight of small ruminants due to its higher N concentration (Shenkute et al., 2013).

The results of FarmDESIGN show alternatives that outperform the current farm performance of farm households in terms of SOM and N-balance objectives. Trade-offs exist with increasing livestock numbers, especially small ruminants like goats and sheep that are popular in northern Uganda, and the available economic resources to farmers. In addition, changing livestock diets to for example fiber-dense concentrates can increase the availability of farm yard manure which can subsequently lead to higher crop productivity for both farm types. Livestock feed can be gradually changed to either the improved pastures or commercial concentrates as household incomes improve, which would ultimately enhance farmers' livelihoods.

Family labor remains an important resource component in smallholder farming in northern Uganda. The use of hired labor remains low due to limited financial. Worse-still, many youths have abandoned farming in the study districts for alternative employment alternatives in near-by cities. Women do much of the farm work, especially regarding crop and livestock management, are primarily responsible for household care, and also assist men during peak labor demand (Doss & Quisumbing, 2020). The

FarmDESIGN results show labor surplus for both farm types. Taking up such labor time for productive farm activities is an option for increasing crop production and freeing up women time to cater for other household needs and off-farm activities.

In terms of profit maximization, smallholders in northern Uganda primarily produce for own household consumption, but the surplus is sold on local markets. We found low and negative economic performance from the model results---Figure 4.4. This is illustrated by the household economic profit module, and is partly due to the high farm operational costs. Smallholders primarily rely on income from crop and animal product sales. However, the profits remain marginal, especially for LRF households. Improving crop productivity for example through increasing SOM is an option to lead to more sales and extra household income. In turn, the enhanced incomes could enhance access to productive farm inputs such as mineral fertilizer and improved seeds.

Further, our results show that there are better alternatives towards improving the household budget and overall household operating profit, with both more surplus farm labor and higher SOM (Figure 4.4). Smallholders in northern Uganda are greatly challenged by comparatively high costs of fertilizers and pesticides. We found that HRF smallholders partly use pesticides to control pigeon pea pests such as the pod-sucking bugs with the two broad spectrum systemic insecticides *Profenos 40%* and *Cypermethrin 4% EC*, whereas LRF rarely used any chemical inputs on their farms. These pests can cause up to 35 to 60 % damage to pigeon pea (Hillocks et al., 2000). Another alternative is information access from the government provided extension services at sub-counties to and districts offices, such technical information can be a step in the right direction on improving crop and livestock management at household level.

SOM is one of the most important soil fertility indicator in smallholder farming systems (Zake et al., 2015). The soils of northern Uganda are nutrient depleted implying low soil fertility, exacerbated by the low use of organic and mineral fertilizers (Chianu et al., 2012). This is partly attributed to the high cost of mineral fertilizers like diammonium phosphate, nitrogen-phosphorus-potassium, and calcium ammonium nitrate. We found no fertilizer use across the representative farms households, and barely 1% in the larger sample of 257 smallholders in the three districts of this study (Namuyiga et al 2022). Soil nutrients are commonly lost through continuous cropping, crop harvests, removal of crop residues, leaching, and soil erosion (Stoorvogel & Smaling, 1990). One option for the low input system like northern Uganda is intercropping of legumes such as pigeon pea for nitrogen-fixation, and many smallholders highlighted how this is an important attribute in the farming system (Namuyiga et al 2022).

Similarly, the rate of soil nutrient depletion does not match nutrient addition (and demand) since farmers partly depend on crop residues such as straw and stover, and green manures for mulching at the end of each season. In addition, livestock manure is scarce and costly, and often either inappropriately applied or used at the wrong time. Many LRF smallholders keep goats, sheep, and poultry but few rear cattle and oxen. The latter is more common and popular among HRF as among other benefits, sources of manure, and HRF can also afford purchases of mineral fertilizers such as NPK. Much of the large livestock was lost during the Civil War and later through cattle rustling (Rockmore, 2020). Only HRF households can afford to keep cattle and oxen, for manure, milk, meat, draught power, and prestige. Without a doubt, improving organic matter through the proper application of stover, straw, and animal manure can considerably improve SOM and overall crop productivity in northern Uganda.

The current performance of LRF and HRF with regard to SOM and N balances is quite low. This is partly because of low input – low output cycles, in which much of the N is lost through crop harvest, soil erosion and leaching. In this context, the FarmDESIGN results suggest alternatives for improving SOM and N balance, especially for the HRF (Figure 4.4. The application of farm yard manure and crop residues can substantially improve agricultural productivity (Kangalawe, 2014). Pigeon pea and other legumes also have a particularly high potential to improve SOM and N as a low-cost fertilizer through the N fixing bacteria of its roots and where crop residues are incorporated into the soil after harvest (Vanlauwe et al., 2019). Moreover, forage legumes like pigeon pea benefit crops by providing additional N for the subsequent (of cereal) crop, leading to higher yields when legumes are part of the crop rotation (Peoples et al., 2009).

Northern Uganda is semi-arid and thus categorized as an agro-pastoral zone. Here livestock is most often fed with readily available crop bi-products such as fodder grazing, straw, and forage, thus competing with the use of crop residues for soil fertility improvement which ultimately affects crop productivity. Moreover, livestock manure is often not used productively as organic fertilizer. LRF smallholders have few no- or low-cost potentials to improve SOM and N. In general, a combination of using crop residues and livestock manure would greatly improve soil fertility, though socio-economic constraints might pose limits, especially for LRFs.

For livestock rearing and crop management, labor is the most important resource available to smallholders, at the same time one of the constraints. We found variations in labor allocation across the farm types (Figures 4.5 & 4.6), with much labor allocated to goats for the HRF and oxen for the LRF. This shows the importance of oxen as a source of labor especially for the LRF due to labor shortages during peak seasons. Further, land and labor are the main resources available in this low input-low output system of northern Uganda (Figures 4.5 & 4.6). Our results show that much of the land is allocated to cereal-legume intercrops, which is a common practice with many smallholder farmers. The main cereal crop in this farming system is millet followed sorghum, which are both important food security crops and commonly found in all households. Households make both millet and sorghum bread and accompany these with any available form of sauce such as peas and common beans.

4.6 Conclusion

This study employed the multi-objective decision modeling framework FarmDESIGN for providing alternatives for two groups of smallholders in northern Uganda. We used empirical data from two representative farm types, namely low and high resource smallholders, taken from our earlier developed smallholder typology (Namuyiga et al 2022). We focused on the *Describe*, *Explain*, and *Explore* phases of the DEED framework as a revised model from the earlier version of the FarmDESIGN (Ditzler et al. 2019)The accuracy and performance of FarmDESIGN are well documented. Based on our empirical data collected in a survey in northern Uganda in 2019 and 2020, we reported costs, prices, and farm household expenditures, which were then converted to the US dollar rate at the time of the survey.

Overall, results indicate better alternatives for all model objectives to improve the performance of the farm households. Such alternatives include example; improved use of the locally available farm resources such as crop residues, livestock and farm-yard manure to enhance soil fertilization. Further, the application of such manure at the right time when it's more beneficial to crops remains an action point for agricultural extension and programs. Land allocation is still priotized for intercrops including the common cereals and legumes (especially pigeon pea for northern Uganda), which smallholders consider the most important for food, nutrition and livelihood security. However, further research on how farmers maximize benefits from intercropping; for insistence which crops give the highest productivity.

5 CONCLUSIONS AND OUTLOOK

5.1 Summary

This study assessed smallholder mixed farming system in the three districts in post-conflict rural northern Uganda, with a focus on pigeon pea as a multi-purpose legume and as an important crop for farmer livelihood. The main aim was to describe, analyse and categorize pigeon pea producing smallholder farms and farmers, and provide targeted recommendations using a multi-objective whole-farm model for improved smallholder livelihoods and sustainable agricultural intensification and transformation. This study contributes to the SDGs, particularly SDG 1 (No poverty), and SDG 2 (Zero hunger) (FAO 2017), and results constitute an important step in understanding the role and contribution of legumes (pigeon pea)- based cropping system to livelihoods in northern Uganda.

We employed the farming systems analysis approach to understand the smallholder farming system complexities and boundaries; the particular preferences, and needs of smallholders using econometric, multivariate statistical and qualitative research approaches, and the application of a multi-objective FarmDESIGN model.

Notably, we argue that previous and current rural development programs in Uganda, such as NAADS, Operation Wealth Creation, and currently the Parish Development Model (2021-2026), have applied general and standardized approaches to smallholder agricultural development. In turn, with large heterogeneity in smallholder socio-economic and resource endowment, such blanket programs and policies have added limited value. Further, exacerbated by the 20 year long civil war, volatile climate and market conditions in the region, compared to other regions of Uganda (Rockmore, 2020) increases the vulnerability of the northern Uganda further. northern Uganda remains the poorest region of Uganda, at 34.5% poverty rates (UBoS 2020).

Legumes, pigeon pea play an important role for food and nutrition security and the livelihoods of smallholders in northern Uganda, particularly for women, and especially the poorer and resource-constrained parts of the population (Namuyiga et al., 2022; Obuo et al., 2004) . In general, legumes have a unique ability to fix nitrogen, thus reducing the need for N fertilisation and contributing to sustainable intensification of cropping systems (Peoples et al., 2009). The role and potential of pigeon pea is often neglected by research and development programs, making it an under-researched and underutilized 'orphan crop' (Tadele, 2019). We apply the FSA approach, which is a fundamental framework for an in-depth understanding of mixed farming systems, using empirical data from 257 representative low, medium and high-resourced smallholders who grow pigeon pea in 18 villages in three districts of northern Uganda. We additionally applied the FarmDESIGN multi-objective model on representative low and high resource farm households to enhance their current performance and provide targeted recommendations for farm improvement.

