Tailoring Agroforestry Technologies to the Diversity of Rwandan Smallholder Agriculture

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Abstract

Smallholder livelihoods in sub-Saharan Africa (SSA) are constrained by a number of factors that limit food production and thereby threaten food security. Soil fertility is one of the major factors explaining the decrease in per capita food production in SSA. Nutrient deficiencies in particular N and P severely limit agricultural production in many regions in the tropics. Supply of adequate amounts of nutrients through fertiliser application is therefore a prerequisite to balance soil fertility budgets and to boost food production. However, mineral fertilisers are not accessible to the large majority of smallholder farmers. Farmyard manure, an important source of organic fertiliser for smallholder farmers, is available at limited quantities due to low livestock densities in many regions, for example Rwanda. Agroforestry, a low-input technology, was shown to contribute to the enhancement of food production while ensuring sustainability in sub-Saharan Africa. Agroforestry may contribute to soil fertility by increasing nutrient availability and providing other various benefits and services. However, to be successful agroforestry technologies need to match the characteristics of different smallholder farming systems, like for example soil fertility status, socioeconomic status and farmer management. These factors are rarely studied in an integrated manner.

This thesis aims to understand and characterise different farming systems, evaluate the potential for the most promising agroforestry practices and suggest the most suitable agroforestry recommendations for different farming systems in targeted agro-ecological zones of Rwanda. The approach combined characterization of farming systems, participatory tree testing, farmer's evaluations of technologies, and scenario and trade-off analyses in two agro-ecological zones: Central Plateau (moderate altitude) and Buberuka (high altitude zone). Two locations, Simbi and Kageyo sectors were selected as representative study sites. Wealth ranking techniques allowed the identification of three farm resource groups (RGs). Though three farmer classes were identified in

the two locations and referred as RG 1, RG 2 and RG 3 respectively, farmer classes were unique to each location. Averaged over sampled villages, 76% of all households belong to RG 1 class in Simbi versus 67% in Kageyo. This least resourced group with on average 0.20 ha of land and with 1 goat was the most vulnerable farmer group in terms of food security (20 to 25% protein deficient). RG 2 (9 to 31%) was intermediate between RG 1 and RG 3. RG 3 (2 to 7 %) was the wealthiest (1 to 3 ha, 2 or more cattle) and food-secure for at least 10 months. Soil nutrient balances were negative in most farms due to small amounts of nutrients applied, which did not compensate for nutrient removal during harvest. From an agroforestry perspective, Simbi contrasted with Kageyo in tree diversity and density but tree niches and management were similar between the locations. The main agroforestry species may be categorised into three classes including timber, legume and fruit tree species based on the main functions. The results clearly indicated the need to improve soil fertility and food production using integrated soil fertility approaches that promote a combined use of agroforestry resources and other fertiliser sources to replenish the soil nutrients and improve the efficiency and cost effectiveness of inputs use at farm level.

Experiments evaluated the potential effects of agroforestry species on production within different farming systems. *Tephrosia* species were tested as a source of mulch in coffee plantations in the Central Plateau agro-ecological zone. Application of *Tephrosia* mulch resulted in higher biomass and better economic returns when established in coffee fields, particularly when *Tephrosia* mulch was combined with NPK. Application of prunings of *Calliandra* increased maize productivity, net returns and the ratio between gross margin and costs of inputs on all farms except the richest farms. This positive effect of *Calliandra* was larger in Kageyo than in Simbi. The effect was even more pronounced with P application. The results indicated that fields responded differently within farms, and significant differences between locations were present.

The assessment of fodder availability within different farming systems revealed that animal feeds are widely diversified, with *Pennisetum* being largely used in wealthier farms (RG 3), while RG 1 farmers use larger quantities of marshland-herbs and crop residues. There was a strong variation in seasonal feed availability. Napier and *Calliandra* were more available during the wet season, while banana pseudo-stems were used more in the dry seasons. Quantification of the year-round fodder availability showed that RG 1 farmers are unable to keep a cow, while RG 2 and RG 3 could keep local or improved cows under specific scenarios. Biophysical (rainfall, field type) and socio-economic conditions (wealth status) as well as farmer preferences were factors influencing the choice and performance of agroforestry technologies. The study recommends revisiting current agroforestry research policies and taking into account farmer's preferences as priorities in the agroforestry research agenda.

