Integrating legumes in mixed crop-livestock systems in east Africa: Farmers' perceptions, ecosystem services and support for decision making

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Cover: Maize/common bean intercrop with *Calliandra* hedgerow in runoff experiment in Rongo, Kenya
(photo: T. Muoni)

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Abstract

Challenges faced by smallholder farmers in east Africa include limited access to inputs, small farm sizes, and erratic rainfall patterns. Legume intensification and species diversification have been recommended for improving food and nutritional security, controlling soil erosion, improving soil fertility, supplying income and providing fuel. The aim of the thesis was to assess the various contributions legumes make in integrated crop-livestock systems and to facilitate their efficient use. The approaches used included: 1) an on-farm survey of 268 farmers in Kenya and Democratic Republic of the Congo to assess farmers' perceptions of legumes and their functions; 2) a meta-analysis on the effects of crop management practices on legume productivity and biological nitrogen fixation (BNF) in sub-Saharan Africa; 3) an on-farm experiment in Kenya investigating the effects of crops and crop mixtures including legumes on soil erosion control; and 4) providing inputs from literature review and experimental results to further develop the LegumeCHOICE decision support tool. Results showed that farmers appreciated legumes more for their food and income functions than for provision of fodder, fuel, soil fertility or erosion control. Furthermore, according to survey work, the concept of "legumes" had little meaning for farmers. The meta-analysis showed that crop management practices directly influenced legume productivity. Intercropping increased the total land equivalent ratio (LER). Focusing on the legume component, pigeon pea (*Cajanus cajan*) had a relative LER of 90%, while for species such as groundnut (*Arachis hypogea)* and common bean (*Phaseolus vulgaris*) the figure was around 60%. Inoculation and phosphorus (P) application increased legume grain and biomass yield, and species and soil type helped explain the variation of legume productivity in response to those management practices. Inoculation also increased the amount of nitrogen (N) fixed by legumes. Experimental work showed that incorporating different crop types and crop mixtures with legumes increased rainfall infiltration and earthworm population, and reduced runoff and soil erosion. *Calliandra* hedgerows, mulching and sole Mucuna reduced soil erosion and runoff more than maize/common bean intercropping. Developing literature-derived values as a complement to the expert scores, which presently underlie the LegumeCHOICE tool improved the relationships between the scoring and actual provision of food, livestock feed and soil fertility improvement using grain and biomass yield and BNF as proxies. This thesis shows that farmers in east Africa have some knowledge about legumes although their perception of the various functions legumes provide is limited. Despite heterogeneity of smallholder farming systems, legumes respond consistently to intercropping, inoculation and P-application. Combining literature values with expert scores enhanced the validity of the LegumeCHOICE tool for supporting farmer decision making.

Keywords: grain legume, herbaceous legume, intercropping, soil erosion, sustainable intensification, tree legume

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Dedication

To my parents Langton and Respina Muoni. Mom, I will always love you for all your prayers and unconditional love.

Murimi munhu
Oliver Mutukudzi

Contents

List of publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I. Muoni T.*, Barnes A.P., Öborn I., Watson C.A., Bergkvist G., Shiluli M., Duncan A.J. (2019). Farmer perceptions of legumes and their functions in smallholder farming systems in east Africa. *International Journal of Agricultural Sustainability*, 17 (3), pp. 205-218.

II. Muoni T., Jonsson M., Öborn I., Watson C.A., Bergkvist G., Barnes A.P., Duncan A.J. Effects of management practices on legume productivity in smallholder farming systems in sub-Saharan Africa: A meta-analysis (manuscript).

III. Muoni T.*, Koomson E., Öborn I., Marohn C., Watson C.A, Bergkvist G., Barnes A. P., Cadisch G., Duncan A.J. (2019). Reducing soil erosion in smallholder farming systems in east Africa through the introduction of different crop types. *Experimental Agriculture (in press).*

IV. Muoni T, Öborn I., Duncan A.J., Matching choice of legumes with farmer needs to support decision making – the LegumeCHOICE tool (manuscript)

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The contribution of Tarirai Muoni to the papers included in this thesis was as follows:

I. Planned the study together with co-authors. Conducted data collection, entry and analysis with guidance from supervisors. Wrote the manuscript together with co-authors.

II. Planned the study together with co-authors. Conducted literature search, data extraction and analysis with guidance from co-authors. Wrote the manuscript together with co-authors.

III. Planned the study together with co-authors. Performed field work together with the second author and conducted data collection and analysis with guidance from co-authors. Wrote the manuscript together with co-authors.

IV. Planned the study together with co-authors. Conducted literature search, data collection and analysis with guidance from co-authors. Wrote the manuscript together with co-authors.

List of tables

List of figures

Abbreviations

Avail	available
BD	Bulk density
BNF	Biological nitrogen fixation
CAN	Calcium ammonium nitrate
C:N	Carbon to nitrogen ratio
DAP	Diammonium nitrate
DRC	Democratic Republic of the Congo
ha	Hectare
K	potassium
kg	kilo gram
LSD	Least significant differences
N	Nitrogen
NS	Not significant
Org C	Organic carbon
P	Phosphorus
p-value	Probability value
SSA	Sub-Saharan Africa
t	tonne
TLU	Tropical livestock unit

1 Introduction

More than 45% of land in Africa is affected by desertification and approximately 55% of that land is vulnerable to further degradation due to factors including deforestation to meet fuel and food demands (ELD Initiative & UNEP, 2015). Most farmers in east Africa farm less than 2 ha of land and the increasing demand for food and fuel, due to population growth, in combination with low incomes among consumers makes it challenging for them to produce enough food and income to sustain their farms (United Nations, 2019; Rapsomanikis, 2015). Much of east Africa receives rainfall in a bimodal pattern and many farmers depend on natural rainfall for productivity (Biazin *et al.*, 2012; Yang *et al.*, 2015). The rainfall patterns are affected by climate change and are now often characterised by long mid-season dry spells which reduce crop yields (Serdeczny *et al.*, 2017). Also, poor soil fertility that is common in the region, accompanied by low fertiliser use is resulting in significant yield gaps (Barron *et al.*, 2003; Vanlauwe & Giller, 2006). Low fertiliser use results in crops that are deficient in major nutrients including nitrogen (N), phosphorus (P) and potassium (K) (Bekunda *et al.*, 2002; Druilhe & Barreiro-Hurlé, 2012). Thus, food and nutrition insecurity remain a key challenge in east Africa and many people remain in hunger and poverty (FAO & ECA, 2018).

Many farmers in east Africa practice integrated crop and livestock farming (Herrero *et al.*, 2010). In these systems livestock are a source of food, income, manure, as well as draft power; crops provide food, income and livestock feed from crop residues (Rufino *et al.*, 2009; Archimède *et al.*, 2014; Tittonell *et al.*, 2015). Although these farming systems have great potential, productivity of both livestock and crops is below their potential. Thus, sustainable intensification methods have been suggested to boost productivity. These include increasing crop diversity by introducing legumes with multiple functions, utilising both cropping seasons, increasing fertiliser use, applying climate smart agricultural practices to cope with moisture scarcity and creating conducive markets (Pretty *et al.*, 2011; Vanlauwe *et al.*, 2014; Tadele, 2017). Several studies have shown that incorporating legumes and using them effectively in smallholder farming systems have potential to increase productivity, e.g. Chikowo *et al.*, (2007) and Snapp *et al.*, (2018).

Legumes have been grown in east Africa for a long time, especially grain legumes. Their biological nitrogen fixation (BNF) characteristic which involves rhizobium bacteria helps increase soil N (Giller & Cadisch, 1995). Biological nitrogen fixation is higher in soils low in N, thus this trait is especially suitable or effective in such conditions (Murray *et al.*, 2016). Some legumes, including Mucuna (*Mucuna pruriens* L.), cowpea (*Vigna unguiculata* L.) and jack bean (*Canavalia ensiformis* L.) have fast growth rates which increase soil cover early in the season that reduces weeds pressure, runoff velocity, raindrop energy and soil erosion (Adekalu *et al.*, 2007; Ghahramani *et al.*, 2011; Mhlanga *et al.*, 2015). Legumes can be incorporated in smallholder farms as intercrops, in rotations and as part of agroforestry practices such as hedgerows and planting on field and farm boundaries.

Intercropping is the most common practice in east Africa that involves legumes and is defined as a multiple cropping practice that include two or more crops on the same piece of land and at the same time (Eskandari *et al.*, 2009). Intercropping in this area commonly involves carbohydrate/starch rich crops including maize (*Zea mays L.*) and cassava (*Manihot esculenta* Crantz. Inst.) grown in combination with legumes such as common bean (Zingore, 2011; Midega *et al.*, 2013; Matusso *et al.*, 2014; Hassen *et al.*, 2017). Intercropping has several benefits. These include reduced risk of total crop failure, increased soil cover to protect the soil from direct sun and raindrop impact, improved resource use efficiency, reduce pests, diseases and weeds and increase of overall crop yield (Van Asten *et al.*, 2011; Wu & Wu, 2014). Although intercropping has several benefits, the design of the intercrops needs to consider competition that may affect the productivity of the most important crop in the crop mixture (Ripoche *et al.*, 2010). The designs for intercrops consider species/variety choices, sowing density and crop management practices such as weed control options (Zhang & Li, 2003; Jalilian *et al.*, 2017). It is crucial to consider rooting and above ground system of the crops involved to avoid competition as much as possible (Hauggaard-Nielsen & Jensen, 2005; Wu *et al.*, 2012). When legumes are used as rotational crops, they enhance soil fertility and control of pests, disease and weeds (Mhlanga *et al.*, 2015; Thierfelder *et al.*, 2013). However, due to limited land in smallholder farms, crop rotations are not as commonly practiced as intercropping in east Africa.

Legumes have several benefits which include improving food and nutrition security, supplying income, providing livestock feed, acting as source of fuel, improving soil fertility and controlling soil erosion. However, their use in east

Africa is lower than might be expected, especially for herbaceous and tree legumes. Farmers prefer growing carbohydrate rich crops, which dominate their diets, including maize (*Zea mays* L.), rice (*Oryza sativa* L.), sorghum (*Sorghum bicolor* L.), cassava and banana (*Musa sp*.) for food security reasons (FAO, 2009; Smale *et al*., 2013; Cheesman, 2015). Other factors which reduce adoption of legumes include; a) lack of adequate technical information usually provided by government extension officers and non-governmental organisations, b) limited access to well-functioning markets for inputs and outputs, c) unreliable land tenure systems and d) farmers objectives or preferences (Ojiem *et al.*, 2006).

Efforts have been made to introduce different legume types and increase their effective use in smallholder farms, e.g. Odendo *et al.*, (2011) and Snapp *et al.*, (2018), but the uptake of legumes is below the expected levels. This could be related to high variation in resource endowment, climatic conditions and soil types in smallholder farms which influences decision making and spread of information (Tittonell *et al.*, 2013). There is need to identify legume niches and understand farmers' attitudes as well as their perceptions towards introduction of legumes in the varied environment across east Africa. Research on legumes has tended to focus on their contribution to food, feed and soil fertility improvement but there is little research that has focused on soil erosion control in smallholder farming systems.

1.1 Thesis aim and objectives

The main aim of the thesis was to assess the various contributions legumes make in mixed crop-livestock systems in east Africa and how this might be improved. The overall research question was: What are the contributions of legumes to fulfilling farmers' needs in smallholder farms? The emphasis was on studying farmer perceptions, ecosystem services and support for decision making.

The main aim was split into four objectives;

1.1.1 Farmer perception and knowledge of legumes (Paper I)

To assess farmers' perceptions and knowledge of legumes and the rationale of farmers' current practices in east Africa. The research questions addressed were:

i. What are smallholder farmers' perceptions and knowledge of legume types and functions?

ii. What is the rationale for current use of legumes in smallholder farms?
iii. Are there differences in preferences for functions depending on farmers' socio-economic context?

1.1.2 Effect of management practices on legume productivity (Paper II)

To assess the effect of different management practices on legume productivity in a range of contexts in SSA through a meta-analysis. The research questions of the study were:

I. What is the overall effect of intercropping, inoculation, phosphorus (P) application and minimum tillage on legume productivity in smallholder farming systems?
II. In what situations do selected management practices influence legume productivity?