After the introduction in chapter one, chapter two explores the role of membership of pigeon pea growing smallholders in Farmer Groups (FGs) and its impact on pigeon pea yield and technical efficiency. Farmer groups are deemed important social and institutional components for agricultural transformation, and previous research has highlighted their positive impact on farm productivity and improved smallholder livelihoods in SSA (Abdul-Rahaman and Abdulai 2018). We used the probit and complementary models as analytical approaches on cross-sectional data gathered from 257 smallholder farmers. The results showed that the main motivation for smallholders to become a member in a FG are borrowing and saving, and benefits from collective produce marketing. Further, members of FGs were generally older and more experienced, and had better access to extension services and financial credit compared to non-members.

Technical efficiency for both groups, was low and quite similar for both members and non-members, implying that the FG members continue to face major production and marketing challenges and limitations leading to low efficiency level. One reason for relatively low efficiency is that the services of FGs are delivered rather centrally at few FG meeting and service locations, in most cases in parish and sub-county offices. These places are difficult to reach by many smallholders, given the 'remoteness' of and poor infrastructure in rural northern Uganda. Further, agricultural extension and advisory services are often delivered in English, which is not widely spoken and/or understood by smallholders who mostly speak Langi and Acholi languages.

In chapter three, we explored smallholder heterogeneity of pigeon pea growing smallholders and the factors driving such diversity. We developed six distinct farm types using multivariate statistical analysis; principal component and hierarchical cluster analysis. The identified farm types showed different famer types with varying socio-economic characteristics and resource endowments. The results concur with the argument that 'one fits for all' agricultural development interventions that have long been implemented in northern Uganda and elsewhere across SSA are inappropriate (Dixon et al., 2014). Smallholders in northern Uganda are diverse with regard to their resource endowment and socio-economic factors such as land and livestock owned, education level, age, farming experience, farm asset ownership, crop yield, household location, and the level of market integration.

The results showed that more than half (54%) of the 257 smallholders surveyed were low-resourced, with below average land sizes, livestock and household income. These results concur with other studies in SSA that explored smallholder diversity, such as (Kuivanen et al. 2016; Makate and Mango 2017; Kansiime et al. 2018; Makate et al. 2018). This points to the high poverty rate in northern Uganda, and the need for more pro-poor targeted and effective development approaches and programs (UBoS 2020). While low-resourced farms almost entirely produced for their own subsistence, medium resourced farms also produced for local markets. Members of high-resourced farms were more experienced and more formally educated compared to low and medium-resourced ones.

We further assessed smallholder's preferences and perceptions regarding production, processing, consumption and marketing of pigeon pea across farm types, gender and the three study districts. Smallholders mainly grow pigeon pea because it is drought resistant and nutritious, in addition to its soil improvement ability through nitrogen fixation, compared to other legumes. Female smallholders often underlined that they grow pigeon pea because it requires less labor than other crops. However, smallholders highlighted that pigeon pea production is challenged by high levels of pest and diseases.

In chapter four, we simulated the mixed farming systems to gauge the current performance of selected representative farms and suggest practical alternatives for higher productivity and improved smallholders' livelihoods. The objectives were to maximize farm profitability and labor surplus and to improve SOM and nitrogen. The results provide many alternatives for more tailored and effective pro-poor smallholder decisions. We identified trade-offs and synergies such as improving SOM through the use of crop residues as mulch material instead of using these as livestock fodder. The low-resourced farm types could improve farm profitability through better allocation of farm labor to crop production and other off-farm activities.

Sustainable use of soil and water, for example through mulching, are further recommended, given the low soil fertility and the uni-modal season exacerbated by the increasingly variable rainfall in northern Uganda. Further, high-resourced smallholders who depend on selling surplus produce require better market linkages, through improved road infrastructure and tailored FG services, as reported in Namuyiga et al., (2024). Improved livestock feeding, e.g., with concentrates, would reduce dependence on farm yard manure for soil fertilization and increase available manure, which improve soil fertility and crop productivity. Similarly, low-resourced smallholders could substantially benefit from intercropping of pigeon pea with cereals for biological nitrogen fixation.

5.2 Synthesis and Outlook: re-designing the northern Uganda mixed farming system

Given the significance of smallholder agriculture to the economy and people of Uganda, and especially of northern Uganda, the poorest region of the country, as well as the importance of pigeon pea for food and nutritional security, particularly for poor smallholders, this study provides essential contributions towards an in-depth understanding of mixed farming systems and their role for pro-poor agricultural development and increasing smallholders' livelihoods. Northern Uganda provides a hitherto rather scientifically neglected but particularly relevant special case given its legacies of the 20-years long civil war, its strategic geographic location between DRC, South Sudan and Kenya and the intertwined social, economic, political and environmental challenges that have contributed to persistent marginalization and high poverty rates.

This study provides insights of the heterogeneity among pigeon pea growing smallholder farmers in northern Uganda, their preferences, perceptions and needs, and the trade-offs and synergies. It develops recommendations based on refraining from "blanket" agricultural development programs that have been the norm in Uganda (and beyond) and advocate for tailored, targeted programs that support specific smallholders types according to their socio-economic characteristics, resources and needs. All too often, development practitioners and researchers cluster smallholders in one country or region under one 'umbrella crop' (such as the coffee farmers, the maize farmers, the pigeon pea farmers) without taking into account the high diversity between them as well as the complexity within these farms.

The results show a high diversity among pigeon pea smallholders in northern Uganda with regard to their socio-economic background, their resource endowment and specific needs. The six farm types that are developed in this research allow for adapted and context-specific approaches to agricultural development and sustainable livelihoods. Low-resource smallholders majorly produce for subsistence and can hardly orient their efforts towards increasing agricultural productivity and towards marketing their produce. However, all farm types are to some extent resource-constrained, mostly affected by marginalization, poverty and hunger, and hence should be targeted specifically in development efforts.

We recommend targeted efforts in training of extension agents that incentivize and enable them to apply participatory approaches to work with and for smallholder farmers. Particular focus should be on providing services to the group of low-resourced smallholders, those who have been traditionally underserved by extension work, often due to their geographical 'remoteness', low education and/or language barriers. We believe that extension, also in written documents, in northern Uganda should not only be provided in English or *Luganda*, but primarily in the *Langi* and *Acholi* languages, as many rural people, especially women and older persons, in northern Uganda rarely speak English or *Luganda.*

Our results stress the need for strengthened collective efforts in northern Uganda. The main motivation for smallholders to become members in FGs are borrowing and saving services. Relatedly, we recommend improving the agricultural credit services in northern Uganda through, for example, strengthened Village Savings and Loans Associations (VSLAs), a system which was first established in Uganda in 1998 by CARE (Leon-Himmelstine and Phiona 2021). Farmers groups need to be based more on peer-to-peer horizontal social learning which would facilitate a better diffusion of best agronomic practices than via top-down approaches. In this context, governance and leadership structures that help to make smallholder FGs (more) effective and sustainable is a thematic area that is still under-researched in northern Uganda, and Uganda in general – and needs to be better understood. We hence recommend future interdisciplinary research on smallholder collective action networks and initiatives in northern Uganda, and Uganda at large.

While breeding of new crop varieties has been a strong focus of agricultural development and research services in Uganda and SSA in general, with millions of dollars invested during the last decades. However,, such activities all too often do not take into consideration smallholder's needs, perceptions and preferred crop traits. Breeding efforts mostly aim to increase the maximum yield of a few cash crop varieties that fulfill the needs of larger commercial farms or high-resourced farmers. Pigeon pea breeding programs have been highly underfunded and disregarded in Uganda and beyond in the last decades, despite the importance of the legume for the livelihoods of millions of smallholders, women in particular, and its ecological potential growing on poor soils in arid climates.

Pigeon pea breeding should also aim at the development and dissemination of early maturing, pest- and drought-resistant varieties that are easy to intercrop with cereals. Such breeding programs should not solely focus on higher yields, as they often do, but should directly address crop attributes crucially needed by smallholders. Smallholder farmers demand for varieties that are easily adaptable and that should be provided to smallholders at low cost (or even no cost) to help increase their food production and overall livelihood resilience. Such new pigeon pea varieties are not only important for smallholders in northern Uganda, but also for millions of smallholders in neighboring countries with similar agro-ecological characteristics (such as large parts of Kenya and South Sudan). Further, we recommend subsidies for mineral fertilizer and awareness creation about new legume varieties to encourage uptake. In addition, inclusive value chain approaches that help link smallholders to high-value markets, through the improvement of infrastructure, is a way forward.

On-farm integration, right incentives and tailored crop and livestock innovations are important to improve smallholder livelihoods and spur development. Further, rural agricultural extension and training programs should not focus any longer on the classic "head of the household" approach, who is usually an older male, but should target all smallholder family members to identify their specific needs. Programs should target particularly women who are mostly involved in the cultivation, processing and to some extent the marketing of pigeon pea and other legumes in northern Uganda, since they are often faced with specific challenges like limited access to land, credit and market information. Women continue to play multiple roles - productive, household and community services as well as reproductive activities - further tied by cultural norms and beliefs that define their roles and limit their rights in northern Uganda. In general, agriculture research should take a more context-specific approach given the complexity and heterogeneity within farming systems in Uganda and beyond.