Keywords: food security, biophysical and socioeconomic conditions, farmer resource groups, productivity, economic evaluation, scenario analysis

The doctoral journey has been a mix of excitement and challenges but finally reaching destination. During the journey, collaboration with scientists, friends and other fellow PhD students has tremendously contributed in addressing some of the critical issues. It is quite impossible to name all of them here, but let me say thank you so much to you all.

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Dedicated to my dear family, living and deceased, with deep gratitude for their support.

Contents

Chapter 1

General introduction

1.1 **The problem of food insecurity in sub-Saharan Africa and the role of agroforestry**

Smallholder farming systems of sub-Saharan Africa (SSA) are generally characterized by poor productivity. In the highlands of East and Central Africa, high population densities lead to strong pressure on land, resulting in poor and declining soil fertility due to continuous cultivation of land. The majority of smallholders removes nutrients from the soils without applying sufficient quantities of manure or other fertilizers to replenish the soil, resulting in negative soil nutrient budgets (Stoorvogel and Smaling 1990). Poor agricultural production of smallholder farmers is the direct cause of food insecurity in sub-Saharan Africa (Sanchez 2002). These problems are likely to increase, as the human population is growing faster in Africa than in other parts of the world (Sanchez et al. 1997).

The farming systems of Rwanda are predominantly focused on subsistence, producing food for home consumption. Agricultural activities take place on small pieces of land scattered over plateau and hills. Major crops include food crops including banana, root and tubers, cereals, coffee and legume crops. Coffee provides the main smallholder income in those areas where it is grown. However, smallholder coffee growers are confronted with the limited mulch availability to sustain coffee production, mostly relying on mulch material collected from food crop fields, resulting in increased soil fertility in coffee fields at the expense of food crop fields.

Cattle are the major type of livestock in Rwanda. The cattle population is likely to increase significantly with the current “one cow for one poor farmer” policy (MINAGRI 2006) whereby cattle are donated to most vulnerable households across the country. With such an increase in the cattle population, cattle feeding is likely to be a major challenge for smallholder farmers with little land. Alternative options for animal feed are important.

Given the dense population and the lack of alternative employment, agricultural intensification is key to meeting the needs of the rural poor in Rwanda. Considerable focus has been placed on the role of agroforestry (den Biggelaar 1994; Balasubramanian and Egli 1986). Agroforestry may supply basic needs including firewood, food, medicine, fodder, timber, boundary markers, windbreaks, soil erosion barriers, beauty and shade (Young 1997; Franzel et al. 2002). In addition, the potential of agroforestry in Rwanda lies in the fact that the majority of smallholder farmers rely on organic residues to maintain soil fertility, to use as mulch as well as for fodder. It may be expected that farmers are open to further intensification of these practices.

The majority of agroforestry research conducted in the 1990s focused on improving soil fertility (Balasubramanian and Sekayange 1992; Roose and Ndayiragije 1997), on erosion control (König 1992) and on leguminous forage quality (Roose and Ndayiragije 1997; Niang et al. 1998). However, the promoted agroforestry technologies are not necessarily the trees that appear to be most preferred by farmers as the most commonly observed species are *Eucalyptus* spp. and *Grevillea robusta*. Legume trees and shrubs have the particular benefit of being able to fix N_2 from the atmosphere (Giller 2001). Given the poor soil fertility status in smallholder farming systems of Rwanda, and the lack of mineral fertilizers, legume shrubs deserve particular attention.

1.3. **Legume species as an option for enhancing farm productivity in Rwanda**

Numerous studies in sub-Saharan Africa have reported on the potential of fast-growing nitrogen fixing legumes in maintaining crop productivity (Mugendi et al. 1999; Nziguheba and Mutuo 2000; Drechsel et al. 1996) and improving livestock production (Paterson et al. 1998; Wambugu et al. 2011).

Among the widely-grown legume species by smallholder farms in Rwanda, *Calliandra* is particularly preferred because of its good leafy biomass production. However, legume residues are unable to supply sufficient P to meet crop requirements (Palm 1995). *Calliandra calothyrsus* leaf biomass provides highly palatable and nutritious fodder for livestock has positive benefits on milking performance (e.g. Wambugu et al. 2011). The question for *Calliandra* remains as to how the effectiveness of its use in smallholder farming systems in Rwanda can be improved.