1.1.3 Reducing soil erosion through introduction of different crop types (Paper III)

To assess the effect of different crop types (herbaceous, grain or woody plants) in reducing surface runoff and soil erosion compared to maize-common bean intercropping. The research questions of this study were:

I. What is the effect of crop mixtures involving legumes and different crop types on soil and water conservation in smallholder farms?
II. What is the effect of incorporating legumes in cropping systems on soil structure using infiltration capacity and earthworm populations as indicators?

1.1.4 Matching choice of legumes with farmers' needs to support decision making – the LegumeCHOICE tool (Paper IV)

To assess the validity of expert scores used in determining the functional fit of legumes in relation to farmers' needs in the LegumeCHOICE tool. The research questions addressed in this study were:

I. Is there a relationship between expert scores and literature-based data of legume species on their contribution to provision of food, feed, and soil fertility improvement?
II. Will literature-based data improve the expert scores for legumes species contribution to provision of food, livestock feed and soil fertility improvement through BNF?

2 Background

2.1 Smallholder farming systems in SSA Africa

About 70% of SSA population is involved in agriculture on smallholder farms that are smaller than 2 ha per household (AGRA, 2017; Salami *et al.*, 2010). Many of the farming systems involve mixed crop and livestock farming such as maize mixed, cereal/root mixed, and root crop farming systems which together occupy about 35% of the land area in SSA (Garrity *et al.*, 2012). Main crops in these farming systems include maize, cassava, tobacco (*Nicotiana tabacum*), sorghum (*Sorghum bicolor*) and common bean. Livestock kept in SSA smallholder farms include cattle, sheep, goats, poultry and camels. Rainfall in SSA ranges from less than 400 mm per year in arid areas to over 2000 mm per year in central Africa (Livingston *et al.*, 2011) but, due to climate change, the frequency of mid-season droughts has increased in some regions (Serdeczny *et al.*, 2017). Less than 5% of smallholder farms have access to irrigation facilities (Rosegrant *et al.*, 2009) hence moisture scarcity is a serious challenge to both crop and livestock production. Some regions, those that are close to the equator, receive rainfall in a bimodal pattern. In these regions farmers utilise both cropping seasons; commonly termed long rains which lasts five months (March to July) and short rains which lasts four months (September to December). There is high variability in management practices and soil types include *Acrisols*, *Vertisols*, *Lixisols*, *Ferralsols* and *Arenosols* among others (Wilkus *et al.*, 2019).

Land preparation, weed management and incorporation of manure or crop residues are usually done using ox-drawn mouldboard ploughs and hand hoes (Zingore *et al.*, 2008; Vogel, 1994). Conventional ploughing methods can reduce soil productivity due to soil erosion and loss of organic matter which may reduce crop yields in smallholder farms (Amini *et al.*, 2015). Challenges with soil erosion and low soil organic matter may be ameliorated by intensification use of legumes with different growing habits (Garcia-Estringana *et al.*, 2013).

2.2 Benefits and challenges of incorporating legumes in smallholder farming systems in sub-Saharan Africa

2.2.1 What are legumes?

Legumes are flowering plants which belong to the Fabaceae (or Leguminosae) family (Allaire & Brady, 2010). They can be grouped based on their types: grain legumes, herbaceous legumes (crops grown specially for livestock feed or to be used as green manure, some leaves are also part of the human diet) and tree legumes (Figure 1). Household, soil and livestock are the entry points where legumes are used directly for food, income, feed, as well as soil protection and fertility improvement. Legumes can be categorised based on their life cycles as annual, biannual and perennial legumes. Legumes fulfil several functions within the farm including provision of food, fuel, livestock feed, income, soil fertility improvement and soil erosion control. Since legumes provide several products and serve several functions while they are growing, or after they are harvested, they are often referred to as multi-purpose or multi-functional plants.

2.2.2 Benefits of legumes

Provision of food

Grain legumes contribute to provision of food through seeds and sometimes leaves (Snapp *et al.*, 2018; Dixon & Sumner, 2003). Commonly grown grain legumes in SSA include cowpea (*Vigna unguiculata* L. Walp), soybean (*Glycine max* L. Merr), groundnut (*Arachis hypogea* L.), pigeon pea (*Cajanus cajan* L. Millsp), common bean (*Phaseolus vulgaris* L.) and bambara groundnut (*Vigna subterranea* (L.) Verdc) (Franke *et al.*, 2018) (Table 1). Grain legumes have higher protein content than cereals; typically, 20-45% vs 7-17%, respectively (Day, 2013; Watson *et al.*, 2017). Legumes thus provide a cheap source of protein for human consumption and they provide important amino acids including tryptophan and lysine, which have lower concentrations in cereals (Snapp *et al.*, 2018). Legume grains are usually cooked before consumption and their inclusion in the diet increases diversity as well as increasing fibre (soluble and insoluble), starch, B-group vitamins, iron, magnesium, calcium and zinc (Snapp *et al*., 2018; Watson *et al*., 2017). In addition to improved diets, legumes, also help reduce cholesterol in humans e.g. soybean (Polak *et al*., 2015; Duane, 1997).

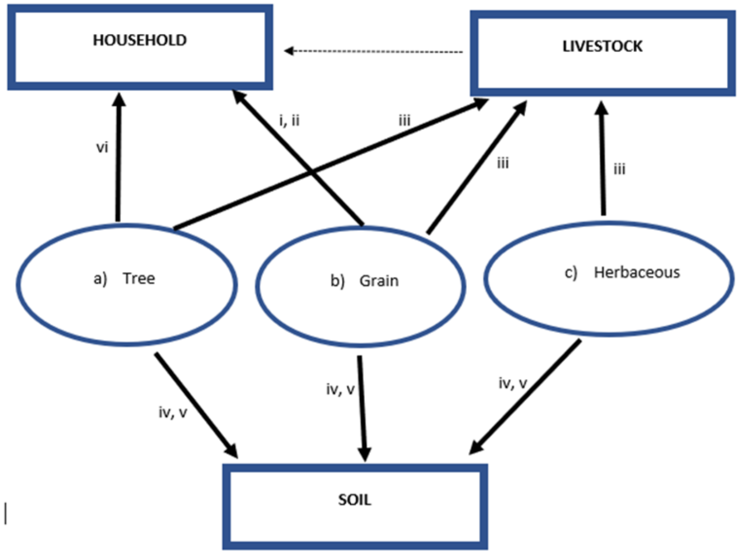


Figure 1. Entry points, in rectangles, for different legume types - a) tree legumes, b) grain legumes and c) herbaceous - and their functions i) food, ii) income, iii) feed, iv) soil erosion control, v) soil fertility improvement and vi) fuel. Examples of legume species a) Calliandra, Sesbania, Gliricidia and Leucaena; b) common bean, groundnut, cowpea, soybean, chickpea and pigeon pea and c) Mucuna, Lablab, lucerne, red clover, silver leaf desmodium and common vetch (see Table 1 for scientific names of the legumes). The dotted line shows animal products for household use or sale.

Some legume leaves, including common bean and cowpea, are cooked and consumed as a relish in SSA (Barrett, 1990). Legume leaves are richer in vitamins than legume grains hence leaves and grains have a complementary benefits on the dietary needs for human beings (Edelman & Colt, 2016). However, picking and consumption of leaves during the growing season reduces photosynthetic material which may reduce grain production (Edelman & Colt, 2016). This becomes a trade-off when farmers are interested in grain yield for food and for generating income.

Table 1. *Contribution of legume types and species to important legume functions (references are in Appendix 1)*

Legume types	Common name	Scientific name	Food (kg ha^{-1})	Feed (kg ha^{-1})	Soil fertility (BNF ha^{-1})
Grain, seasonal	Common bean	*Phaseolus vulgaris*	290-1561	760-4039	10-81
Grain, seasonal	Cowpea	*Vigna unguiculata*	187-3850	646-4770	21-201
Grain, seasonal	Faba bean	*Vicia faba*	321-6100	653-10400	39-350
Grain, seasonal	Field pea	*Pisum sativum*	1314-7400	946-12280	4-204
Grain, seasonal	Groundnuts	*Arachis hypogaea*	109-4540	2903-8875	12-200
Grain, seasonal	Chickpea	*Cicer arietinum*	472-2180	1181-5554	12-186
Grain, seasonal	Soybean	*Glycine max*	300-3334	1910-6821	36-165
Grain, seasonal	Mung bean (green gram)	*Vigna radiata*	433-2171	1133-7478	20-63
Grain, perennial	Pigeon pea	*Cajanus cajan*	530-3000	2110-10940	6-250
Grain, seasonal	Sweet lupin	*Lupinus lupins*	400-2420	2300-8600	119
Grain, seasonal	White lupins	*Lupinus albus*	800-5798	1400-13395	19-359
Grain, seasonal	Bambara groundnut	*Vigna subterranea*	311-3597	1543-2030	24-83
Grain, seasonal	Cluster bean	*Cyamopsis tetragonoloba*	504-2093	1214-8900	-
Herbaceous, seasonal	Velvet bean	*Mucuna pruriens*	166-3090	804-10740	30-171
Herbaceous, seasonal	Persian Clover	*Trifolium resupinatum*	-	8800-17950	37-128
Herbaceous, seasonal	Common vetch	*Vicia sativa*	-	1800-10200	46-154
Herbaceous, seasonal	Black sunnhemp	*Crotalaria ochroleuca*	-	1561-15140	-
Herbaceous, seasonal	Lablab	*Lablab purpureus*	-	1707-8701	-
Herbaceous, seasonal	Silverleaf desmodium	*Desmodium uncinatum*	-	514-3221	-
Herbaceous, seasonal	Lucerne/Alfalfa	*Medicago sativa*	70-630	3891-23445	38-407
Tree, coppicing	Calliandra	*Calliandra calothyrsus*	-	2192-7700	15-177
Tree, coppicing	Gliricidia	*Gliricidia sepium*	-	2213-13910	6-151
Tree, coppicing	White lead tree	*Leucaena leucocephala*	-	933-31940	78-140
Tree, non-coppicing	Sesbania	*Sesbania sesban*	-	200-4400	363

Provision of livestock feed

Legumes have high protein content compared to many other fodders that are used to feed livestock. In this thesis, legumes grown to feed livestock will be referred to as herbaceous legumes. There are at least 1500 species of legumes which can be used as livestock feed and only around 60 are generally used as cultivated forages worldwide (Hanson, 2000).

Herbaceous legumes may be consumed as fresh or as dry hay by livestock or processed into supplementary feeds (Hanson, 2000). The hay made from herbaceous legumes is more digestible than cereals/grasses and hence, improves milk and meat production (Ball *et al.*, 2001). Preserving forage legumes in the form of hay and supplementary feeds such as leaf meal helps provide feed during the dry season when grazing pastures have low biomass and are of poor quality (Pamo *et al.*, 2007).

Grain legumes can also be used to make concentrates for livestock feed. For example, unprocessed seeds of lupins and cowpea among others have been used to feed livestock (Lanza *et al.*, 2003; Paduano *et al.*, 1995). Their crop residues may also be fed to livestock, although the dry matter productivity of legumes is relatively low to compared to cereals (Balete, 2016). Another grain legume with potential as livestock feed is groundnut where both haulms and seeds can be fed to livestock. The haulms may be fed directly or mixed with other fodder crops (Gupta *et al.*, 2012). Feeding lambs with groundnut hay and concentrate resulted in higher lamb live weight gain than for lambs which were free grazing (Mohamed Ali *et al.*, 2015).

When using herbaceous legumes as livestock feed, care should be taken for anti-nutritional factors which may affect livestock (Soetan & Oyewole, 2009). For example, *Acacia angustissima* contains condensed tannins, simple phenolic and non-protein amino acids and may lead to mortality in ruminant animals (McSweeney *et al.*, 2008; McSweeney *et al.*, 2002).

Soil and water conservation

Legumes contribute to soil and water conservation in several ways including provision of soil cover during and after cropping seasons. The soil cover could be from crop residues laid as mulching material (Mupangwa & Thierfelder, 2014) or from the live crop (Mhlanga *et al.*, 2015). High soil cover blocks the sun from directly heating the soil which reduces evaporation of water (Farzi *et al.*, 2017).