The FarmDESIGN whole farm model generated practical alternatives that can be explored by low and high-resourced smallholders to improve agricultural productivity and livelihoods. The intercropping of pigeon pea with cereals is recommended for its BNF benefits, together with the use of locally available organic residues such as compost and livestock feed. The complementarity between crops and livestock for smallholder farmers cannot be understated. Moreover, our study showed that many smallholders leave much of the land under fallow. More research on the underlying reasons for fallowing, such as understanding the land tenure system and on how smallholders can make (better) use of the land under fallow in a sustainable way is recommended.

This study had limitations. The use of data from a cross-sectional survey is usually faced with selection bias, a problem discussed in the context of the econometric model in Chapter 2. Further, the COVID-19 outbreak at the time of carrying out field work in northern Uganda made data collection particularly difficult and sometimes near impossible due to the strict pandemic-related restrictions in Uganda.

Future research should broaden the scope and should also consider other farming systems in Uganda and provide further contextual analysis for targeted programs. Since farming systems are dynamic, the application of a static FarmDESIGN model has its shortcomings. Future research could explore use of dynamic models such as agent-based modelling. In our research, we focused on four objectives in FarmDESIGN; SOM balance, nitrogen balance, household budget and labour balance. Future studies should include other modules, for example ‘*nutrition*’, to provide better understanding of the household nutrition and dietary diversity for different smallholder farm types. Overall, approaches should address the different farm types as well as on-farm diversity and put more emphasis on flexible technological and social components for the different contexts in which members of smallholder farms live and operate.

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Appendix A

Table A 3.1: Description of variables used to cluster smallholders in Northern Uganda

Variable	Description	Unit
Household-related characteristics		
Age	Age of respondent	Years
Family size	Number of people living under the same roof	Number
Education level	Number of years in school for household head	Years
Farming experience	Farming experience (respondent)	Years
Household farm assets		Acre
Average monthly income	Average monthly income, both farm and off-farm	USD
Total land owned	Total land owned by the household	Hectares
Value of farm assets	Monetary value of farm assets owned for 2019	USD
Proportion of land: crop production	Proportion of the total land allocated to crop production	Percentage
Proportion of land: livestock production	Proportion of the total land allocated to livestock production	Percentage
TLUs	Total livestock units (TLUs)	Units
Livestock value	Monetary value of livestock as at October 2019	USD
Pigeon pea related attributes		
Proportion of pigeon pea sold	Proportion of pigeon pea sold for 2019	Percentage
Pigeon pea acreage	Total land used for pigeon pea production	Hectares
Quantity of Pigeon pea produced	Quantity of pigeon pea produced (2019 harvest)	Kilogram
Intercropped pigeon pea	Whether farmer intercropped pigeon pea or otherwise	Dummy; 1=intercropped, 0 =otherwise
Number of years growing pigeon pea	Number of years for growing pigeon pea in the household	Years

Note: Tropical Livestock Unit (TLU) conversion: cattle=1, goats, sheep and pigs=0.1, donkeys=0.5, oxen=1.42, chicken, turkeys, ducks and guinea fowls=0.01, rabbits=0.02 (Jahnke, 1982). USD is United States dollars.

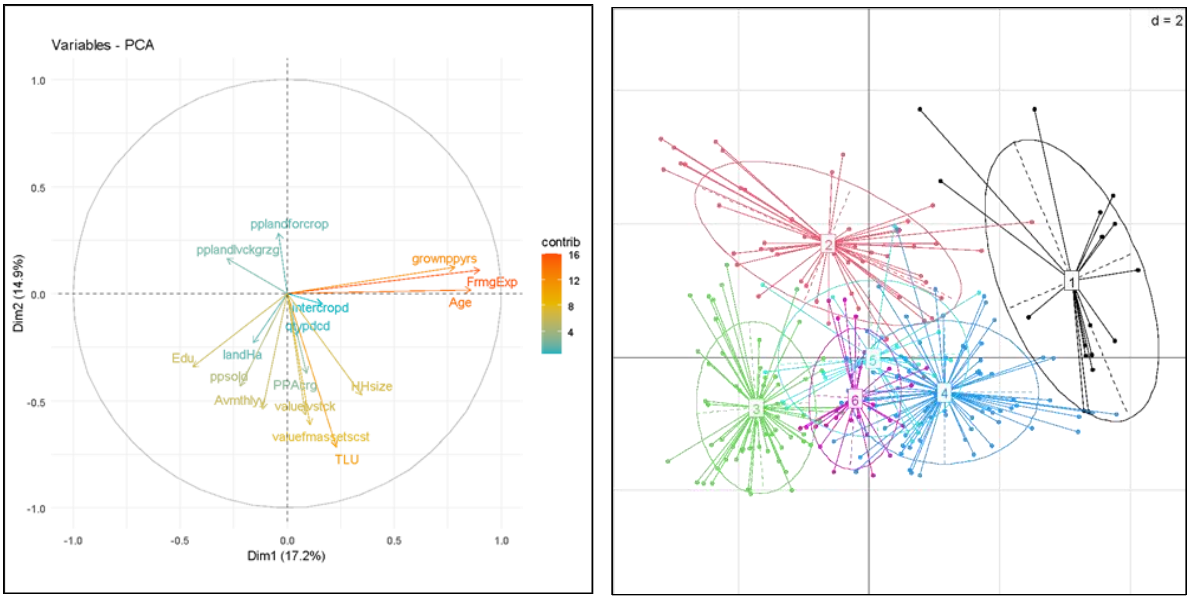


Figure A3.1: PCA and CA output (PC1-PC2), correlation circles and scatter plot along the first two principal components. The directions and lengths of arrows within the circles show the strengths of correlations between variables and PCs. Each smallholder is connected to its individual cluster mean with a line.

Table A3.2: Selected principal components, loadings, Eigenvalues and variance from principal component analysis

Variables	Correlations between each variable and the principal components					
	PC1	PC2	PC3	PC4	PC5	PC6
Age	0.86	0.02	-0.12	-0.19	0.01	0.06
Family size	0.35	-0.47	0.19	0.27	0	-0.01
Education level	-0.44	-0.34	0.09	-0.42	-0.11	0.04
Farming experience	0.9	0.11	-0.14	-0.15	-0.01	-0.02
Average monthly income	-0.15	-0.54	0.11	-0.27	0.02	-0.14
Total land owned	-0.18	-0.23	-0.74	0.1	0.27	-0.17
Value of farm assets	0.07	-0.61	-0.08	-0.09	-0.37	-0.06
Proportion of land: crop production	-0.02	0.28	0.67	-0.13	-0.19	-0.15
Proportion of land: livestock production	-0.27	0.16	-0.62	0.04	-0.39	-0.03
Livestock value	0.09	-0.57	-0.03	0.29	-0.29	0.14
TLUs	0.23	-0.72	0.05	0.06	-0.26	0.01
Pigeon pea acreage	0.06	-0.37	-0.12	-0.09	0.63	-0.09
Proportion of pigeon pea sold	-0.25	-0.43	0.19	-0.27	0.34	0.44
Quantity of pigeon pea produced	0.04	-0.19	0.22	0.12	0.12	-0.82
Intercropped pigeon pea	0.16	-0.05	0.24	0.69	0.18	0.23

Numbers of years growing pigeon pea	0.79	0.12	-0.05	-0.24	-0.02	0.03
Eigenvalue	2.75	2.39	1.64	1.14	1.10	1.02
Variance explained (%)	17.2	14.9	10.3	7.1	6.9	6.4
Cumulative variance (%)	17.2	32.1	42.4	49.5	56.4	62.8

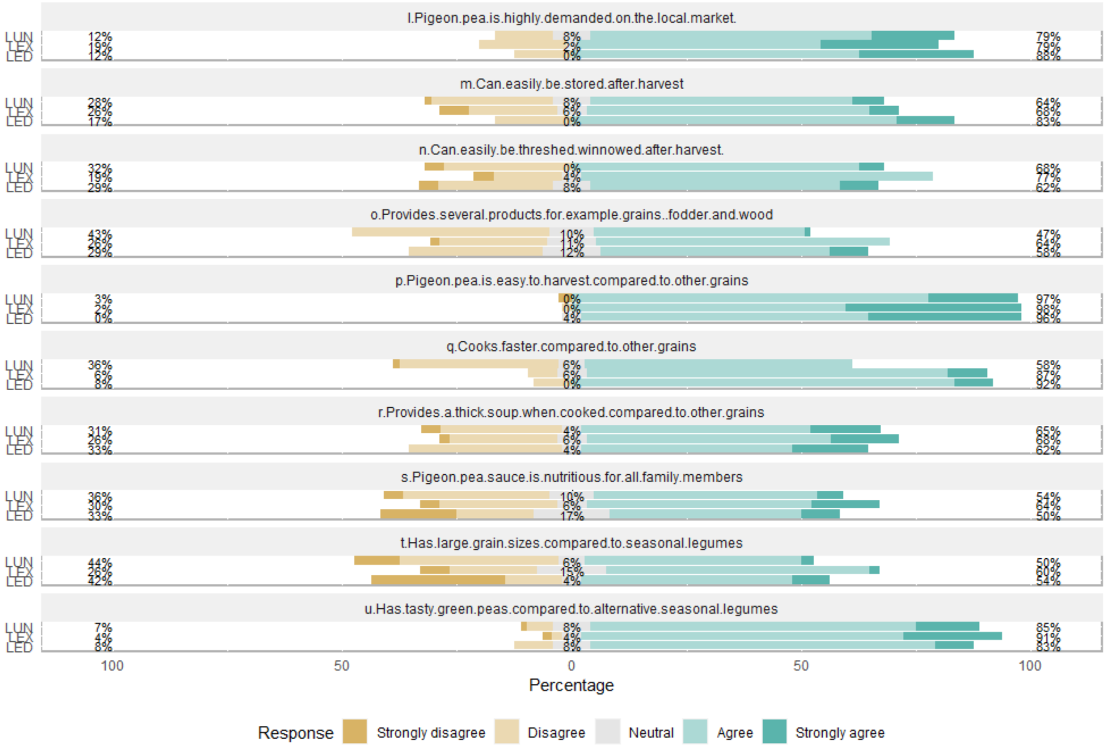
Source: survey data 2019. Factor loadings of > 0.400 show high correlations between selected variables and principal components.