Other leguminous species are also underutilized. *Tephrosia* species were identified as among the most promising fast-growing legume shrubs in Rwanda (Balasubramanian and Sekayange 1992; Drechsel et al. 1998). Currently, however, its uses are limited to use in fish harvesting, as a livestock medicine to control ticks, or as a pesticide in stored cereal grains due the high concentration of rotenone in the foliage. Elsewhere, *Tephrosia* has successfully been tested as a source of mulch in smallholder farming systems (e.g. Fagerström et al. 2001). Currently, there is limited information on the potential use of *Tephrosia* as source of mulch in perennial crops in different farms in East African countries.

Smallholder farmers operate under diverse agro-ecological, socio-economic and farm management conditions (Giller et al. 2006 2011; Tittonell et al. 2005a; Shepherd and Soule 1998a). The wide diversity of farmers in terms of resource endowment and variability in soil fertility status of different fields within farms within farming community may influence the suitability and effectiveness of different interventions such as agroforestry technologies. It is therefore necessary to assess the most suitable agroforestry approaches within the range of different farms and farming systems to identify specific best-fit packages for different contexts.

1.4. **Rationale of the study**

For agroforestry technologies to play their full role in the improvement of smallholders farming systems, selection of appropriate species is required. Integrating agroforestry technologies within a specific farming system should be driven by biophysical, socio-economic, farmer preference and agronomic performance. Important biophysical constraints include soil nutrient deficiencies, soil acidity and moisture availability (Giller and Cadisch 1995). Socio-economic factors such as farm size, type of land use may determine farmer's particular interest for specific species (Ojiem et al. 2006). Use of agroforestry species such as legume species may be affected by land availability, soil fertility and labour requirements. These complex and diversified factors act simultaneously and any attempt to analyse options for agroforestry integration within farming systems should be done in an integrated manner to achieve sustainable productivity of the overall farming system.

1.5. **Overall hypothesis of the study**

The basic hypothesis underlying this study is that:

> On-farm agroforestry practices differ among farms and farming systems because of differing biophysical, socio-economic conditions and specific farmer preferences.

Thus, different farmers experiment with different agroforestry technologies, methodologies and approaches. Given that farmer's socioeconomic characteristics have significant effects on his/her decision about the type of agricultural investment and management practices, it is expected that agroforestry technologies will widely differ within and between agro-ecological zones. A corollary hypothesis is that:

> Farmers testing the same agroforestry technology (i.e. the same tree species) within similar or different agro-ecological zones would achieve different results.

1.6**. Objectives of the study**

The overall objective of the study was to explore the potential of agroforestry to meet the different needs of smallholder farmers in Rwanda. To address this it was necessary to characterise different farming systems and farmers' interest in growing trees on their farms, evaluate the potential of a wide range of promising agroforestry practices and identify from these the best options for integration within two different agro-ecological zones (Central plateau and Buberuka agro-ecological zones) of Rwanda. The two agro-ecological zones were selected out of the six zones covering the whole country. The two zones represent the most densely populated areas in the country with the highest agricultural potential in Rwanda. In addition, the two zones were identified earlier as suitable for application of agroforestry technologies. The two zones contrast in terms of altitude, rainfall and temperatures and population density. The topography of the Central plateau zone is dominated by hills and valleys at an altitude of 1700 m and moderate annual rainfall of 1200 mm and warmer temperature of about 20^{o}C. On contrary, the northern Buberuka zone is characterised by high altitude plateaus traversed by quartzitic chains that may attain 2300 m a.s.l with an average of 1300 mm of rainfall annually and cool temperature ranging from 15 to 16^{o}C (Verdoodt 2003). Two villages (Simbi and Kageyo respectively) selected as representative of the two agro-ecological zones indicate that population density was higher in Central Plateau zone with an average of 520 inhabitants km^{-2} in Simbi against 430 inhabitants km^{-2} in Kageyo. Due to high population pressure on land and continuous land fragmentation, the average farm size is small in both locations. Mixed crop/livestock is the predominant farming system particularly in Central Plateau where smallholder farms intensify crop production on small landholdings.

The specific objectives of the thesis were:

(i) To describe the farming systems and understand farm heterogeneity, with emphasis on biophysical aspects and farmer resource management

(ii) To assess the effect of farm heterogeneity on farmer agroforestry preferences and practices

(iii) To explore agronomic and socio-economic benefits of two promising agroforestry practices in smallholder cropping systems in Rwanda by

- Evaluating the potential use of *Tephrosia* mulch in smallholder coffee farms of southwest of Rwanda

- Assessing maize yield response to *Calliandra* biomass residues with P (phosphorus) mineral fertiliser application on different farms and fields in two agro-ecological zones of Rwanda.