Perennial legumes such as pigeon pea, lucerne and silver leaf desmodium are more effective as a living mulch than annual legumes (Hartwig & Ammon, 2002). They continue growing after the rainy season, which ensures there is adequate ground cover most of the year. High soil cover reduces the direct impact of raindrops that loosen soil particles and thus reduces soil loss by splash and overland flow (Ghahramani *et al.*, 2011). Also, the presence of soil cover intercepts runoff which promotes more water infiltration (Adekalu *et al.*, 2007). Some legumes, including pigeon pea and tree legumes, have deep root systems that enable them to access water from deeper soil horizons. This was observed in Zambian smallholder farms and recovery of leached nutrients was also noted (Sekiya and Yano, 2004).

Addition of mulch increases soil organic matter which contain fulvic acids, polysaccharides and humic acids that binds soil aggregates (Boyle *et al.*, 1989). Furthermore, addition of crop residues provide food for macro and micro-organisms that increase soil biological activity including earthworm activity (Ashworth *et al.*, 2017; Bertrand *et al.*, 2015). Soil particles, root hairs, mucilage and microbes are in intimate contact, which binds the soil particles and reduces their susceptibility to soil erosion (Watt *et al.*, 1993). This characteristic can be further utilised by intercropping legumes with cereals, which increases root density leading to more soil binding (Ramirez-Garcia *et al.*, 2014).

Soil fertility improvement: Biological nitrogen fixation

Legumes can form a symbiotic relationship with bacteria where fixation of atmospheric di-nitrogen (N_2) occurs (Hu *et al.*, 2012). The nitrogenase enzyme complex binds N_2 and the reduce iron (Fe) proteins binds to ATP. The reduced molybdenum protein donates electrons to N_2 producing HN=NH. In further cycles the HN=NH is reduced $H_2N\text{-}NH_2$ to $2NH_3$ (Mus *et al.*, 2016). The bacteria provide N in the form of NH_3 to the host and receive carbohydrates and other nutrients from the host (Garg & Geetanjali, 2009). The bacteria contain the enzyme nitrogenase that reduces the nitrous oxide under anaerobic conditions. According to Dixon & Kahn, (2004) the stoichiometry of BNF is as follows (Eq. 1);

$$N_2 + 8H^+ + 8e^- + 16\ ATP \rightarrow 2NH3 + H_2 + 16\ ADP + 16\ Pi \qquad \text{(Eq. 1)}$$

Rhizobia are free-living organisms in the soil, which elaborate signals with legumes under N-limited environments. The rhizobia may be introduced in the rhizosphere by inoculation at sowing. The legume roots release chemicals including flavonoids and betaines that are sensed by rhizobia hence they accumulate near the roots of the hosts (Hu *et al.*, 2012). The root hairs of legumes release lectins which facilitate attachment of rhizobia to the root hairs (Garg & Geetanjali, 2009). After the attachment, the rhizobia induces nod genes that initiates degradation of the root hair cell walls, intracellular calcium oscillation, membrane depolarization and infection of cortex till the nodules are formed (Garg & Geetanjali, 2009).

Depending on environmental factors, N is fixed, and the host plants utilise it. Nitrogen fixation is affected by water availability, soil pH, P availability, host susceptibility and soil N (Wahbi *et al*., 2016; Tu *et al*., 1970). Drought results in reduced leaf area (supply of photosynthate to the roots decreases) and reduced nodulation on roots. Also, respiration in roots and nodules decreases under drought conditions and may fail to recover when moisture is available because they decay during the drought stress periods (Nandwal *et al*., 1991). Nitrogen fixation responds variably to soil pH (4-8) and temperature (Bordeleau & Prévost, 1994). Rhizobium survival and nodulation are deleteriously affected by low soil pH. At low soil pH, levels of soluble aluminium, manganese or iron may affect nodulation and growth of rhizobia (Al-Falih, 2002). Also, low and high soil pH affect the availability of P which has a direct effect on N fixation (Cerozi & Fitzsimmons, 2016; Yang, 1995). Hence, it is important to keep soil pH at levels that have little effect on rhizobia, nodulation and nutrient availability.

Due to their N fixation capability, legumes are often incorporated in smallholder farms to help improve soil N and organic matter. For example, grain legumes can fix N at rates of up to 150 kg N ha^{-1} for field pea, 200 N kg ha^{-1} for cowpea and 70 kg N ha^{-1} for groundnut (Table 1). Tree legumes also fix considerable amounts of N, e.g. sesbania can fix approximately 330 kg N ha^{-1} (Table 1). Use of legumes with this high N fixation capability in smallholder farms, reduces N fertilisation requirements. Use of tree legumes as green manure reduced fertiliser requirements up to 75% in east and southern Africa (Ribeiro-Barros *et al.*, 2018). Some legumes such as common bean are poor N fixers, hence they need some additional N application to obtain high yields (Da Silva *et al*., 1993; Manrique *et al*., 1993; Bliss, 1993).

Provision of fuel

Approximately 80% of households in SSA use solid fuel for cooking and this results in a high demand for wood energy (Iiyama *et al.*, 2014; World Bank, 2011). There is shortage of trees to meet the requirements for wood fuel, but this shortage can be reduced by incorporating trees in smallholder farms (Cerutti *et al*., 2015) as hedgerows, farm boundaries or as part of reforestation measures. Tree legumes can survive under harsh conditions and show fast growth rates and thus can produce wood in a short space of time (Table 1). Some are adapted to coppicing (e.g. Calliandra and Gliricidia (Table 1)). In east Africa, 5-27 t ha^{-1} wood was harvested within 1-3 years from different tree legume species plantations, including sesbania (Kimilu, 2010). In Zambia, legume fallows for wood production yielded approximately 15 t ha^{-1} of sesbania wood per annum (Kimilu, 2010). These tree legumes are possible options in meeting wood energy requirements in SSA.

Income

Legumes help generate income in smallholder farms. This is through selling the products from legumes including grain, construction poles, livestock feed or livestock products derived from better feeding. The success of income generation is dependent on access to value chains and market performance in different countries. The prices of grain legumes generally fluctuate between country and season e.g. common bean (Figure 2). In a Kenyan study, the gross margins and profitability for common bean, groundnut, soybean, cowpea and Lablab were found to be highly variable (Onyango *et al.*, 2016). Differences were observed in labour and fertiliser costs, and the lowest production costs were observed in cowpea. In Tanzania, an improved common bean variety produced US$366 ha^{-1} profit per season (Venance, 2016), and this figure could be doubled since farmers grow two crops per year in areas where they receive rainfall in a bimodal pattern.

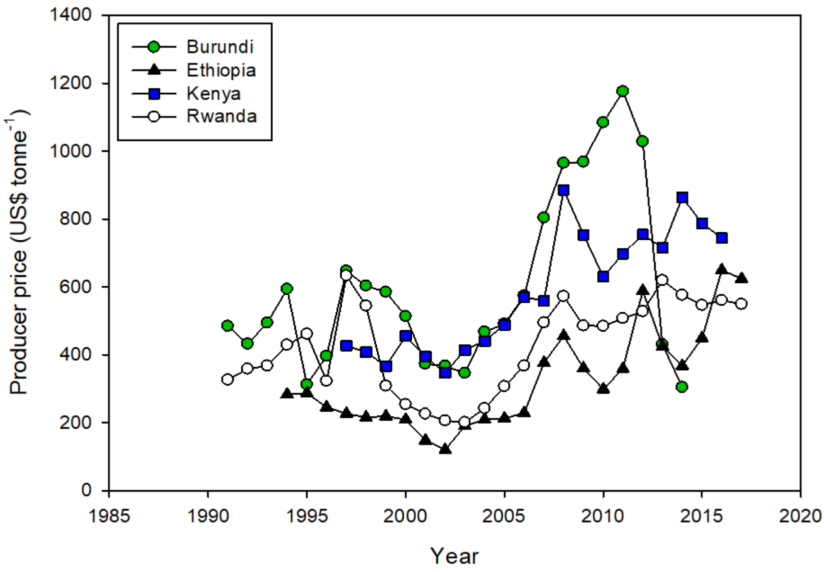


Figure 2. Common bean producer price in some east African countries. Source FAOSTAT http://www.fao.org/faostat/en/#data/PP date accessed 07.03.2019.

Other benefits

Legumes play a role in reducing weed pressure in cropping systems by smothering them as live crops or mulch during the cropping season (Storkey *et al.*, 2011). Legumes have faster growth rates than some weeds, hence they can have a competitive advantage over weeds (Mhlanga *et al.*, 2015b). Some legumes including velvet bean and jack bean (*Canavalia ensiformis*) produce allelochemicals that suppress weed growth. Decomposition of velvet bean has also been found to reduce nematode infestation in tomatoes (Caamal-Maldonado *et al.*, 2001). When legume crop residues are applied as mulch, they block the sunlight from reaching the weed seeds and seedlings, which is essential for their growth (Mhlanga *et al.*, 2015). Also, when legumes are included in crop rotations e.g. soybean there is a gradual decrease in weed pressure over-time (Muoni *et al.*, 2014).

2.2.3 Challenges

Despite the various benefits offered by legumes, their utilisation is lower than expected in east Africa due to several reasons. Five important reasons have been identified. (1) Farmer unwillingness to test legumes species that are new to them. Farmers with limited resources are risk-averse towards new technologies hence they have developed a *wait and see* strategy (Sheahan & Barrett, 2017; Muyanga & Jayne, 2006); (2) Insecure land tenure system in smallholder farms. This results in farmers failing to invest in soil conservation techniques fearing to lose their land (Wortman & Kirungu, 2000); (3) Limited access to input and output markets. Famers are not always realizing profit due to high labour and inputs costs (Mhango *et al.*, 2013; Amede, 2004); (4) High disease and pest incidences associated with management of legumes both in the field and storage (Mhango *et al.*, 2013); and (5) East African farming is cereal-dominated due to farmers' food habits and also legume grain yields are lower than cereal yields (Amede, 2004).

Some grain legumes such as common bean respond to environmental conditions, i.e. with enough rainfall and crop protection it yields well but when stressed (e.g. long dry spells) crop yields decrease drastically (Lizana *et al.*, 2006). Hence, some farmers avoid growing it on a large scale due to the high risk associated with crop failure and prefer to intercrop with e.g. maize (e.g. Rusinamhodzi *et al.*, 2017).

2.2.4 Decision support tools involving legume use

Challenges faced by farmers in use of legumes in SSA could be addressed by improved extension services supported with decision support tools (Wambugu *et al.*, 2011). Decision support tools aim at providing clear decision stages and helping visualize the likelihood of various outcomes which helps in making evidence based decisions (Rose *et al.*, 2016). Examples of decision support tools include: a) Lexsys a decision support tool for integration of legumes into tropical farming systems (Weber *et al.*, 1997), b) FEAST a livestock feed assessment tool (Duncan *et al.*, 2012); c) the LegumeCHOICE tool (Duncan *et al.*, 2019). Of interest in this section is the LegumeChoice tool, which was developed in the LegumeCHOICE project that aimed at improving food and nutrition security and the production environment in smallholder farms through integration of legumes in crop-livestock systems.

The LegumeCHOICE tool focus on six key functions of legumes, which are provision of food, income, livestock feed, fuel, soil erosion control and soil fertility improvement. The tool's approach involves participatory exercises with farmers about legume types and species that are suitable to meet their needs for products and functions. The LegumeChoice tool includes 44 legume species of different types and life cycles, which can be incorporated into smallholder farming systems in SSA. Experts involved in the LegumeChoice project generated this list of legumes. The LegumeChoice tool comprises of three main filters namely an agro-ecological filter, a socio-economic filter and a farmer aspiration filter which when put together generate a “hit list” of suitable legumes for the site in question from the list available. The agro-ecological filter includes average rainfall, average annual temperature, altitude and soil pH using information obtained from literature and other existing decision support tools. The socio-economic filter considers factors limiting legume use, which include land, labour, seeds, inputs and services, water/rainfall and markets based on farmers’ views. The last filter, farmer aspirations, quantifies what local farmers are looking for from legumes i.e. assesses their preferences about legume functions.