Table A3.3: Variable mean that characterize the partitioning of the six different farmer types

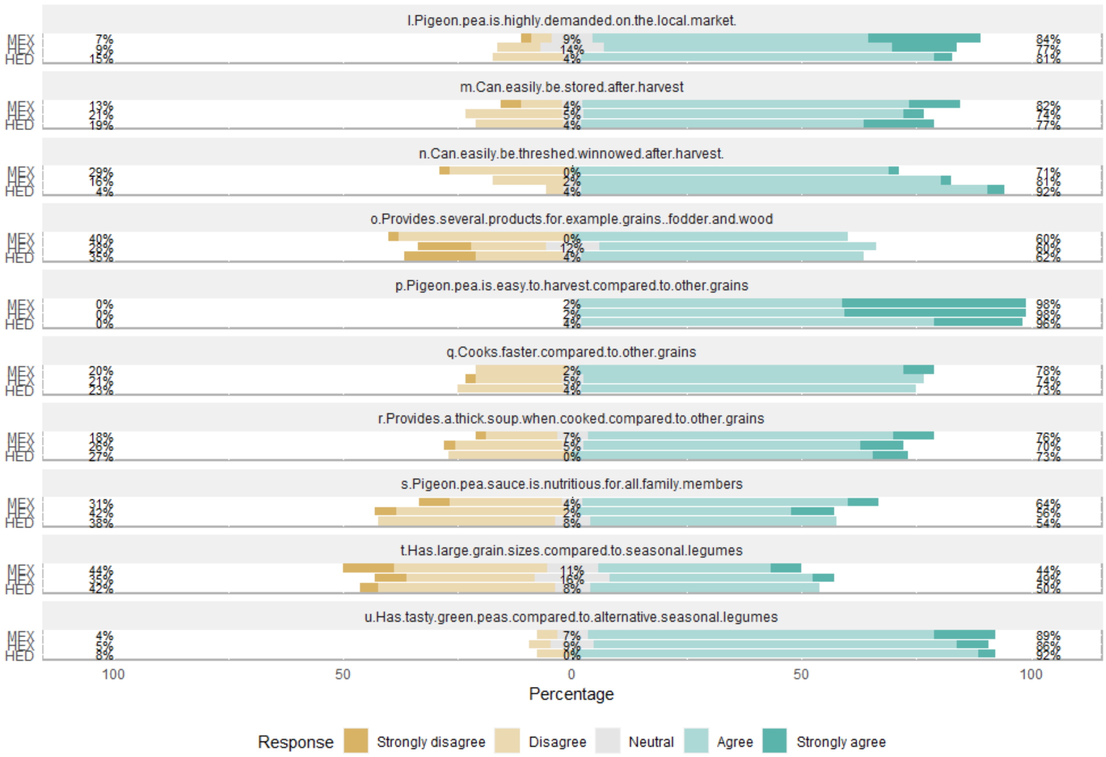
Resource category	Low	High	Low	Medium	High	Low	
Variables	LEX	HEX	LED	MEX	HED	LUN	*P- value*
Age	57.88[a]	38.53[d]	29.55[d]	48.26[b]	42.75[c]	38.22[c]	0.001
Family size	5.24[a]	6.75[b]	5.27[b]	7.97[a]	10.05[a]	6.89[a]	0.001
Education level	3.53[c]	5.53[ab]	7.69[ab]	4.04[bc]	6.8[a]	3.1[c]	0.001
Farming experience	44.47[a]	18.73[de]	8.68[e]	29.62[b]	18.1[cd]	16.61[c]	0.001
Average monthly income⧫	11.18[b]	21.76 [b]	26.56 [ab]	21.03 [ab]	32.77 [a]	10.98 [b]	0.001
Land owned	2.92[b]	6.36[a]	1.59[b]	1.34[a]	2.38[b]	1.12[b]	0.001
Value of farm assets	18.43[b]	33.27[bc]	22.24[c]	34.64[ab]	49.34[a]	15.22[bc]	0.001
Proportion of land: crop production	54.86[a]	43.96[b]	74.28[a]	71.11[b]	49.11[b]	72.96[a]	0.001
Proportion of land: livestock grazing	11.83[b]	20.52[a]	9.88[b]	5.86[b]	8.3[b]	10.86[b]	0.001
TLUs	2.54[b]	3.34[bc]	2.19[c]	3.69[b]	10.22[a]	1.13[bc]	0.001
Livestock value	23.77[b]	77.05[b]	35.35[b]	37.98[b]	324.03[a]	10.72[b]	0.001
Pigeon pea acreage	0.64[bc]	0.75[c]	0.42[c]	0.58[a]	0.83[ab]	0.36[c]	0.001
Quantity of pigeon pea produced per ha	355.9[b]	374.7[b]	364.3[b]	401.6[b]	475.9[ab]	327.2[a]	0.001
Proportion of pigeon pea sold	13.29[d]	26.79[cd]	39.62[ab]	24.64[bc]	54.31[a]	11.64[d]	0.001
Number of years growing pigeon pea	38.76[a]	9.78[c]	5.48[c]	18.35[b]	10.2[bc]	7.89[bc]	0.001

Survey results- 2019: Means followed by the same superscript letter in the same row are not significantly different by HSD-test at the 5% level of significance. HSD = Tukey's honestly significant difference test. LEX, LED and LUN refer to low resource endowed and experienced, educated and unexperienced, whereas MEX refers to medium resourced and experienced, HED and HEX refer to high resource endowed and educated or experienced. ⧫ The total monthly income indicator was calculated as the sum of off-farm income and on-farm income generated from crop and livestock sales. Farm product sales were calculated from local prices, retrieved at the time of the survey.

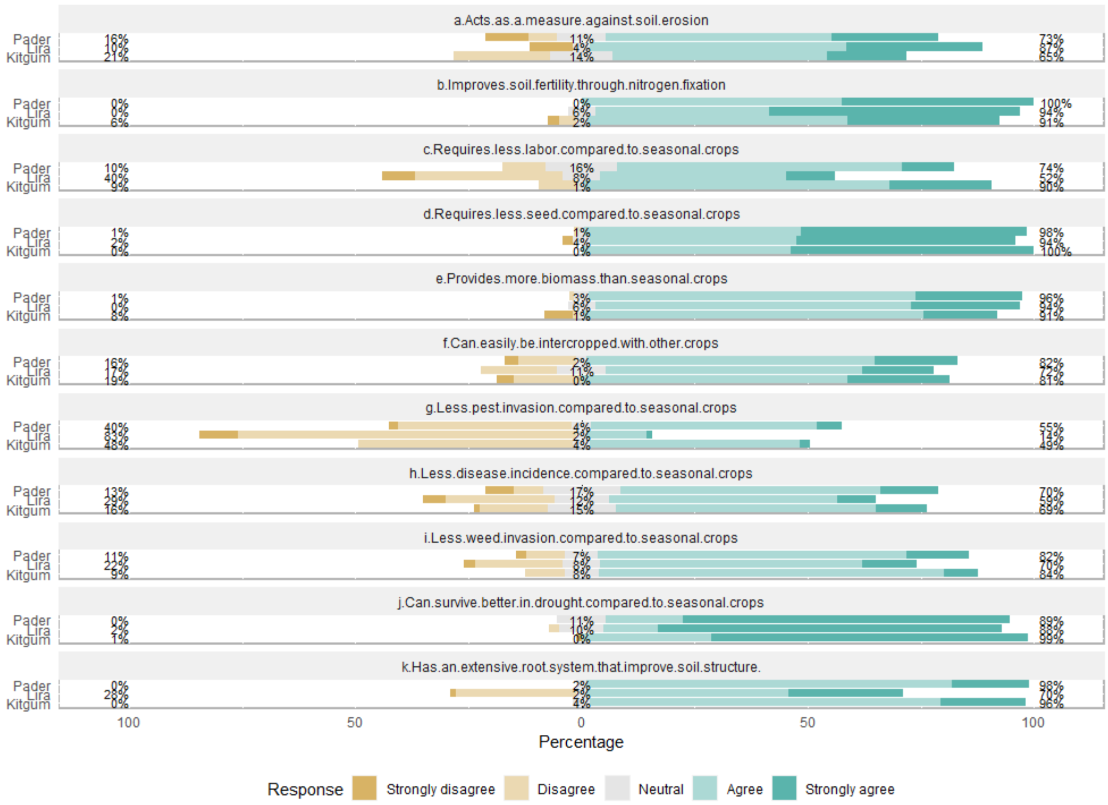
A. Pigeon pea processing, marketing and consumption attributes by resource type: LUN, LEX & LED