(iv) To explore the potential of agroforestry for feed provision in mixed crop and livestock farming systems

(v) To identify possible trade-offs relating to agroforestry resources and suggest feasible options for improvement of crop-livestock based farming systems in Rwanda.

A conceptual framework was used to identify the most suitable agroforestry recommendations for different farms. Within the framework, several research tools were applied. Existing literature (based on the International Council for Research in Agroforestry, ICRAF criteria) was used to select agro-ecological zones most appropriate for agroforestry.

Farming systems were described using formal surveys, focus group discussions and resource nutrient flows. Experimental trials, measurements and scenarios analyses were used to evaluate the potentials for using agroforestry in different farms selected from the resource groups. Promising options for agroforestry technologies in farming systems of Rwanda are identified using trade-off and scenario analyses.

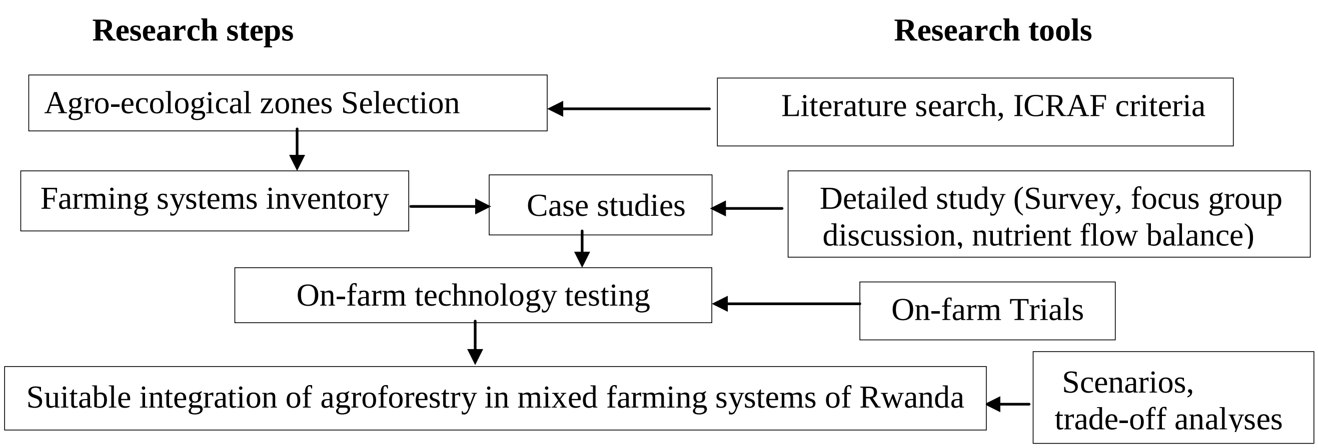


Figure 1.1 Structure of the research approach showing different steps and research tools involved in the study.

1.7. **Outline of the thesis**

Chapter 2 describes the heterogeneity in farming systems by identifying the major land and farm resource uses and relationships with food security in two agro-ecological zones of Rwanda (Central Plateau AEZ and Buberuka AEZ). Farm types are differentiated based on farmer socio-economic criteria and available resources. The resources allocated to different farm fields are quantified. Partial nutrient balances and the amount of protein and calories produced are estimated. In Chapter 3, farmers' interest in agroforestry was assessed by first making a thorough inventory of current agroforestry situation, estimating tree density and diversity in the targeted agro-ecological zones. On-farm testing of different species of trees was related to the tree management, growth and productivity and constraints faced by farmers. Farmers' perceptions and perspectives with regards to tree planting in the different locations were also assessed. In Chapter 4, the growth and biomass production of two *Tephrosia* accessions and their use as mulch in smallholder coffee plantations were assessed in degraded soils of south-west of Rwanda. *Tephrosia* biomass production and nutrient accumulation when intercropped within coffee or grown in pure stands with or without NPK fertilizer and the effects of the mulch on coffee production were assessed. In addition nutrients limiting growth of *Tephrosia* in the soils of the Maraba area were identified through a pot experiment. The economics of using *Tephrosia* to improve coffee production was evaluated by performing a cost-benefit analysis. Chapter 5 reports on maize response to different N fertilization rates in combination with P with the objective of assessing the potential contribution of *Calliandra* biomass as an N source to improve maize yields on degraded soils. Maize grain, nutrient use efficiency and economic profitability of maize crop are reported for different farms and fields in different seasons. Chapter 6 quantified the animal feeds available and on offer to livestock by farmers in different farm types of southwest of Rwanda and potential feed availability under different management scenarios. Lastly, the major findings are discussed in

Chapter 7, together with a trade-off analysis between allocating *Calliandra* biomass as green manure for maize or animal feed under different scenarios in different smallholder farming systems.