3 Materials and methods

3.1 Study overview

The thesis involved field experiment, participatory methods (surveys) and literature review (Table 2). Each country had four data collection sites in sub-counties in Kenya and districts in Democratic Republic of the Congo (DRC) (Table 2).

Table 2. *Research methods applied in this thesis*

	Participatory methods	On-farm experiments	Literature review	Sites
Paper I	X			DRC [a], Kenya [b]
Paper II			X	sub-Saharan Africa
Paper III		X		Rongo, Kenya
Paper IV			X	sub-Saharan Africa

[a] Democratic Republic of the Congo, South Kivu (Luduha, Madaka, Bushumba Centre and Mulengeza), [b] Kenya (Rongo, Suna West, Kitutu Chache and Nyaribari Chache).

3.2 Study sites

The study used for paper I was conducted in DRC and Kenya. The DRC sites located in South Kivu are considered to be part of east Africa because they share many things in common to the east African countries, e.g. the agro-ecological conditions and language, and in addition, DRC is observer in the East African Community. Paper II and IV involved literature search of studies conducted in SSA countries with different soil types and annual rainfall. Paper III included a field experiment set up in Migori County (Rongo), Kenya.

In Kenya, sites were situated in Migori county, and Kisi county (Figure 3). These sites have a sub-humid climate and receive rainfall in a bimodal pattern; average approximate precipitation in the region during short rains (SR) is 550 mm and during long rains (LR) is 800 mm. The average land size per farm is 1.2 ha (Table 3). Dominant soils at Suna West are classified as *Planosols* and the other sites are dominated by *Acrisols* (Jones *et al.*, 2013).

In DRC, study sites are in South Kivu province with humid climatic conditions (Figure 3). Annual average rainfall ranges between 1100 and 2700 mm, received in a bimodal pattern. During the long rains the precipitation is approximately 600 mm from March to July and during the short rains approximately 530 mm from September to December. Sites are dominated by *Umbric Ferralsols* (Jones *et al.*, 2013).

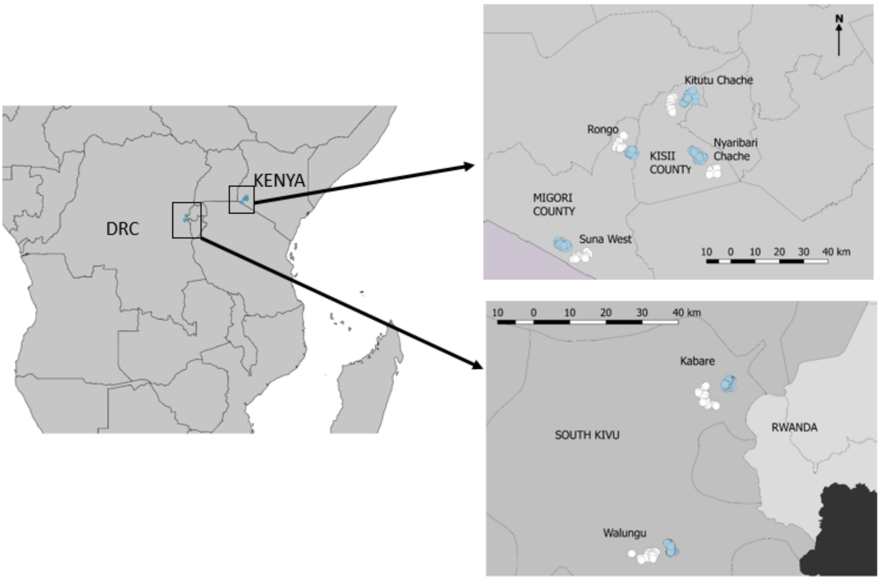


Figure 3. Sites in Kenya and DRC. Blue circles in each country represent LegumeCHOICE farmers, while white circles are non-LegumeCHOICE farmers (Paper I).

Common crops at all sites include maize, common bean, tea (*Camellia sinensis*), sugarcane (*Saccharum officinarum*) and cassava (*Manihot esculenta*). Cattle (*Bos Taurus*), goats (*Capra aegagrus hircus*), sheep (*Ovis aries*) and chicken (*Gallus domesticus*) are among the common livestock species kept in Kenya sites. In DRC, farmers were keeping less livestock, but the same species as in Kenya (Table 3).

Table 3. *Household characteristics in DRC and Kenya study sites (Paper I)*

	Mean	Standard Deviation	Mean	Standard Deviation	*t-test*‡
	Kenya		DRC		
Age of household head	48.1	14.9	44.4	13.6	0.038
Land size (ha)	1.2	1.6	1.0	3.1	NS
Livestock units (TLU)	1.9	1.7	0.5	1.1	<0.001
Livestock: cattle	2.4	2.2	0.6	1.5	<0.001
Livestock: goats	0.9	1.7	1.0	1.4	NS
Livestock: sheep	0.4	1.5	0.2	1.0	NS
Livestock: chicken	9.7	8.5	1.6	3.1	<0.001

3.3 Research methods

3.3.1 Literature search (Paper II and IV)

A literature search for the meta-analysis (Paper II) was conducted, in order to extract data for legume grain and biomass yield as well as fixed N, using Google Scholar, ISI Web of Science and Scopus search engines up to December 2018. The search strings included the following key words: intercrop, crop mixtures, grain yield, biomass yield, shoot yield, phosphorus fertilization, inoculation, rhizobia, rhizobium, BNF, ndfa - nitrogen derived from atmosphere, nitrogen fixation, tillage, minimum tillage, no-tillage, zero tillage, conservation tillage, reduced tillage and Africa. In all search strings, common and scientific names of legumes were added.

For paper IV, the study was interested in legume grain yield, biomass yield and fixed N grown as sole crops. The key words were grain yield, biomass yield, BNF, ndfa and common names as well as scientific names for legumes. The

3.3.2 Meta-analysis (Paper II)

For the meta-analysis, studies on legumes that focused on major management factors affecting legume productivity were selected. The investigated factors were intercropping, P-application, inoculation and minimum tillage. The treatments included in the meta-analysis were;

I. Intercropping vs sole cropping.
II. Phosphorus fertiliser application vs no phosphorus application.
III. Inoculation vs non-inoculation.
IV. Minimum tillage vs conventional ploughing.

This study included papers which met the following requirements; i) the reported research was conducted in SSA on-farm or on-station experiments, ii) the experiment had to include contrasting groups iii) means, sample size and statistical data such as coefficient of variation (CV), standard deviation (SD) or standard error (SE) had to be reported for interventions and control groups.

The following rules were set to ensure independence of observations: i) for studies with the same treatments applied at the same site for several years, their averages were calculated per year and the number of years was treated as the sample size; ii) when the treatments were applied on different sites, averages per site were calculated and used as independent observations; iii) where authors published many papers based on the same data, only one of their publications was considered for data extraction and high preference was placed on the paper with most data provided; iv) observations from the same study were considered independent if they had different managements including fertilizer applications, used different inoculum strains and also different tillage methods (basins, rip lines or direct seeding).

3.3.3 Identification of participants for household survey (Paper I)

The study of farmer perceptions on legumes involved farmers who participated in the 'LegumeCHOICE project' which ran from 2014 to 2017 and those who were not in the project. Farmers included from the LegumeChoice project had participated in the project from the beginning while non-project farmers were approximately 5 km away from project farmers in any direction. Non-LC farmers were selected based on their willingness to participate in the survey and lack of awareness about the LC project. A total of 162 farmers in Kenya and 106 in DRC were interviewed, of which 119 were from the LegumeCHOICE project. Of the 268 farmers interviewed, 130 were women.

3.3.4 Household survey instrument (Paper I)

The questionnaire comprised of three sections; i) household characteristics; ii) farmers' knowledge of legumes and their functions, and iii) the rationale of legume uses in smallholder farms.

The first section collected data for household characteristics including gender and age of household head, family size, land size, crops grown, and farmers’ interests in farming. The location global position system (GPS) geo-coordinates and contact details were recorded.

The second section categorised knowledge into ‘no knowledge’, ‘weak knowledge’ and ‘strong knowledge’. ‘No knowledge” was when farmers could not mention any legume while “weak knowledge” was allocated to farmers who could give at least one legume example or characteristic. “Strong knowledge” was allocated to farmers who could mention at least two legume species or characteristics. Farmers were asked about legume functions and to identify twelve legume species depicted in photos without hints from enumerators.

The third section was a scoring of six key legume functions; provision of food, livestock feed, income, control of soil erosion, soil fertility improvement and provision of fuel. Scoring was conducted using 30 counters that were distributed among the six functions based on their importance to the farmer. Farmers’ source of legume information was categorised into “yes frequently”, “yes occasionally” and “never” using a Likert scale (Jamieson, 2004).

3.3.5 Runoff experiment (Paper III)

The runoff experiment was conducted on a farmer’s field in Rongo district (00°77'S, 34°60'E; 1474 meters above sea level), located in Migori county in western Kenya. The experiment had five treatments that were replicated three times in a randomised complete block design;

I. Maize/common bean intercrop (maize intercrop; control)
II. Groundnut, sole crop during LR and intercropped with maize during SR (groundnut)
III. Lablab (*Lablab purpureus*), sole crop (Lablab)
IV. Mucuna (*Mucuna pruriens*), sole crop (Mucuna)
V. Maize/common bean intercrop plus *Calliandra calothyrsus* hedgerow and leaf mulch (Calliandra).

The slope at the site was around 20% and the dominant soil type was sandy clay loam (Table 4).

Table 4. *Soil properties at the experimental site in Rongo district, Migori County, Western Kenya (Paper III)*

Depth (cm)	pH	Org C (%)	Total N (%)	C:N ratio	BD (g cm^{-3})	Avail P (mg kg^{-1})	Avail K (mg kg^{-1})	Sand (%)	Silt (%)	Clay (%)
0–20	4.8	1.0	0.1	9.9	1.3	0.9	61.0	63	12	25
20–40	4.9	0.9	0.1	10.0	1.4	0.1	77.0	56	13	31

pH (measured in 0.01M $CaCl_2$ extraction with soil to extraction solution ratio of 1:2.5); Org C = organic carbon, N = nitrogen, C:N= the carbon-nitrogen ratio, BD=bulk density, Available phosphorus (P) and potassium (K). Available P was determined by Bray 1 with Beckman coulter Du, UV – Du 640 spectrophotometers, USA. Available K was analysed by Calcium–Acetate–Lactate–extraction method.

Each main plot measured 12 m × 6 m (72 m^2) and consisted of a bounded runoff plot (with aluminium sheets buried 0.20 m in the ground) measuring 12 m × 4 m (48 m^2) in the centre of the main plot. At the bottom of each runoff plot, a triangular cross-section was constructed with a 5 cm diameter iron pipe outlet connected to two 100L tanks to collect runoff and soil sediments. The first tank had six equidistant levelled splitter outlets and one splitter was connected to a second tank, to account for the overflowing water from the first tank.

The crops were sown (using recommended spacing and fertiliser application rates (Table 5)) after the first effective rains in all seasons, except for the LR 2016 season when crops were established a bit later. Land preparation was done using an ox-drawn mouldboard plough to a depth of approximately 0.20 m, at the onset of the experiment to remove African Bermuda-grass (*Cynodon nlemfuensis* Vanderyst). In the following seasons (September 2016 SR and March 2017 LR), land preparation was carried out with hand hoes (tilling depth approximately 0.20 m) 2 weeks after harvesting the preceding crops. From the SR 2016 cropping season, 50% of the harvested leaf and stem biomass in all treatments was retained in the respective plots and was uniformly spread soon after sowing the following crop, following recommendations from Mupangwa & Thierfelder (2014) and allowing the remaining crop residues to be used for feeding livestock or other purposes.

Table 5. *Crop spacing and fertiliser application rates (paper III).*

Crops	Spacing	Basal dressing kg/ha (DAP)		Top dressing kg/ha (CAN)
		N	*P*	*N*
Maize	0.75 m × 0.30 m	18	46	26
Common bean	0.75 m × 0.20 m	8	21	0
Mucuna	0.50 m × 0.20 m	8	21	0
Lablab	0.50 m × 0.20 m	8	21	0
Groundnut	0.45 m × 0.15 m	8	21	0
Calliandra	4.00 m × 0.50 m	-	-	-

DAP: Diammonium phosphate, CAN: Calcium ammonium nitrate, N - nitrogen, P-phosphorus

Data collected included runoff, soil erosion, water infiltration, earthworm abundance, grain and biomass yield.