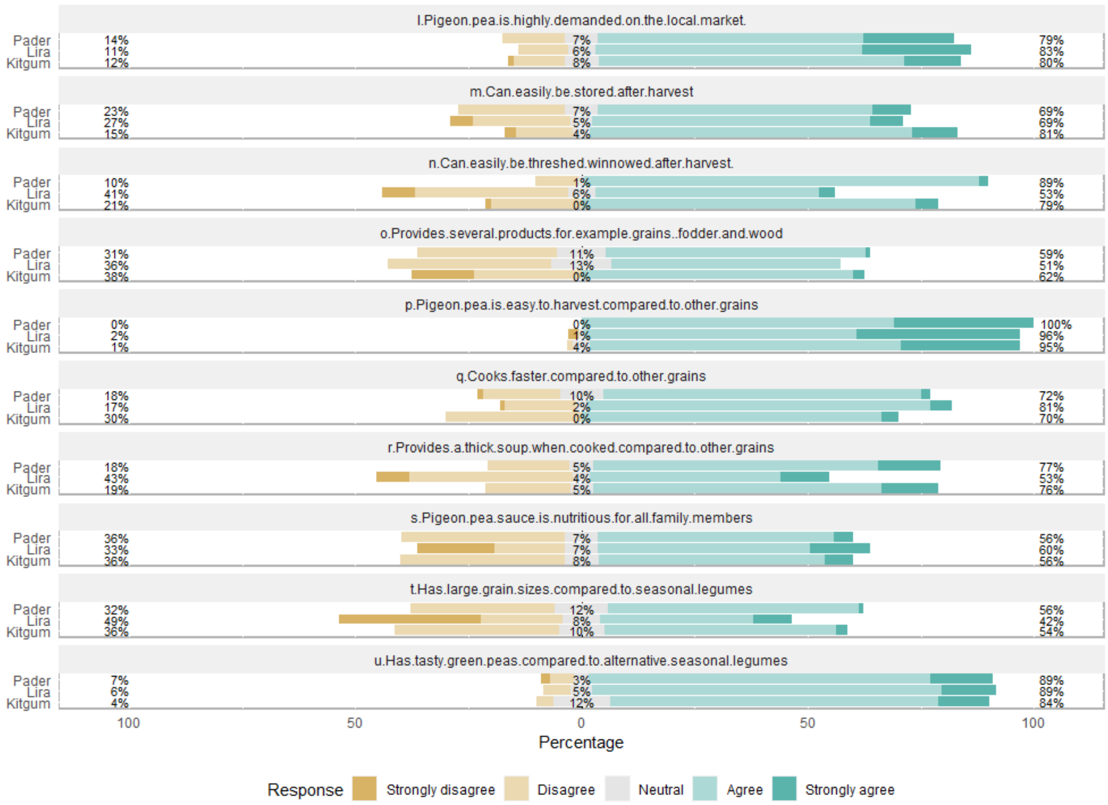
C. Pigeon pea processing, marketing and consumption attributes by resource type: MEX, HEX & HED

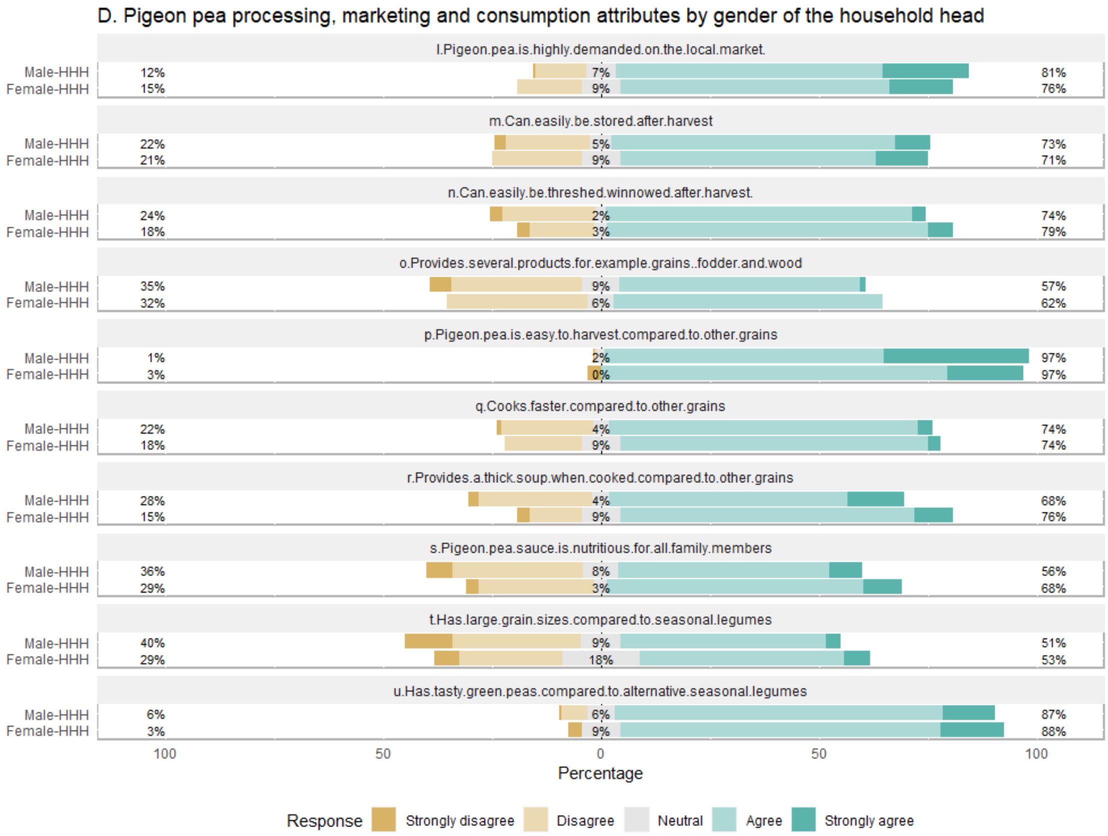


A. Pigeon pea production attributes by District



B. Pigeon pea processing, marketing and consumption attributes by District





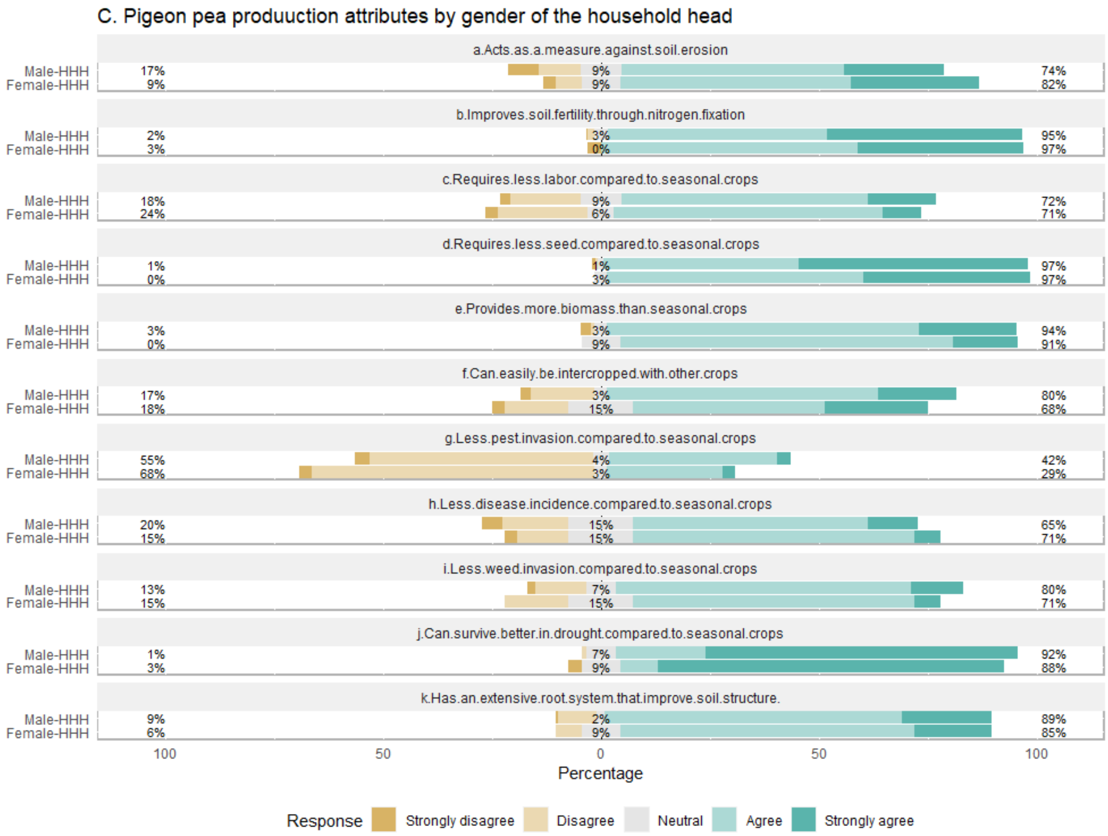


Figure A3.2 (A-D): Smallholders' perceptions of pigeon pea (the sample size was 257). Likert type rate; 1=strongly disagree, 2=disagree, 3=neutral, 4=agree and 5=strongly agree. The percentage on the left side indicate the share of respondents answering with

1 or 2 on the Likert scale. The percentage in the middle indicate the share of smallholders answering with 3 (neutral) on the Likert scale. The percentages on the right side indicate the share of smallholders answering with 4 or 5 (agreement) on the Likert scale. Pigeon pea production, processing, marketing and consumption attributes by district and gender of smallholder.