Chapter 2

Resource use and food self-sufficiency at farm scale within two agro-ecological zones of Rwanda.

This chapter is to be submitted as:

Bucagu, C., Vanlauwe, B., van Wijk, M.T. and Giller K.E. Resource use and food self-sufficiency at farm scale within different agro-ecological zones of Rwanda. *Food Security*

Abstract

Resource use and management are major determinants of the food self-sufficiency of smallholder farmers in sub Saharan Africa. At farm level, access to production resources may be different between smallholder farmers depending on their biophysical conditions or socioeconomic status, and this may determine production levels, food self-sufficiency and income of the farmer. A study was conducted in Rwanda in two contrasting agro-ecological zones (Central plateau and Buberuka AEZs) aiming at characterising different farms of different resource groups (RG) in both agro-ecological zones, quantifying their resource flows, and evaluating the effect of resource management on food self-sufficiency at farm level. The Simbi and Kageyo sectors were selected to represent the two agro-ecological zones. Two villages were selected in each sector. Wealth ranking, focus group discussions and formal survey techniques allowed identification of three farm resource groups (RGs) and selection of three representative farms per RG and per AEZ to analyse major land uses, soil fertility level and resource flows. RG 1 was the least resourced group and the most vulnerable in terms of food self-sufficiency. RG 2 was intermediate between RG 1 and RG 3. RG 3 was the wealthiest, and food-secure group of farms for at least 10 months year^{-1}. Soils were more fertile in Kageyo than in Simbi. Total annual DM yield was the largest in Kageyo (1.77 t ha^{-1} yr^{-1}). Total DM productivity was significantly higher in homefields (1.64 t ha^{-1}yr^{-1}) than in outfields (0.68 t ha^{-1}yr^{-1}). N and P inputs were the largest in Kageyo (20.28 kg N ha^{-1}yr^{-1}; 6.50 kg P ha^{-1}yr^{-1}) and the smallest in RG 1 farms. N partial balance was more negative in Kageyo (-35.87 kg N ha^{-1}yr^{-1}). P balance was negative in close fields and outfields but positive in the homefield (0.43 kg P ha^{-1}yr^{-1}). In Simbi, dietary calories consumption per capita was 26% below the required standards. Consumption of calories was only 40% and 67% of the required standards in RG 1 and RG 2 farms. In Kageyo, a deficit in calories consumption was only noticeable in RG 1. For proteins, RG 1 and RG 2 farms had a 48 and 17% deficit in Simbi while RG 1 farms had a deficit of 44.4% in Kageyo. Food self-sufficiency under a scenario of maximum maize production substantially improved in both RG 1 and RG 2 farms. There is a need to apply integrated approach to better understand differences between farms and identify best options to ensure sustainable agricultural production and food self-sufficiency.

Keywords Agro-ecological zones. Farmer resource group. Field type. Partial nutrient balance. Food self-sufficiency

Introduction

The major challenge for future food security is to match food supply to the rapidly rising demand of an increasing population, and at the same time ensure that this is done in an environmentally and socially friendly way (Godfray et al. 2010). Severe food deprivation is acute in sub-Saharan Africa and is aggravated by a high degree of poverty. The situation of food security is likely to worsen in the future since the population of Africa is projected to continuously grow and reach 1.8 billion by 2050 (United Nations 2004) while per capita food production shows a declining trend (Abdulai et al. 2004). The largest proportion of agricultural production in developing countries come from smallholders and projections showed that this situation will remain like this for at least the next 30 years (Thornton and Herrero 2001).

Smallholder farming faces a number of constraints. Landholdings have shrunk continually in size due to rapid population growth rates. In countries such as Rwanda, 59% of farmers have an average farm size smaller than 0.5 ha (MINAGRI 2009), and these are mostly located on relatively hilly landscapes which are highly susceptible to erosion (Yamoah et al. 1989). Crop production is hampered by widespread land degradation and soil fertility depletion, together with erratic weather (Ruben and Pender 2004; Jones and Thornton 2003).