Runoff and soil erosion

Runoff and soil erosion were quantified after each rainfall event by measuring water and sediments that had accumulated in the tanks. The volume of water and weight of soil sediments from the first tank were recorded as they were, and the splitter tank accounted 1/6 of the overflow from the first tank hence, the volume of water and soil sediments weight in the splitter tank were multiplied by six. Soil sediment subsamples of approximately 500 gram were collected from thoroughly mixed soil sediments to determine dry matter and oven dried at 105 ˚C (24 hours).

Earthworms

Earthworms were collected at three sampling points per plot approximately 60 days after sowing, during the SR 2016 and LR 2017. Sampling was done in the buffer zone measuring, 2 m × 12 m, using a metal frame measuring 0.25 m × 0.25 m which was randomly placed in the plot and soil samples taken 0-0.10 m. The soils were hand sorted for earthworms and after counting, the earthworms were returned to the soil surface.

Infiltration

Infiltration measurements were made at three positions in each plot during the SR 2016 and LR 2017 using a single ring infiltrometer measuring 5.08 cm in diameter and 12.70 cm depth. The ring was driven 5 cm into the soil in an area cleared of plant material. The infiltration was measured by pouring 107 mL of water into the ring and recording the time taken for the water to infiltrate the soil.

Above ground biomass and crop yield

Biomass and grain yield data were collected from eight central rows × 3 m long, of each crop. The total fresh weight of biomass and grain from the net plot was weighed and subsamples (500 g) were collected. Biomass subsamples were oven dried at 80˚C for 48 hours while grain subsamples (10 cobs) were air dried till a constant weight was reached. All three Calliandra hedgerows were pruned during the LR 2017 season at 0.60 m from soil surface in each plot and the leaves and stems in each plot were weighed separately. The average weight of leaves and stems in the three rows were calculated to give fresh weights of each plot. Stem and leaf sub samples of approximately 200 g were collected at each weighing. The sub-samples were oven dried at 80 ˚C for 48 hours.

3.4 Data analysis

In Paper I farmers' background information was analysed using descriptive statistics such as means and standard deviations. All categorical data, including farmers' knowledge and ranking of legume functions, were subjected to chi-square tests while all continuous data was subjected to simple-T tests to assess differences between countries using SPSS.

In Paper II, effect of intercropping, inoculation, P fertilizer application and minimum tillage on legume productivity were analysed using the Meta-Analysis Package for R (Metafor) version 3.6.0, using Hedge's D as the effect size. Heterogeneity test was conducted using the Q-statistic and where it was significant, moderators (soil texture, legume species and annual rainfall) were included in further analysis when there were at least three data points. Land equivalent ratio were calculated using the standard formula (Oyejola & Mead, 1982). Publication bias was checked using the Rosenthal option in OpenMee software (Orwin, 1983; Wallace *et al*., 2017). The Rosenthal publication bias test gives the number of additional non-significant studies (Fail-safe N; Nfs) needed to affect the overall effect of treatments, p-value, on variables.

In Paper III, all data collected was subjected to heterogeneity of variance and normality tests and then analysis of variance (ANOVA) was carried out, using Statistix 9 statistical package for personal computers, to assess the treatment effects on soil loss, runoff, earthworm populations, and total above ground biomass and grain yield (both maize and legumes) produced. The means of the three sampling points for earthworms and infiltration per plot were used in the statistical analysis. Mean separation was carried out using the least significance difference (LSD) test at $P \leq 0.05$ on all significant data.

In Paper IV expert scores were treated as a factor and the study identity were treated as random factors in a linear mixed effects model fitted using lmer functions of R, version 3.6.0. The expert scores were compared with literature-derived values for grain yield, biomass yield and BNF of legume grown as sole crops. Box plots were drawn to show the distribution of values from published sources relative to scores assigned by experts for the respective function. In cases where there was no clear pattern for the scoring of the three functions, suggestions for improvements to scoring were made and they were subjected to statistical tests similar to the method for the expert scores test.

4 Results

4.1 Farmers' knowledge about legumes and their functions (Paper I)

Results show significant differences in farmers' knowledge about legumes in DRC and Kenya (Table 6). More than 50% of the interviewed farmers could give at least a weak definition of legumes. More farmers in the Kenya sites knew about legumes than in the DRC sites.

Table 6. *Farmers' knowledge of legumes and their functions without hints from the enumerators in Kenya and DRC. The number of farmers participating was 106 in the Kenya sites and 162 in the DRC sites*

	Kenya (%)	DRC (%)	χ^2 *significance*‡
Legume knowledge			*0.001*
Strong	38	14	
Weak	40	41	
No	22	44	
	Project farmer (%)	Non-project farmers (%)	χ^2 *significance*ǂ
Legume knowledge			*0.012*
Strong	35	24	
Weak	43	38	
No	22	38	

‡Significance test between farmers in Kenya and DRC using a chi-square test for knowledge of legumes. ǂSignificance test between project farmers and non-project farmers using a chi-square test.

There were significant differences in project farmers' knowledge of legumes compared to non-project farmers; 78% and 62% farmers could give at least a weak definition, respectively.

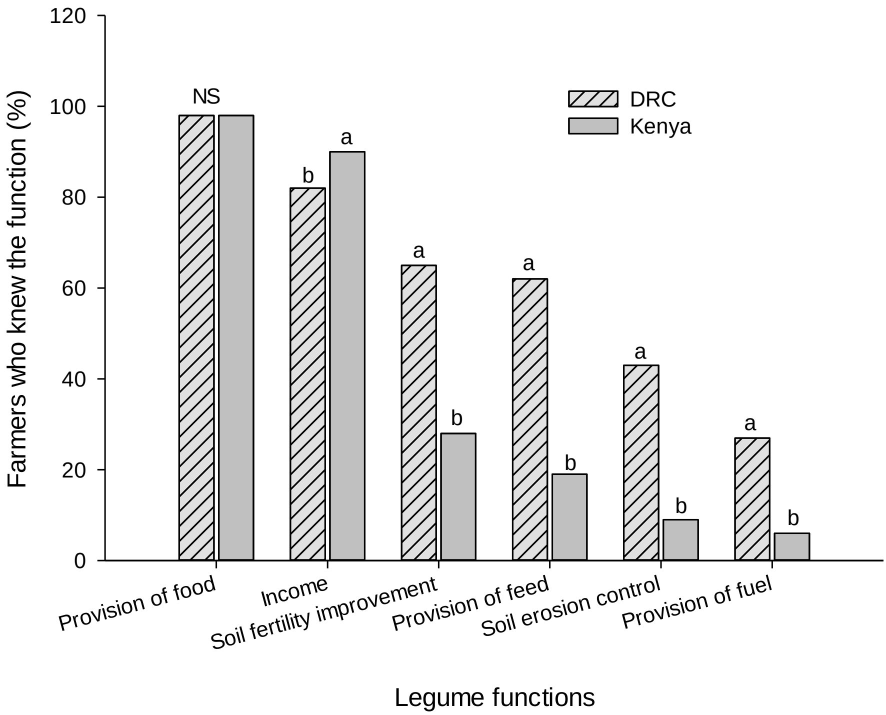


Figure 4. Farmers' knowledge of legume functions in the DRC and Kenya sites. Bars with different letters are significantly different from each other.

There were significant differences in farmers' knowledge on legume functions between the DRC and Kenya sites (Figure 4). More farmers in DRC could mention legume functions than in Kenya. More than 80% of farmers in both countries mentioned provision of food and income as legume functions. In Kenya less than 40 % of the farmers mentioned soil fertility improvement, provision of livestock feed, soil erosion control and provision of fuel as legume functions. In DRC more than 60 % of the farmers could mention at least four legume functions such as provision of food, income, soil fertility and provision of feed as legume functions.

4.2 Farmers' rationale for current legume use (Paper I)

Results show that after explaining the key legume functions to farmers, there were significant differences in scoring for provision of food and provision of fuel functions between DRC and Kenya farmers (Figure 5). Provision of food was scored higher in the DRC sites than in the Kenya sites and provision of fuel was scored lower in DRC than in Kenya.

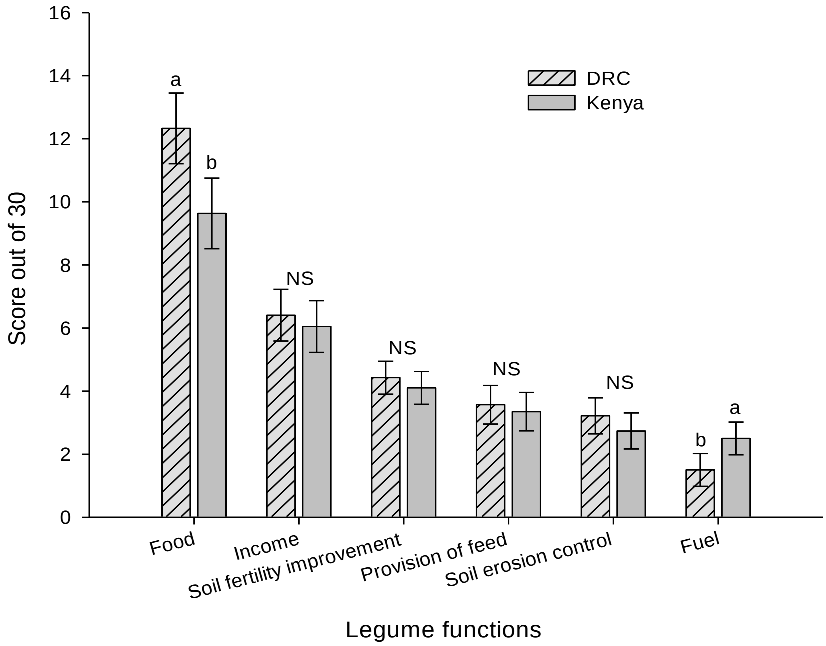


Figure 5. Ranking of different legume functions by farmers in DRC and Kenya. Bars with different letters are significantly different from each other. Bars with stripes are for the DRC sites while filled bars are for Kenya.

4.3 Effects of management practices on legume productivity (Paper II)

The results of the meta-analysis show that intercropping, P-application and inoculation had a significant effect on legume grain and biomass yield (Figure 6). Minimum tillage had no significant effect on legume productivity.

Intercropping resulted in lower legume grain and biomass yield as compared to sole cropping. However, the total LER ranged between 1.20 and 1.95 for both grain and biomass yield. The test for heterogeneity for legume grain yield in response to intercropping was significant (Q = 28275, P-value < 0.001) hence the moderators legume species and soil texture were tested individually.

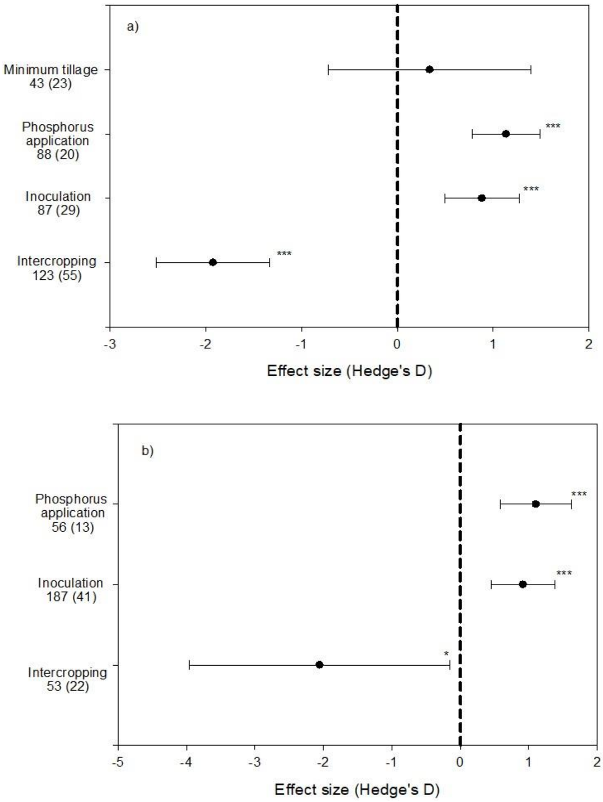


Figure 6. Effect of management practices on legume a) grain and b) biomass yield in smallholder agriculture in SSA. Asterisk are significance codes: '***' 0.001; '**' 0.01, '*' 0.05. The dashed line is x = 0. Number of data points are below the legume species and the number of publications is in parenthesis. The error bars are confidence intervals and they test whether they were significantly different from zero.