Table A4.1: Characteristics for the low-resourced farm (LRF) and high-resourced farm (HRF), northern Uganda

Characteristic	**Low–resourced**	**High-resourced**
Location	Lira District	Kitgum District
Sub-county	Barr	Mucwini
Household size	9	7
Cropped area (Ha)	2	2.5
Livestock units (TLU)	4.7	4.7
Pigs (Number)	2	2
Cows (Number)	2	0
Goat Number	5	5
Farm Area (ha)	2.9	3.8
		0

Table A4.2: Model parameters for the case study low resourced farm (LRF), Lira district, northern Uganda

	Original	**Minimum**	**Maximum**
Decision Variable			
Pigeon pea Cassava bean area (ha)	0.8	0	2
Pigeon pea-cassava-beans-Maize-Area (ha)	0.5	0	2
Pigeon pea-cassava-beans-Sorghum-Area (ha)	0.5	0	1
Pigeon pea-cassava-beans-Millet-Area (ha)	0.5	0	1
Pigeon pea for home consumption (kg)	20	0	50
Pigs Number	2	0	4
Goat Number	5	0	8
Ox Number	1	0	2
Milk cows Number	2	0	5
Hired Casual Labor (hr year $^{-1}$)	30	0	100
Hired Regular Labor (hr year $^{-1}$)	30	0	100
Constraints			
Farm Area (ha)	2.9	2.8	2.9
Livestock units	4.7	0	10
DM intake deviation, grazing period (%)	3.1	0	30
Energy deviation, grazing period (%)	5.4	0	30
N soil losses (kg ha $^{-1}$ year $^{-1}$)	35.5	0	999
P soil losses (kg ha $^{-1}$ year $^{-1}$)	-2.87	-10	999
K soil losses (kg ha $^{-1}$ year $^{-1}$)	16.83	0	999
Leisure time (hr^{1} year $^{-1}$)	2904	0	9999
Econmic profit (USD year $^{-1}$)	51.65	-9999	9999

Table A4.3: Model parameters for the case study high resourced farm (HRF), northern Uganda

	Original	Minimum	Maximum
Decision Variable			
Pigeon-pea Cassava bean area (ha)	0.8	0	2
Pigeon pea-cassava-beans-Maize-Area (ha)	0.7	0	2
Pigeon pea-cassava-beans-Sorghum-Area (ha)	0.7	0	2
Pigeon pea-cassava-beans-Millet-Area (ha)	0.6	0	1
Pigeon pea for home consumption (kg)	20	0	50
Pigs.Number	2	0	10
Goat Number	5	0	8
Ox Number	1	0	5
Milk cow Number	2	0	10
Hired Casual Labor (hr year $^{-1}$)	50	0	100
Hired Regular Labor (hr year $^{-1}$)	50	0	100
Constraints			
Farm Area (ha)	3.8	3.7	3.8
Livestock units	4.7	0	10
DM intake deviation, grazing period (%)	3.1	0	30
Energy deviation, grazing period (%)	5.4	0	30
N soil losses (kg ha $^{-1}$ year $^{-1}$)	21.67	0	999
P soil losses (kg ha $^{-1}$ year $^{-1}$)	-2.6	-10	999
K soil losses (kg ha $^{-1}$ year $^{-1}$)	11.51	0	999
Leisure time (hr^{1} year $^{-1}$)	2547	0	9999
Economic profit (USD year $^{-1}$	114.22	-9999	9999

Appendix B: Questionnaire used for data collection

Study to understand the role and contribution of pigeon pea mixed cropping systems for smallholders' food and livelihood security

Ethics statement

Dear respondent,

My name is ……………………………………………. We are conducting a survey on the above-mentioned topic in northern Uganda. The data we collect will only be used to generate recommendations to improve your livelihood situation. We hope that you will be free to provide true and accurate information. Please feel free to ask any questions or raise any issues you might have before, during or at the end of the interview. Do you agree to continue? YES…….. No………. (Use the consent form for signing).

PLEASE INTERVIEW HOUSEHOLDS THAT HAVE GROWN PIGEON PEA FOR MORE THAN TWO YEARS.

I. Identification/basic data

	Description	Name	Code
1	District		
2	Sub-county		
3	Parish		
4	Village		
5	Farmers' group name/association		
6	GPS coordinates	Xxxxxxx	
7	Enumerator details		
8	Respondent phone number	Phone contact:	
9	Questionnaire Number		ID #

SECTION A: SOCIO-DEMOGRAPHIC INFORMATION

	Respondent details (Household head/spouse)	**Code**
A1	Age (years)	
A2	Marital status	a) Married b) Single c) Widowed d) Divorced e) Other
A3	How many years of school did you attend?	
	Type of household	1) Male-headed 2) Female headed
A4	Main income-generating activity in the household Others	a. Crops production sales b. Livestock sales c. off farm labor d. e. others (specify)
A5	Number of years in farming: proxy for farming experience	

SECTION B1: Household roster

1	Please tell me who the members of your household Note are**:** A household is defined as persons regularly sharing meals and living in the same housing unit for the past 6 months. Start with the respondent him/herself.

Person ID (PID)	First Name	Sex 1=Male 0=Female	Relationship to household head [Rel. code below]	Age (years)	Years of education [Complete years
0					

Relationship code	
1. Household head	6. Brother/sister
2. Spouse	7. Nephew/niece
3. Son/Daughter	8. Cousins
4. Grandson/granddaughter	10. Other, specify:
5. Parent	

B2.1 How many years has your household lived here in this village continuously?	B2.2 Type of house/ dwelling? **[Don't ask directly, mark according to observation]** 1-Independent House 2-Tenement (Muzigo) 3-Independent flat/ apartment 4-Sharing house/ flat/apartment 5-Boys quarters 6- Garage 7- Hut 8- Uniport 99- Other, specify	B2.3 What is the main construction material used for the outside walls? 1- Thatch, straw 2- Mud and poles 3- Timber 4- Un-burnt bricks 5- Burnt bricks with mud 6- Burnt bricks with cement 7- Cement and blocks 8- Stone	B2.4 What is the main construction material of the floor of the dwelling? 1- Earth 2-Earth and cow dung 3-Cement 4-Mosaic or tiles 5-Bricks 6-Stone 7-Wood 8-Other, specify	2.5 What is the main construction material used for the roof of the dwelling? 1 Thatch, straw 2 Mud 3 Wood 4 Iron sheets 5 Asbestos 6 Tiles 7 Tin 8 Concrete/ Cement 9 Tarpaulin	B2.6 What type of toilet is mainly used by your household? 1.Covered pit latrine-private 2. Covered pit latrine-shared 3. VIP latrine-shared 4. Uncovered pit latrine 5. Flush toilet- private 6. Flush toilet- shared 7. Bush 99. Other, specify	

		99 - Other, specify		99 Other, specify		
	CODE	***CODE***	***CODE***		***CODE***	

	B2.8	***B2.9***	***B2.10***	***B2.11***	***B2.12***	***B2.13***
s e a s o n s	What is the principal source of lighting of the dwelling in [SEASON]? 1- Electricity from a Public Electric Company 2- Electricity from a Private Electric Plant 3- Electricity from a Generator 4- Solar Panels 5- Tadooba 6- Candle 7- Rechargeable lamp 8- Gas 9- Liquid fuel (kerosene, petrol) 10- Candle or battery powered source 11- Wood, sawdust or other natural material 12- None 99- Other, specify	What is the principal source of energy for cooking in [SEASON]? 1-Firewood 2-Dung 3. Crop residue 4. Kerosene 5. LP Gas 6. Charcoal 7. Solar 8. Electricity 99. -Other, specify	Do you use another energy source for cooking in [SEASON]? 1-Yes Continue to 3.14 2-No Next season	What is the other source? 1-Firewood 2-Dung 3. Crop residue 4. Kerosene 5. LP Gas 6. Charcoal 7. Solar 8. Electricity 99. Other, specify	**[If they respond 1 – firewood in 3.12 or 3.14, ask the following. If not, write "n/a" and continue with next season.]** How much time do household members spend in a day collecting and carrying firewood?	Who is responsible for collecting and carrying the firewood?
	CODES	CODES	CODES	CODES	**HOURS**	PIDs
Dry season						
Rainy season						

SECTION B2: Household land ownership for the past TWO years

2.1	**Land ownership**	***Acres (Convert to acres)***
	What is the total land owned?	

	How much land is rented in by the HH?	
	How many acres are used for crop?	
	How many acres are used for agroforestry	
	How many acres are used for grazing livestock?	
	HH has access to communal land	(1-yes, 0-No)
	If yes, how many acres?	
	If yes, for what purposes?	
	Do you rent part of your land	1-yes, 0-No
0	If yes, how many acres?	
1	Does your household have any parcel that was inherited?	1-yes, 0-No
2	If yes, how many acres?	
3	Does your household have any parcel that was rented?	
4	If yes, how many acres?	
5		
2	If bought, do you have a document to show ownership?	1. Yes 0. No
3	If yes, what type of document do you have?	1. Title 2. Agreement 3. Others (specify)

SECTION B3: Cropping patterns and pigeon pea varieties grown (Define a plot: local dimensions used)

B3.1	For how long have you cultivated pigeon pea in this household? Years	
B3.2	What varieties of pigeon pea have you grown in the last one year? (1- Improved seed, 0-Local seed) List variety names	
B3.3	Where did you get/buy the seed from? 1. Input Dealer 2. Local seed traders/ retailers 3. Friend/neighbor 4. Extension worker 5. NGOs 99. Others: Specify	
B3.4	Distance to seed source (Kms)	
B3.5	*Is pigeon pea grown for commercial or subsistence purposes?*	*1) commercial* *2) Subsistence*
B3.6	Under what cropping system do you grow the **pigeon peas**?	*1. Mixed/intercrop* *2. Single crop*
B3.7	If intercropped, which crops do you intercrop with **pigeon peas**? 1=Green gram, 2=groundnuts, 3=millet, 4=soybean,5=simsim,6=cassava, 7=sweet potato, 8=rice, 9=Maize, 10=Other specify	*1. Green gram* *2. Groundnuts* *3. Millet* *4. Soybean* *5. Sim sim* *6. Cassava* *7. Sweet potato* *8. Rice* *9. Maize* *99 others (specify)*

B3.8	*Who* from your household is taking care and managing the pigeon pea plot or plots?	*Write the household members (PID):*
B3.9	*How much land was allocated to pigeon pea in the last 12 months ………(acres)*	*Plot IDs and acreage* *1.*
B4.1	What area of land was allocated to pigeon pea in the last one year? (August 2018A- Sept 2019B) (convert into acres)	*Write the area of land (acres):*
B4.2	*Who mainly manages the Pigeon pea plots (s) in this household?*	

B4.3 Apart from pigeon pea, which other seasonal crops do you grow?