The variation in grain yield as result of intercropping could partly be explained by differences between species. Soybean, faba bean, cowpea and common bean grain yield varied in response to intercropping (Figure 7a), while pigeon pea and groundnut grain yields were not significantly affected by intercropping.

The soil texture also explained significant amount of heterogeneity of legume grain yield in response to intercropping (Figure 7b).

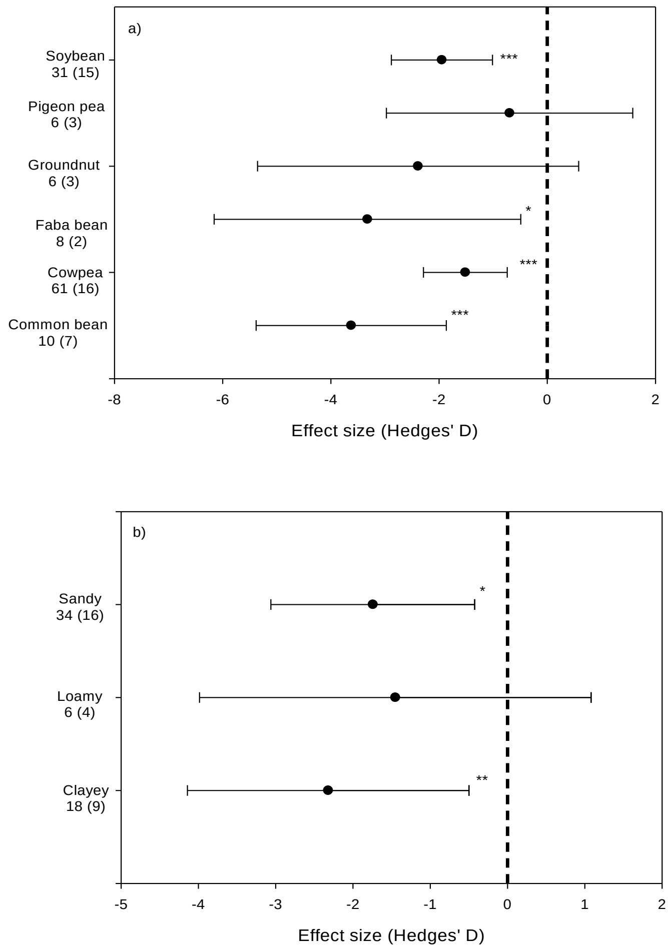


Figure 7. Effects of intercropping on grain yield depending on a) legume species, b) soil type, in SSA. Asterisk are significance codes: '***' 0.001; '**' 0.01, '*' 0.05. The dashed line is x = 0. Number of data points are below the legume species and the number of publications is in parenthesis. The error bars are confidence intervals and they test whether they were significantly different from zero.

Inoculation had a positive effect on legume grain and biomass yield (Figure 6). Legume species and soil texture explained significant amounts of the observed heterogeneity (Q = 439.2, P-value <0.001) (Figure 8). Soybean and common bean responded positively to inoculation while cowpea response was negative.

Inoculation increased legume grain yield in sandy and clayey soils. Legume biomass yield responded positively and significantly to inoculation in sandy soils only.

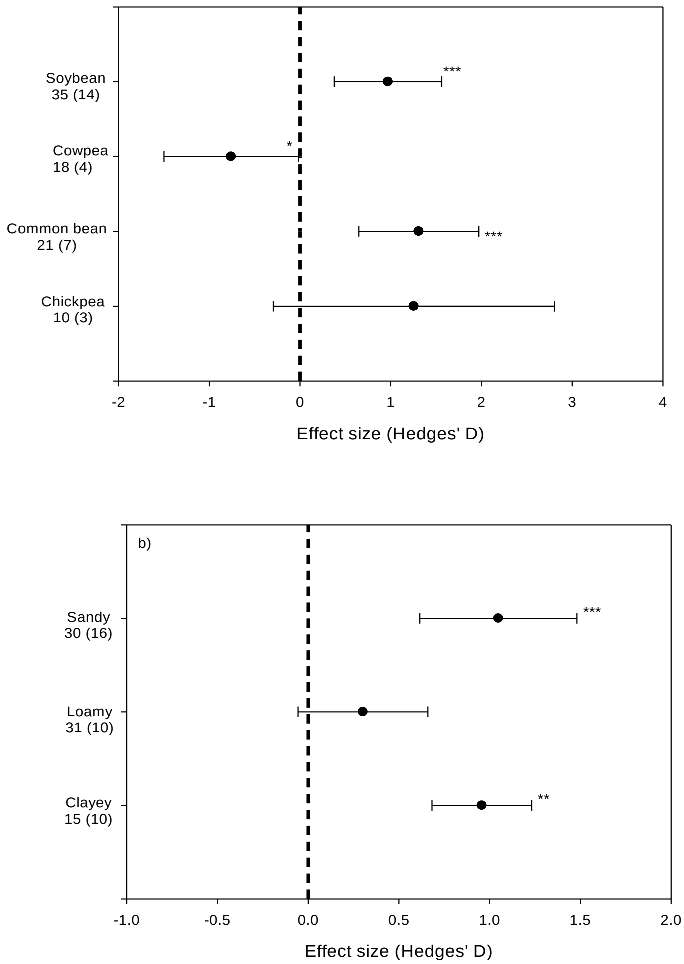


Figure 8. Legume grain yield response to inoculation in SSA depending on, a) legume species and b) soil texture. Asterisk are significance codes: '***' 0.001; '**' 0.01, '*' 0.05. The dashed line is x = 0. Number of data points are below the legume species and soil type and the number of publications is in parenthesis. The error bars are confidence intervals and they test whether they were significantly different from zero.

Phosphorus application had a positive effect on legume grain and biomass yield (Figure 6) and heterogeneity was significant (Q = 109.6, P-value < 0.001). The three moderators P-application rate, soil texture and legume species explained significant amount of variation of legume grain and biomass yield in response to P-application (Figure 9).

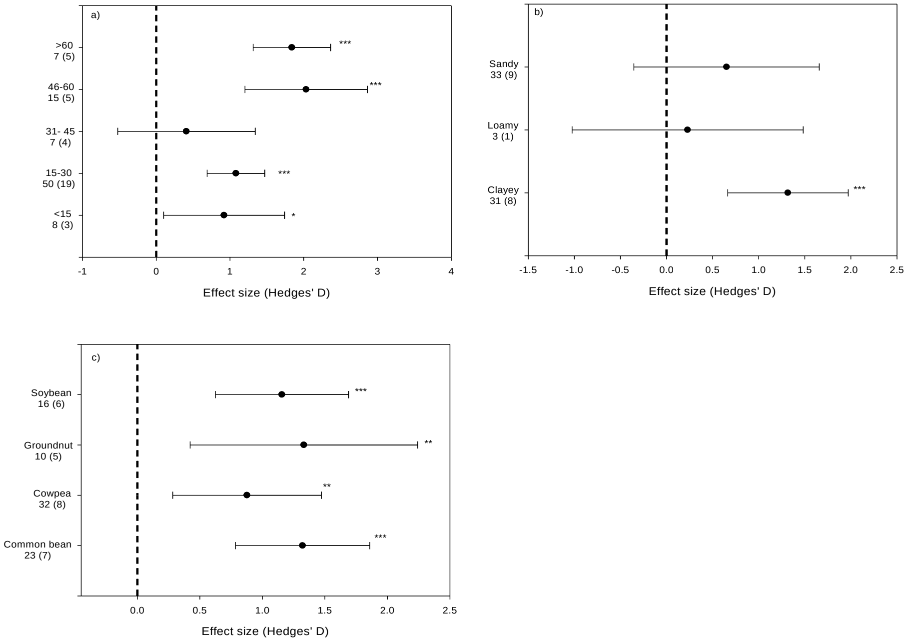


Figure 9. Legume grain yield response to P-application in SSA depending on a) P-application rate, b) soil type, and c) legume species. Asterisk are significance codes: '***' 0.001; '**' 0.01, '*' 0.05. The dashed line is x = 0. Number of data points are given below the P-application rate, soil type and legume species. The number of publications is given in parenthesis. The error bars are confidence intervals and they test whether they were significantly different from zero.

Inoculation had a positive effect on BNF but none of the factors (moderators) legume specie, soil type or annual rainfall explained a significant amount of the heterogeneity.

4.4 Reducing soil erosion through introduction of different crop types (Paper III)

The different crop types and crop mixtures with legumes (treatments) had significant effect on runoff in all three cropping seasons as compared to the maize-common bean intercrop which was the control (farmer practice) (Figure 10). Runoff was higher during the LR 2017 and SR 2016 seasons than in the LR 2016 season. The treatment Calliandra showed the lowest runoff in all seasons. Mucuna was the second most efficient crop in reducing surface runoff across the seasons, while the effects of the other crops were inconsistent. During the LR 2016 cropping season, runoff from the groundnut treatment was as low as from the Calliandra treatment whereas in SR 2016 and LR 2017 runoff under groundnuts did not differ from the control.

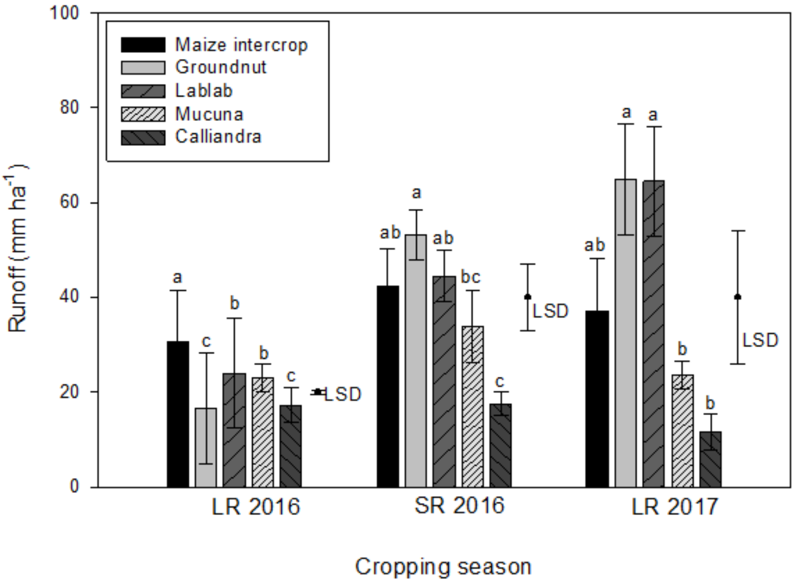


Figure 10. Effect of treatments on runoff during the 2016 long rains (LR 2016) and short rains (SR 2016), and the LR 2017 in Rongo district, Migori County, in Western Kenya. Groundnut was intercropped with maize during the SR 2016 season and grown as sole crop LR2016 and LR 2017. Means with different letters in the same cropping season are significantly different from each other. Error bars are standard error of mean. LSD means least significant differences.

Soil erosion differed by cropping season with more soil erosion occurring in SR 2016 than in LR 2016 or LR 2017 (Figure 11). In the SR 2016 season, maize intercrop, groundnut and Lablab resulted in the highest soil loss, Mucuna was intermediate and Calliandra resulted in the lowest soil loss. Soil erosion was lowest in the Calliandra treatment in all three seasons, and the Mucuna treatment was similarly low as in the Calliandra treatment during the first and the last seasons (<500 kg ha^{-1}) (Figure 10).