Crop	Tick	If yes, how many acres were used to grow this crop in the last 12 months?
Sorghum		
Millet		
Maize		
Beans		
Rice (upland)		
Soybeans		
Groundnuts		
Cassava		
Sweet potatoes		
Vegetables		
Simsim		
Green gram		
Cow peas		
Other (specify)		
Other (specify)		

B4.4	In relation to sorghum? For how many years have grown it?
B4.5	If sorghum is grown? is it grown as an annual, semi-annual or perennial sorghum? 1. Annual/seasonal 2. Semi-annual 3. Perennial sorghum
B4.6	In relation to B1.8, how long have you grown the choice chosen above? (years/seasons)
B4.7	What are the 3 main benefits with regards to your sorghum production?
B4.8	What are the 3 main problems with regards to sorghum production?
B4.9	Have you or any member of your household ever received any agricultural training? (1= yes, 0= No) **If No, skip to C2**

B5.1	*If YES,* Who received the training, when, from which organization and what was the content? *Write down the answers*

Who from HH received the training (PID)	**Organization** provided the training (Name)	**When** the training was delivered (Year/Month)	**How long was** the training course given (/days)	**What was the main** content of the training?	**Follow up visit/event from the organization** (1=yes, 0=no)

B5.2	What farming techniques were you/or your family members trained in? **list**

SECTION B6: Plot sizes per crop grown in the last season (SEASON A 2019) ***(Refer to question C1.6)--- Start with the pigeon pea plots***

Specify for the different plots your household is cultivating (Plot IDs)	Land Size (total area in acres)	Crop (s) currently cultivated on the plot for season B 2019? (use codes)[1]	Who is mainly responsible for this plot? (PID)	Harvests from last season (KG)	Proportion used for food (KG)	Proportion given away (as a gift)-KG	Proportion sold (KG)	At what price per KG?	Total revenue from sales (UGX)
Plot 1									
Plot 2									
Plot 3									
Plot 4									
Plot 5									
Plot 6									
Plot 7									
Plot 8									
Plot 9									
Plot 10									

[1] *Codes 1 Pigeon pea 2 Sorghum 3 Millet 4 Maize 5 Beans 6 Rice 7 Soybeans 8 Groundnuts 9 Cassava 10 Sweet potatoes 11 Vegetables 12 Green gram 13 Cowpeas 99 Others (Specify)*

SECTION B7: Decision making and control over resources

	Crop	Who <u>mainly</u> manages the production of the crop? *a) Male adult b) Female adult c) Youths (15-35yrs) d) Children*	Who <u>mainly</u> receives income from sales (Use codes)	Who controls household consumption of this crop? (Use codes[2])
1	Pigeon pea			
2	Sorghum			
3	Millet			
4	Maize			
5	Beans			
6	Groundnuts			
99	Other (specify)			

SECTION B8: How do you assess the soil fertility on the different plots?

	Plot type	Very good (5)	Good (4)	Medium (3)	Poor (2)	Very poor (1)
1	Inter-cropped plot					
2	Legume-only (pigeon pea only)					
3	Cereal-only					
4	Forested land					
5	Fallow					
6						

SECTION B9: On-farm evaluations of pest and diseases management in pigeon pea plots (2018B and 2019A seasons)

1. Any incidence of pests and diseases for pigeon pea?	**2. Yes 0. No (if no, skip to section C)**
2. If yes, what pests/ diseases (list)	
3. If yes, what remedies did you employ? (list)	
4. If any synthetic chemicals were used, which ones? (list)	
5. How much was the cost of the remedy in UGX? (last two seasons)	
4. If yes, where did you purchase the chemicals from? ***(Do not read out the answers)***	

Category	*Tick*	*Distance to location (km)*	
1. Agro-Input Dealer			
2. Local traders/ retailers			
3. Friend/neighbour			
4. Extension worker/NGO			
99. Others: Specify			

5. Was the remedy a success in controlling the disease or pest**?**		**1. Yes 0. No**			
6.If no, why?					

SECTION C: Pigeon pea details: seed, credit/financial and agricultural extension access

	Male	**Female**	**Both**	**Others**
C1. Who in your household decides on the pigeon pea seed to plant?	1=Yes 0=No	1=Yes 0=No	1=Yes 0=No	1 = Y e s 0=No

C2. What proportion of your pigeon pea seed did you buy vs what you had saved last year? Percentage bought? Also record the Kilograms.

1. --------% bought
2. ___________%_home saved

-------kgs bought, ---------------------kgs saved.

C2.2. *If bought,* What are the sources you purchased/ obtained the seeds from? ***(Do not read out the answers)***

Category	***Check all that apply***	
1. Agro-Input Dealer		
2. Local seed traders/ retailers		
3. Friend/neighbour		
4. Extension worker		
5. NGOs		
99. Others: Specify		

C3. In reference to table B3: you said that you sold _______kg of pigeon pea last season. Where did you sell it? ***(Do not read out the answers)***

Category	***Total kg sold***	
1. At the farm gate		
2. Village collectors/traders		
3. Directly at local market		
4. Directly at urban market		
5. Directly to restaurants/ hotels		
99. Others (Specify)		

4. Did you use agricultural extension in the last 12 MONTHS? 1=Yes 0=No _________

If yes, please fill out the table below for contact with an agricultural extension person (tick)

Who MAINLY provided the agricultural extension?	How was the extension service administered? 1.Group 2.Individual	How frequent did the agent contact you in the last 12 MONTHS	Distance to place of extension (if home, then distance is zero)	Was the information from the extension agent USEFUL for your pigeon pea production activity?	Did you have to pay for the extension service visit?	What type of information was provided to you?	Were you satisfied with the quality of the extension service?
1.International Research Organization 2.Government extension officer/ Directorate of extension services 3.University 4.NGO/ project 5.Media (TV/Radio) 6.Extension agents from seed company 7.Extension agent private processing companies 8.stockiest 9.NaSARRI 99.Other:_________	1. Group 2. Individual	1. Once 2. Twice 3. Thrice 4. Four of more times	kms	1. Not at all 2. Not much useful 3. Useful 4. Very useful	=Yes =No	1. Land preparation 2. Input provision 3. Sowing 4.Disease/pest occur 5.Harvesting 6.Marketing 7. Credit collection 99. Other, specify	=Yes =No
	C5: Did you receive any market information regarding crop sales? 1=Yes 0=No _________						

D5. Do you know where you can get price and market information about your crop harvests?

1=Yes, 0=No

If yes, what were the sources of market information?	*Do not read out the answers*

Information source	Tick all that apply
1. Farmers	
2. Farmer field schools/ farmer association	
3. Neighbors/ friends,	
4. Seed companies	
5. Dealer (Seed, Fertilizer and pesticide)	
6. Government/ local agricultural office	
7. TV	
8. NARO/public extension (eg NgeZARDI-Lira)	
9. Radio	
10. Newspaper	
11. Internet	
12. Mobile phones (SMS/information apps)	
13. NGOs	
14. Grain traders	

99. Others (specify)
99. Others (specify)

C6. What was the frequency of contact over the last 12 MONTHS?	1. Regularly (at least every month) 2. Often (Every season) 3. Rarely (once a year)
C7. What were the means of market information exchange?	1. Demonstration 2. Training 3. Advise 4. Field day 5. Field visit 99. Others (specify)
C8. What types of market information where you provided with?	1. New technology: Variety, agronomic practices 2. Market information 99. Others (specify)

C9. Are you a member of any farmer group/association? (1=Yes, 0=No)

C10. If yes, who initiated the association? A) Farmer-initiated B) Non- farmer initiated

C11. What is the main goal/objective of the association?

C12. In which way do you benefit in being a member of any association

Category	*Tick all that applies*
1. Joint purchase of farm inputs	
2. Supporting each other in work peaks	
3. Organizing transport for produce	
4. Collective marketing	
5. Price negotiation	
6. Regularly exchange business information	
7. Share new knowledge about cultivation methods	
8. Share storage facilities	
9. Others: specify	
10. Others: specify	

C8. How is your produce mostly brought from the field to the homestead? (***Tick only one.***)	
	1. Baskets on foot
	2. Bicycle
	3. Hand cart/push truck
	4. Motor bike
	5. Pick-up truck
	6. Motorized tricycle
	100. Oxen
	8.Other (Specify)

C9. What is the type of packaging you use to transport your crop produce to the market? (***Tick only one?)***	1. Plastic Bag		
	2. Sacks		
	3. Baskets		
	6. Paper boxes/Cartons		
	7. Insulated boxes (for green grain pigeon peas)		
	99. Other (specify)		
	99. Other (Specify)		
C11. What type of storage facilities do you have/own? ***Tick all that apply***	1. None		
	2. Own storeroom at home		
	3. Use neighbors' storage		
	4. Rent/hire facilities		
	5. Use group/association facilities		
	6. Outside/roadside		
	99. Other (specify)		
	99. Other (specify)		
C12. Have you accessed any credit in the last **six months**	1. Yes 0. No		

C13. If No, what are the reasons for not receiving credit?	***Category***	***Tick all that applies***	
	1. Interest rate was too high		
	2. They did not offer the amount I needed		
	3. I did not have enough collateral security		
	4. I did not agree on the repayment terms		
	5. Too much bureaucracy		
	6. I feared I would not be able to repay		
	7. Being female/male (gender)		
	8. Bad experiences with the lender in the past		
	9. Not available in our locality		
	10. Borrowing is risky		
	99. Others (specify)		
	99. Others (specify)_______________________		

C14. If YES, what are the reasons for getting credit?	***Category***	***Tick all that applies***	
	1. Buy seeds		
	2. Buy fertilizer		
	3. Buy pesticides		
	4. Pay workers		
	5. Needed it to hire more land		
	6. Enhance crop production		
	7. Attend a farm training		
	8. Buy farm equipment		
	9. Buy livestock units		
	99. Other (specify)		
	99. Others (specify)_______________________		

C15. Whom did you get the credit from?	***Category***	***Tick all that applies***	
	1. Village lender		
	2. Micro-finance institution		
	3. Commercial bank		
	4. Village Savings and Loan Associations (VSLA)		
	5. Friend/relative/neighbor		
	6. Trader		
	7. NGOs		
	8. Seed company		
	99. Others (specify)		
	99. Others (specify)_______________________		

SECTION D: Perceived functions (social, economic, ecological) and beliefs about pigeon pea (Probe and tick where appropriate)

No.	Do you think pigeon pea provides the following social, economic and ecological benefits?	Strongly agree-5	Agree -4	Neutral-3	Disagree -2	Strongly disagree-1
1.1	Acts as a measure against soil erosion?					
1.2	Improves soil fertility through nitrogen fixation?					
1.3	Lead to less labor requirement compared to annual crops?					
1.4	Requires less seed compared to annual crops?					
1.5	provides more biomass than annual crops?					
1.6	Can easily be intercropped with other short-term cereals and legumes (mixtures)					
1.7	Less pest invasion?					
1.8	Less disease incidence?					
1.9	Less weed invasion?					
1.9.1	Can survive in drought seasons compared to annual crops (for example sorghum and millet)?					
1.9.2	Has extensive root systems thus improved soil structure?					
2.1	Highly demanded on the market?					
2.2	Can easily be stored?					
2.3	Easily shelled					
2.4	Demands a high price on the market?					
2.5	Provides several products for example grains, fodder, fuel wood etc?					
2.6	Leads to more income due to high demand?					
2.7	Is it easy to harvest compared to other grains?					
99	Others (specify)					
3.1	Does it cook faster compared to other grains?					
3.2	Does it have a thick soup when cooked compared to other grains?					
3.3	Is pigeon pea sauce nutritious for all family members?					
3.4	Large size of the grain					

3.5	Tasty green peas					
3.6	Short cooking time					
99	Others (specify)					

SECTION E: Labor allocation for family and hired labor: how much time is allocated by each of the different genders in the HH in relation to pigeon pea plots?

(J01_a) Plot ID (keep same order	J01_b) Sub Plot ID (keep same order	J02) Plot / location name	P01 Land preparation and planting									P02 Weeding						
			P01_1 What did you use for ploughing? .Animal traction (oxen) .Tractor .Hand/manual . other, specify………	P01_2 How many times was this [sub-PLOT] ploughed?	P01_3 Total family labor in person days			P01_4 Total hired labor in person days		P01_5 Planting method . Row planting . Broadcast . Both	P02_1 ow many times was this [sub-PLOT] weeded?	P02_2 Total family labor in person days			P02_3 Total hired labor in person days	
					Male	Female	Children	Male	Female			Male	Female	Children	Male	Female
									0	1	2	3	4	5	6	7

Continued …….

J01_a) Plot ID (keep same order	J01_b) ub Plot ID (keep	*J02) plot / location name*	P03. Fertilizer/ manure application			P04 Pruning/ratooning				
			P03_1 Method of fertilizer	P03_2 Total family labor in person days	P03_3 Total hired labor in person days	P04_0 Did you prune or ratoon your		P04_2 Method of pruning . Manual	P04_3 Total family labor in person days	P04_4 Total hired labor in person days

	same order		applicat ion . Manual . Knapsa ck Sprayer . Mecha nical sprayer . Others (specify)………	Male	Female	Children	Male	Female	pigeon pea? 0.No **(Go to next crop)** 1.Yes **(continue to P04_1)**		. Clippers . Other (specify)…………	Male	Female	Children	Male	Female
									0		1	2	3	4	5	

J01_a)	J01_b)	J02*)*	P03. Harvesting						P04 Threshing/winnowing							
lot ID (keep same order	ub Plot ID (keep same order	lot/ loca tion nam e	03_1 Method of harvesti ng . Manual . Combin e harvest er . Other (specify)………	P03_2 Total family labor in person days			P03_3 Total hired labor in person days		P04_0 s pigeon pea threshable ? 0.No **(Go next activity)** 1.Yes **(continue to P04_1)**	P04 _1 as cro p har vest thre she d? .No .Yes	P04_2 Method of threshing . Manual . winnower . Other (specify)…………	P04_3 Total family labor in person days			P04_4 Total hired labor in person days	
				Male	Female	Children	Male	Female				Male	Female	Children	Male	Female
									0		1	2	3	4	5	6

SECTION F: Profitability of the pigeon pea farming (reference to SEASON A 2019) in UGX

E1. Who **mainly** keeps a record of the income and expenditure in your household?	1. Husband 2. Wife 3. Youths 4. Children 5. Others (specify)

E2: Overall expenses incurred by the household in pigeon pea farming (reference to SEASON 2-18B and 2019A)-reference to Pigeon pea plots

	Expense	**Unit**	**Unit price-UGX**	**Quantity used per season**		**Total cost-**	Area to which input was applied **(acres)**
				2018B	**2019A**		
a	**Inorganic fertilizers**						
	DAP						
	NPK						
	CAN						
b	Organic manures						
c	Hired labor						
d	Hired land per season						
e	Family labor						
f	Home-saved seed						
g	Purchased seed (kgs)						
h	Hire of oxen						
i	Hire of ploughs						
j	Purchase of packaging/storage materials						
k	Transport costs to markets						
l	Extension services						
m	Trainings attended						
n	Use of banking services (credit/financial access)						
o	Irrigation costs per plot						
p	Ratooning cost						
99	**Other (specify)**						
99	**Other (specify)**						

Section G: Overall farm benefits/revenues (reference to SEASON 2019 A) in UGX- reference to Pigeon pea plots

	Revenue item	Unit (kg, baskets, etc): please record in kgs	Quantity in kgs (Convert to kgs)	Selling price per kg (UGX)	Total price (UGX)
1	Pigeon pea grain sales				
3	Pigeon pea post-harvest products sold				
4	Sale of leaves for animal fodder				
5	Sale of stalk for mulch				
6	Sale of pigeon pea sticks for firewood				

99	Other (specify)				
99	Other (specify)				

SECTION G: Farm and off-farm income, tools and machinery

G1.1 What is the household's average total monthly income (UGX)?...

G1.2 What are the other sources of income in the household (details in the table below)

	Income source	**Monthly average (UGX)**	**Who receives this in the household 1-M 2-F**	**Who spends the money? 1—M 2-F**	**Who makes the decision for spending (codes) in the HH?**
1	Salary				
2	Wage (casual labor payments)				
2	Remittances				
3	External support				
4	Social protection (government funds)				
5	livestock sales				
6	Pension income				
7	Crop sales				
8	Brick making				
9	Land rentals				
99	Others (specify)				
99	Others (specify)				

G1.3 Household expenditures: list the most important household expenditures in monthly average

	Expenditure item	Monthly average (UGX)	Who decides (M/F)	Any remarks?
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				

G1.3 What is the household's status of ownership of operational assets as listed below?

	Name	**Number**	**Owned**	**Rented**	**Rental cost/unit**	**Approx. value (UGX)**
1	Hand hoe					
2	Axe					
3	Panga					

4	Rake					
5	Gardening fork					
6	Shovel					
7	Winnower					
8	Wheelbarrow					
9	Watering can					
10	Knapsack sprayer					
11	Ox-plough					
12	Disc plough					
13	Sickle					
14	Harrow					
15	Yoke					
16	Power tiller					
17	Tractor					
18	Bicycle					
19	Motorbike					
20	Radio					
21	Solar panel					
99	Other (specify)					
99	Other (specify)					

SECTION G2: Livestock ownership, Households' ownership of livestock and value attached Resource endowments indicators (land ownership, TLU index, wealth proxy indicators, asset ownership)

	Name of livestock/animal **CODE**	Number of live animals /birds owned	Consumed some .Yes .No	Number sold	Amount sold(kg)	Average selling price (USh/unit)	Name of livestock product **CODE2**	Amount of product produced(kg /trays/litres)	Consumed some product? (**Codes 2**	Amount sold(kg)	Average selling price (USh/unit)	Amount consumed (kg)

Code 1: 1-Cows, 2- Pigs 3-Goats 4-Chicken 5-Duck 6-Sheep 7- Oxen 8-Rabbits 9 Duck 10-Donkey 99-Other (specify). Code 2: 1-Eggs 2- Pork 3-Milk 4-Meat 5-Beef 6-others

SECTION H1: Opportunities and challenges faced with growing pigeon pea or long-term perennial crops

	List up to 5 major opportunities	List up to 5 major challenges/ constraints
1		
2		
3		
4		
5		
6		
7		

Any questions or clarifications concerning this interview?

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