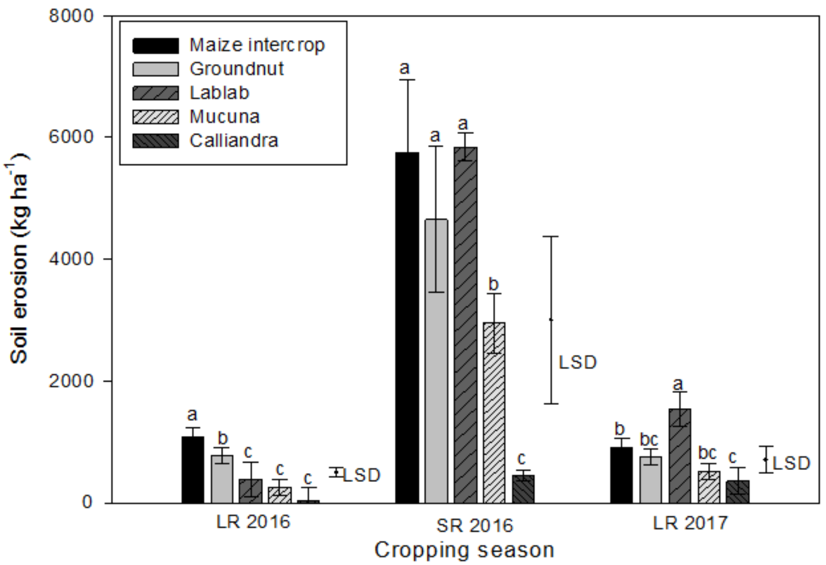


Figure 11. Effect of treatments on soil loss during the LR 2016, SR 2016 and LR 2017 cropping seasons. Groundnut was intercropped with maize during the SR 2016 season. Means with different letters in the same cropping season are significantly different from each other. Error bars are standard error of mean. LSD means least significant differences.

The treatments had a significant effect on earthworm populations during the LR 2017 season only (Table 7). Mucuna and Calliandra supported similar, large earthworm populations compared to other treatments.

Treatments had a significant effect on water infiltration during the SR 2016 only. The highest water infiltration was observed under Calliandra and Mucuna treatments, while the lowest was observed in the Lablab treatment. Calliandra resulted in a 154 % higher infiltration rate than Lablab and a 107 % higher rate than the maize intercrop treatment.

Table 7. *Effect of treatments on earthworms during SR 2016 and LR 2017 cropping seasons in Rongo*

Treatments	SR 2016	LR 2017
Maize intercrop	35	56[b]
Groundnut	16	32[b]
Lablab	19	60[b]
Mucuna	37	229[a]
Calliandra	67	165[a]
SEM	NS	28.8
P-value	NS	0.0051

4.5 Matching choice of legumes with farmers' needs to support decision making – the LegumeCHOICE tool (paper IV)

Literature values and current expert scores for legume functions

Grain legumes were allocated high expert scores, between II and IV, for provision of food and low scores for provision of feed (ranging between I and III) (Table 8). Some grain legumes such as sweet lupins and pigeon pea were allocated high scores for soil fertility improvement and overall the expert scores for this function for grain legumes were between I and IV.

Herbaceous legumes expert scores were high for provision of livestock feed and soil fertility improvement only (Table 8). The same trend was observed for tree legumes. The biomass yield reported in published sources ranged between 2 t ha^{-1} (grain legume) and approximately 13 t ha^{-1} (tree legumes). Amount of fixed N ranged between 40 kg ha^{-1} (common bean) and 213 kg ha^{-1} (lucerne) (Table 8).

Table 8. *Literature values and expert scoring of different legume types to their contribution to food, feed and soil fertility improvement functions using legume grain and biomass yield and BNF as proxy for food, feed and soil fertility improvement functions*, *respectively*

Legume name (type)	Food				Feed				Soil fertility			
	Grain (t ha^{-1})	SD	N	Expert score	Biomass (t ha^{-1})	SD	N	Expert score	BNF (kg ha^{-1})	SD	N	Expert score
Common bean (G)	1.3	1.3	30	4	2.1	1.4	74	2	40.6	17.2	16	2
Cowpea (G)	0.9	0.6	126	4	2	1.3	85	1	51.5	48.6	23	2
Faba bean (G)	3.2	1.2	59	4	6.1	2.1	54	2	103.1	43	17	3
Field pea (G)	4.1	1.1	18	4	6.9	3.4	13	3	111.5	54.6	16	2
Groundnut (G)	1.7	1.0	50	3	5.0	2.2	42	2	126.9	59.6	21	3
Chickpea (G)	1.4	0.5	43	4	3.1	1.2	29	2	39.9	34.9	25	2
Soybean (G)	1.5	0.8	149	3	2.2	1.5	76	2	71.8	68.3	85	2
Mung bean (green gram) (G)	1.1	0.4	34	4	3.8	1.7	22	1	39.7	9.6	23	1
Pigeon pea (G)	1.6	0.7	35	4	5.8	2.8	15	2	61.2	39.6	40	3
Sweet lupin (G)	1.5	-	-	2	7.4	3.5	35	1	-	-	-	4
White lupin (G)	3.4	1.4	33	2	8.1	3.9	21	1	179.2	73.5	20	4
Bambara groundnut (G)	1.3	1.0	30	4	-	-	-	0	46	26.4	4	2
Cluster bean (H)	1.4	0.5	23	3	6.3	2.5	22	1	-	-	-	3
Velvet bean (H)	1.4	0.8	17	0	6.2	2.7	59	1	118.2	63	24	3
Persian clover (H)	0	-	-	0	11.5	5.5	14	4	80	27.9	10	2
Common vetch (H)	0	-	-	0	7.4	2.1	23	4	105.4	32.1	12	3
Black sunnhemp (H)	0	-	-	0	6.9	4.2	10	1	-	-	-	4
Lablab (H)	-	-	-	4	4.4	1.8	35	4	-	-	-	3
Silverleaf desmodium	0	-	-	0	1.5	0.8	12	4	-	-	-	3
Lucerne/Alfalfa	0.3	0.2	26	0	13.6	9.6	37	3	213.7	128.8	43	3
Calliandra (T)	0	-	-	0	4.5	2.1	17	4	88.2	61.8	5	3
Gliricidia (T)	0	-	-	0	10.2	5.4	25	3	-	-	-	4
White lead tree (T)	0	-	-	0	6.0	5.0	43	4	116.3	27.2	6	4
Sesbania (T)	0	-	-	0	1.2	1.0	64	4	-	-	-	3

G, H and T means grain legumes, herbaceous legumes and tree legumes respectively. – indicates that no data available

Validity of expert scoring of legumes to different functions.

Results from comparing the expert scores for food, feed and soil fertility functions with data values derived from the literature show that there were significant differences for scores on food, feed and soil fertility improvement using grain yield, biomass yield and BNF as proxies. Score IV was associated with the highest grain yields reported in the literature but the means derived from the literature for scores II and III were not significantly different from each other (Figure 12a). To improve the scores, categories were developed for grain yields; <1 t, 1-2t and >2t ha^{-1} for scores II, III and IV. The results for the new suggested scores showed that score II and III were significantly different from score IV (Figure 12b).

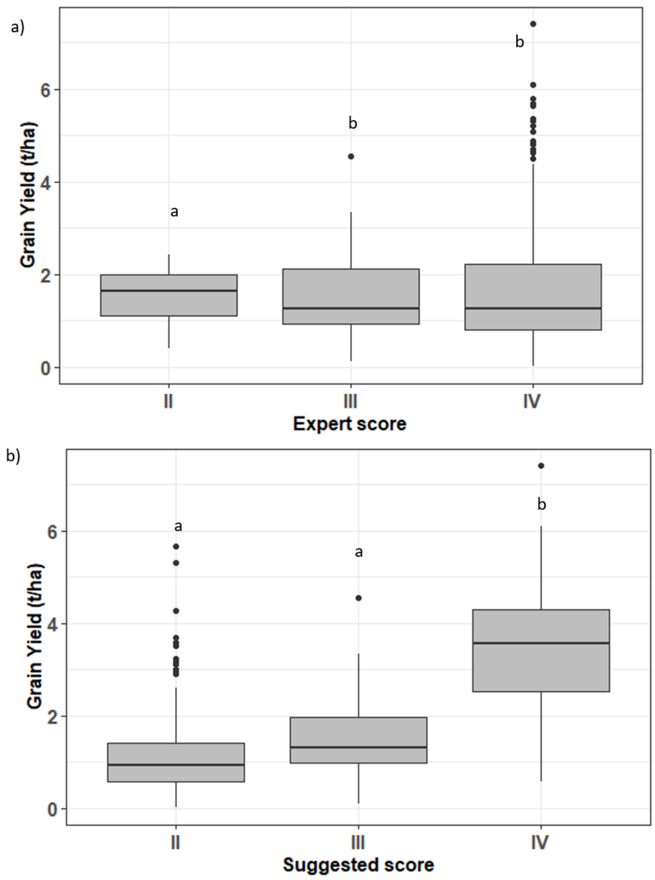
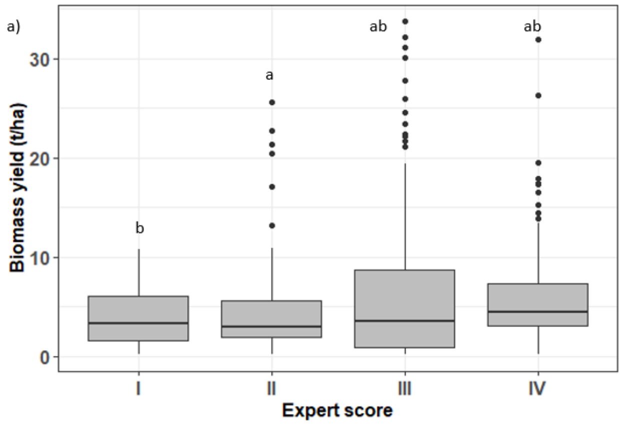


Figure 12. Distribution of legume species grain yield in a) the different expert scores, and b) the literature-derived suggested scores. Scores with different letters are significantly different from each other.

Literature-derived means for biomass yield differed significantly when mapped to the scores assigned by experts for provision of livestock feed between legume species (Figure 13a). However, there was no clear pattern and the literature-derived mean for species assigned a score of I was higher than the mean for species assigned a score of II. Scores III and IV were not significantly different from each other or from scores I and II. To improve the expert scores, new suggested scores were developed by creating four categories for biomass yield: <2 t, 2-5 t, 5-10 t and >10 t ha^{-1} for scores I, II, III and IV respectively. The results show that the literature derived means mapped to each suggested score differed significantly. Scores I and II were significantly different from scores III and IV and scores III and IV also differed significantly (Figure 13b).



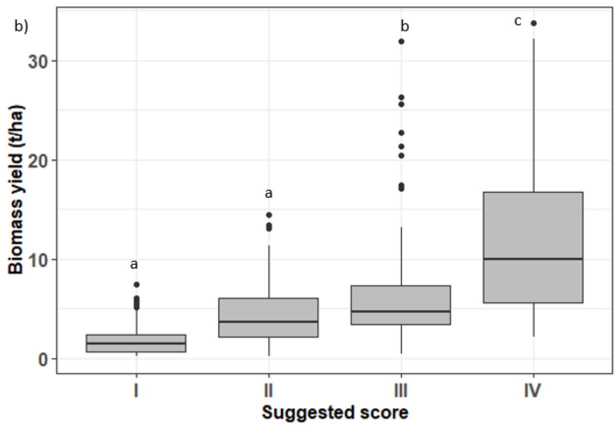


Figure 13. Distribution of legume species biomass yield for a) current expert scores, and b) suggested literature-derived scores. Scores with different letters are significantly different from each other.

The results show there were significant differences in mean values from the literature for legume species falling into different expert score categories for BNF (Figure 14). Although there were significant differences between expert scores there was no clear pattern for scoring, only scores II and III were different from each other. This was because many legume species which can fix >100 kg N ha^{-1} were scored low e.g. cowpea, field pea, soybean and chickpea.

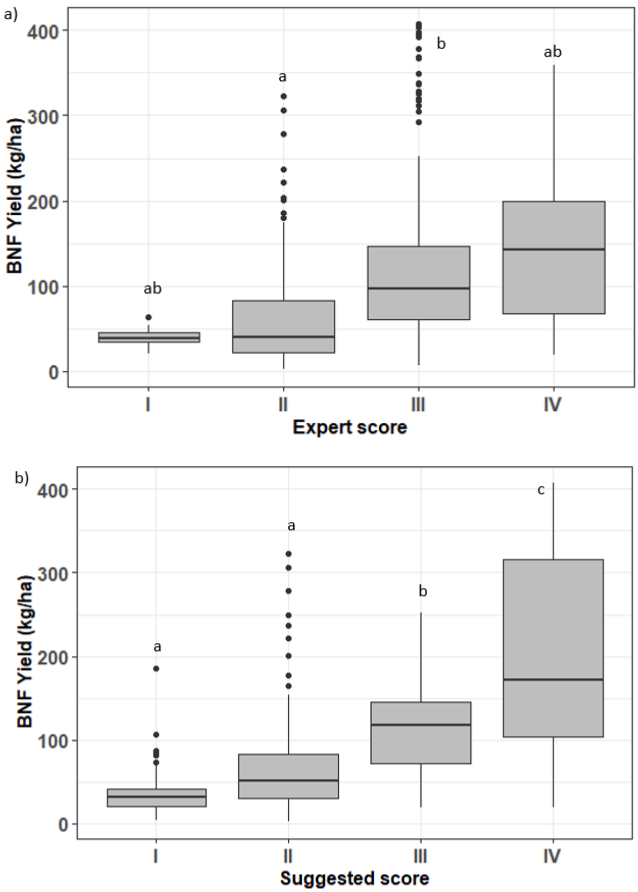


Figure 14. Distribution of legume species based on their biological nitrogen fixation (BNF) capacity in a) current expert scores, and b) literature-derived scores. Scores with different letters are significantly different from each other.

To establish literature-derived scores for fixed N, four categories were suggested: <50 kg N, 50-100 kg N, 100-150 kg N and >150 kg N ha^{-1} for scores I, II, III and IV, respectively. The results show significant differences between the scores suggested based on literature values for legume species BNF (Figure 14b).

5 Discussion and conclusions

5.1 Discussion

5.1.1 Farmers' perceptions on legumes and their functions

Although legumes are well known to scientists as a plant group the extent to which this is true among farmers in SSA has been unclear. In the present work, taking DRC and Kenya as case studies, it is clear that farmers in both countries have some knowledge about legumes (Paper I). This could be as simple as knowing about the presence of legumes in their cropping systems, especially grain legumes including common bean and groundnut, which were generally easily identified by farmers. However, herbaceous and tree legumes could not be readily identified by most farmers, as well as their benefits in soil fertility improvement through BNF (Paper I). Farmers in DRC had less knowledge about legumes than farmers in Kenya. This could be linked to low agricultural productivity in DRC as a result of civil wars that have affected its economic development in recent years including failures of markets and transportation systems (Ochieng *et al.*, 2016). Limited access to markets constrains farmers' choice on which crops to grow on their farms. Differences in farmers' knowledge about legumes were also observed between farmers who had been exposed to an agricultural research for development project, LegumeCHOICE and those who had not. This suggests that interaction between researchers and farmers. For example, in research trials and focus group discussions, can help farmers increase their knowledge on different legume types and their uses. This finding supports the finding of Kangmennaang *et al.*, (2017) who reported that farmers' engagement in projects/research led to higher adoption of a recommended technology.

5.1.2 Legumes ecosystems services and effects of management practices on legume productivity

Some legume "functions" were well known by farmers while others were less well known (Paper I). In the LegumeCHOICE project six legume functions were identified; to provide food, livestock feed, generate income, improve soil fertility, reduce soil erosion and supply the need for fuel (Duncan *et al* 2019). Food and income as benefits of legume growing were better known and appreciated by more farmers than soil erosion control and soil fertility improvement (Paper I). This was supported by the observation that grain legumes are more common in the study sites than herbaceous and tree legumes, and food and income were ranked the two most important legume functions after farmers had all the functions explained to them in detail. The short-term need for income and food makes farmers prioritize these before more long-term benefits, such as soil fertility build-up. Another reason why the long-term effects seem to be neglected is the insecure land tenure system in some areas of east Africa with farmers fearful of losing land in which they have made long term investments (Place, 2009). However, using legumes has potential to increase productivity through reduced soil erosion, runoff and improved soil biological activity as shown in Paper III. When Calliandra was established in hedgerows along the contour lines and its leaves were used as mulch in maize and common bean intercropping, water infiltration was improved, earthworm populations increased and erosion reduced. This is due to increased soil cover which reduce raindrop energy that results in low runoff velocity which encourages more infiltration of water (Salako *et al.*, 2006). If farmers are interested in increasing soil fertility and livestock feed availability, herbaceous legumes such as Mucuna which provides high ground cover and produces high biomass are a promising option.

The meta-analysis showed that legumes respond positively to inoculation and P-application systems and that the result were consistent across various environment in SSA (Paper II). These two management practices are directly related to BNF that further boost productivity by adding N to the system (Manrique *et al.*, 1993; Hoffman *et al.*, 2014). The soil mineral-N and total-N might eventually increase because more N enters the system through BNF, but the extent to which this happens depends on how much N leaves the system through losses and sold products. Increasing mineral N in the soil increases grain and biomass yield of crops that are not able to form associations with rhizobia. In addition, several studies have reported that farmers could obtain additional yield benefits from inoculation with rhizobia if it is combined with an application of P (e.g. Vanlauwe *et al.*, 2019). Thus, these management practices can be generally recommended in SSA farms to increase legume yields. Some legume crops responded more to inoculation than others. This is due to the capability of some legumes, usually promiscuous legumes, e.g. cowpea, to nodulate effectively with the indigenous rhizobia population (Vanlauwe *et al.*, 2019), hence not inoculated yields of such crop species are comparable with that of inoculated crops of the same species.

Although intercropping resulted in lower legume grain and biomass yields than when sole cropped, the total productivity of the companion crops was higher in intercrops (Paper II). These results support Himmelstein *et al.*, (2017; Kermah *et al.*, (2017); Masvaya *et al.*, (2017) and Rusinamhodzi *et al.*, (2017) who observed total LER greater than 1 in smallholder farms under intercropping. Reasons for this may include reduction in weed and disease pressure, soil conservation and maintenance, better nutrient capture and optimizing resource use efficiency (Agegnehu *et al.*, 2008; Bationo *et al.*, 2012; Wick *et al.*, 2017; Ryan *et al.*, 2018). Some legume crops including groundnut and pigeon pea were less affected by intercropping than others. This may be due to improved shade tolerance of these species through breeding for example through increased specific leaf area and higher chlorophyll content (Gong *et al.*, 2015). Pigeon pea and groundnut has a slow growth during the first 8 weeks and are non-climbers hence there is little competition with the companion crop (Kimaro *et al.*, 2009; Jat *et al.*, 2011; Saxena *et al.*, 2018). Pigeon pea has wider row spacing than other legumes and its often intercropped with crops with similar row spacing and between the companion crops rows (e.g. maize) that leads to similar plant population in intercrops and sole crops (e.g. Rusinamhodzi *et al.*, 2017). In the meta-analysis, the rLER of pigeon pea was found to be 90%. Hence, when designing intercrops advisors and farmers should consider the competitiveness and adaptability of species in crop mixtures.

5.1.3 Supporting decision making for legume use with LegumeCHOICE tool

Use of expert scores in the LegumeCHOICE tool helps in making well-informed decisions on legume options and the potential of different type of legumes to fulfil food, feed, fuel, income and soil improvement requirements in smallholder farms (Paper IV). The expert scores are based on experts' knowledge and experience and the results of expert scores validation indicate that were generally in line with literature-derived values. However, lack of clear and expected patterns on expert scores for food, feed and soil fertility functions were observed. This was because the experts included other factors besides legume productivity in their scoring. For example, for provision of food, experts included yield stability, nutritional value and farmers' preferences when scoring legume species for this function. The adjusted scores helped improve the validity of scores of legume species for food, feed and soil fertility improvement functions using grain and biomass yield and BNF as proxies. This was achieved by developing categories based on literature-derived values that separated legume species based on their grain yield, biomass yield and N fixation. Species that were scored below their BNF potential, e.g. cowpea, field pea, soybean and chickpea, were suggested to get revised scores for their potential to improve soil fertility. Thus, addition of literature-derived data in scoring of legume species for the three functions improved the reliability of the scores. Lack of significant differences on low scores (I and II) could be improved by introducing other factors such as yield stability where species with high stability and which produce high yields are scored higher than those with low yield stability.

5.1.4 Limitations of the current LegumeCHOICE tool

Although the LegumeCHOICE tool is potentially useful in providing legume options and supporting legume use in smallholder farms it has some weaknesses (Paper IV). These include that farmers who are expected to benefit more from making well-informed and improved decisions on suitable legumes in their locations lack understanding of what legumes are as a concept (Paper I). Thus, there is need to inform/educate farmers more about legumes and their properties, and how they can be incorporated in their farming systems to address challenges they face.

The LegumeCHOICE tool makes recommendations for suitable legumes at species level and is silent on how, where and when legumes could be incorporated into smallholder farms. However, the tool can be further developed and suggest options for management practices. The meta-analysis study (Paper II) has shown that legumes respond consistently to key management practices such as intercropping, inoculation and phosphorous (P) application. Thus, general recommendations for management can be made.

There is limited information on contribution of legumes to control soil erosion in SSA. In paper III, cropping systems with different legume types effectively reduced soil erosion e.g. velvet bean and Calliandra hedgerows with mulching. In these experiments, legumes were also intercropped which increased overall productivity. Also use of legumes increases soil cover which improves water conservation that increases crop yields.

5.2 Conclusions and Recommendations

Farmers perceive legumes as a source of food and income, thus grain legumes were more readily identified by interviewed farmers than herbaceous and tree legumes. Their knowledge about other key functions including soil fertility improvement (through BNF), provision of livestock feed and fuel are not well articulated. Thus, farmers put more value on short-term benefits of legumes than long-term benefits such as natural resource management. Satisfying food requirements among farming communities could leave more scope for longer-term perspectives and hence more value placed on non-food functions with potential environmental benefits.

Farmers with high tropical livestock units scored provision of livestock feed function higher than farmers with lower tropical livestock units. Thus, farmers' socio-economic context may influence their preferences for legume functions. However, there were no significant differences between DRC and Kenya farmers on scoring for income, soil fertility improvement, provision of feed and soil erosion control. Thus, I conclude that farmers require more than just knowledge to realize the more long-term benefits associated with growing legumes.

Intercrops involving legumes are an attractive option in smallholder farms since they improve crop productivity. Pigeon pea was more compatible than other grain legumes in intercropping because of different crop habits and differences in time of demand for resources when grown with main crops like maize and cassava. Inoculation helped to increase legume grain yield, biomass yield and BNF. Phosphorus application was shown to be crucial for legume productivity under different conditions in SSA, hence their emphasis in legume production may help increase legume grain and biomass yields. Legume productivity is influenced by legume species, soil texture and annual rainfall in response to management practices.

Incorporating a mixture of crop types in cropping systems has the potential to reduce runoff and soil loss, increase earthworm populations and rainwater infiltration in smallholder farms. Use of a mixture of crop types including herbaceous and woody species in cropping systems increases soil cover, which reduces runoff and soil erosion. Mucuna as sole crop and Calliandra hedgerows in maize-common bean intercrop produced both higher soil cover and more above ground biomass compared to farmer practice (maize-common bean intercrop), which resulted in higher infiltration rates and numbers of earthworms. Larger earthworm populations contributed to increase water infiltration through soil aggregate formation and increased porosity.

The LegumeCHOICE tool has potential to support informed decision making on legume selection in smallholder farms. Use of expert scores in the

LegumeCHOICE tool is helpful in developing a list of legume options, which can provide the functions needed/requested by smallholder farmers. Lack of clear patterns in the current scoring system for grain yield, biomass yield and fixed N suggests that some revision of scores may be needed based on published data for scoring of these functions. Due to high variation of grain and biomass yield factors including yield stability could usefully be considered in arriving at new scores. For example, high yielding species which have high yield stability would be scored higher.

Overall, this research has re-emphasized the important role of legumes for multiple purposes in smallholder farming systems in east Africa. It has pointed to various hindrances to broader integration and use of legumes in mixed crop-livestock systems including lack of farmer knowledge on tree and herbaceous legumes, the strong focus on short-term gains among farmers, the need for better agronomic management and the refinement of extension tools to support farmer decision-making. These are all areas which will require more attention in future work if the full potential of multi-purpose legumes is to be realised among the smallholder farmers of east Africa.

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