Applying fertilisers to address the problem of poor soil fertility is essential to increase on farm food productivity. However, mineral fertilisers use is very limited due to difficulties for farmers to access these inputs (Lal 2009). Animal manure is an important source of soil nutrients but is in short supply due to limited livestock numbers. The consequence is widespread nutrient deficiencies (Sanchez et al. 1997; Smaling et al. 1997; Mokwunye et al. 1996). The lack of inputs results in severe soil fertility depletion (Stoorvogel and Smaling 1990; van der Zaag 1982). Nutrient balances have been used extensively as an indicator of land degradation (Smaling and Braun 1996; Scoones and Toulmin 1999; De Jager 2005; Grote et al. 2005) or sustainability of farming systems (Ebanyat et al. 2010). The nutrient balance provides an insight of the management practices that influence the flows of nutrients in and out of a given farming system. For Rwanda, information on nutrient balance is still scanty and the most used information refers to the estimates from the 1990s (Stoorvogel and Smaling 1990). Though these estimates may provide a broad idea to what extent soils are depleted, they may be less meaningful on informing about the current rates of nutrient use, removal and the nutrient budget at farm scale.

The approach in setting-up strategies for sustainable production systems in Rwanda has to take into account the diversity in biophysical, socio-economical and farmer management conditions. Climatic conditions differ between agro-ecological zones of Rwanda (Niang and Styger 1990). At farm level, farmer resource endowment may differ from one farmer to another and access to production resources (land, labour and various inputs) may determine production levels, food self-sufficiency and income of the farmer. Several other studies (e.g Pinchón 1997) found that soil fertility, topographical location of farm land and household endowments significantly influence land use decisions. Also farm household demographic characteristics (education level of household head, family and wage labour) had significant effects on land use decisions. Relating nutrients balances to farm households characteristics can help to identify factors that influence sustainability of farming systems.

Improved understanding of factors underlying the diversity and heterogeneity of smallholder systems, and ability to identify patterns of variability, should help to better target technologies to specific socio-economic niches (e.g. Ojiem et al. 2007). The present study aims at identifying major land and farm resource uses and the resulting food self-sufficiency status in different agro-ecological zones of Rwanda as a basis for designing appropriate interventions for improving the existing farming systems. The specific objectives were (i) to characterise different resource group farms in two agro-ecological zones of Rwanda; (ii) to quantify resource flow trends within different farming systems, (iii) to evaluate the effect of current resource management on food self-sufficiency at the farm level and (iv) to assess changes in food self-sufficiency under a maximum maize production scenario at farm scale.

Methods

Sampling frame

Agro-ecological zones selection

We studied two of the six agro-ecological zones in Rwanda, namely the Central plateau and Buberuka agro-ecological zones (Figure 2.1), which represent the most densely populated areas with good agricultural potential. These two zones are located in areas classified as suitable for agroforestry based on ICRAF criteria (1000 m a.s.l and over 1000 mm of rainfall) (Djimde et al. 1988). The topography of the Central plateau zone is dominated by hills and valleys at an altitude of 1700 m and moderate annual rainfall of 1200 mm and mean annual temperature of 20^{o}C. The dominant soils on uphill areas are cambisols, leptosols and acrisols, with histosols and vertisols mainly occurring in the valleys. On contrary, the northern Buberuka AEZ zone is characterised by high altitude plateaus traversed by quartzitic chains that may reach 2,300 m a.s.l with 1,200 to 1,400 mm of rainfall annually and cool temperature ranging from 15 to 16^{o}C (Verdoodt 2003). Cambisols, nitisols and leptosols are the dominant soil types in uphill areas and histosols and vertisols in wetland areas (den Biggelaar 1994). In both locations, rainfall follows a bimodal pattern allowing two growing seasons, a short rainy season running from September to December (4 months) and a long rainy season that runs from February to May/June (3 to 5 months) with the dry season sometimes shortened to 2 months (Verdoodt 2003). Due to high population density (400 to 500 inhabitants km^{-2}) and land fragmentation, the average farm size is small in both locations. Mixed crop/livestock is the predominant farming system, particularly in the Central Plateau zone where smallholder farms intensify crop production on small landholdings. The pictures (Fig. 2.2) taken during the short rains 2008 season explicitly highlight moderately sloping hills and large valleys features in central plateau agroecological zone (A), contrasting with higland mountains and steep slopes leading to narrow valleys in northern Buberuka (B).

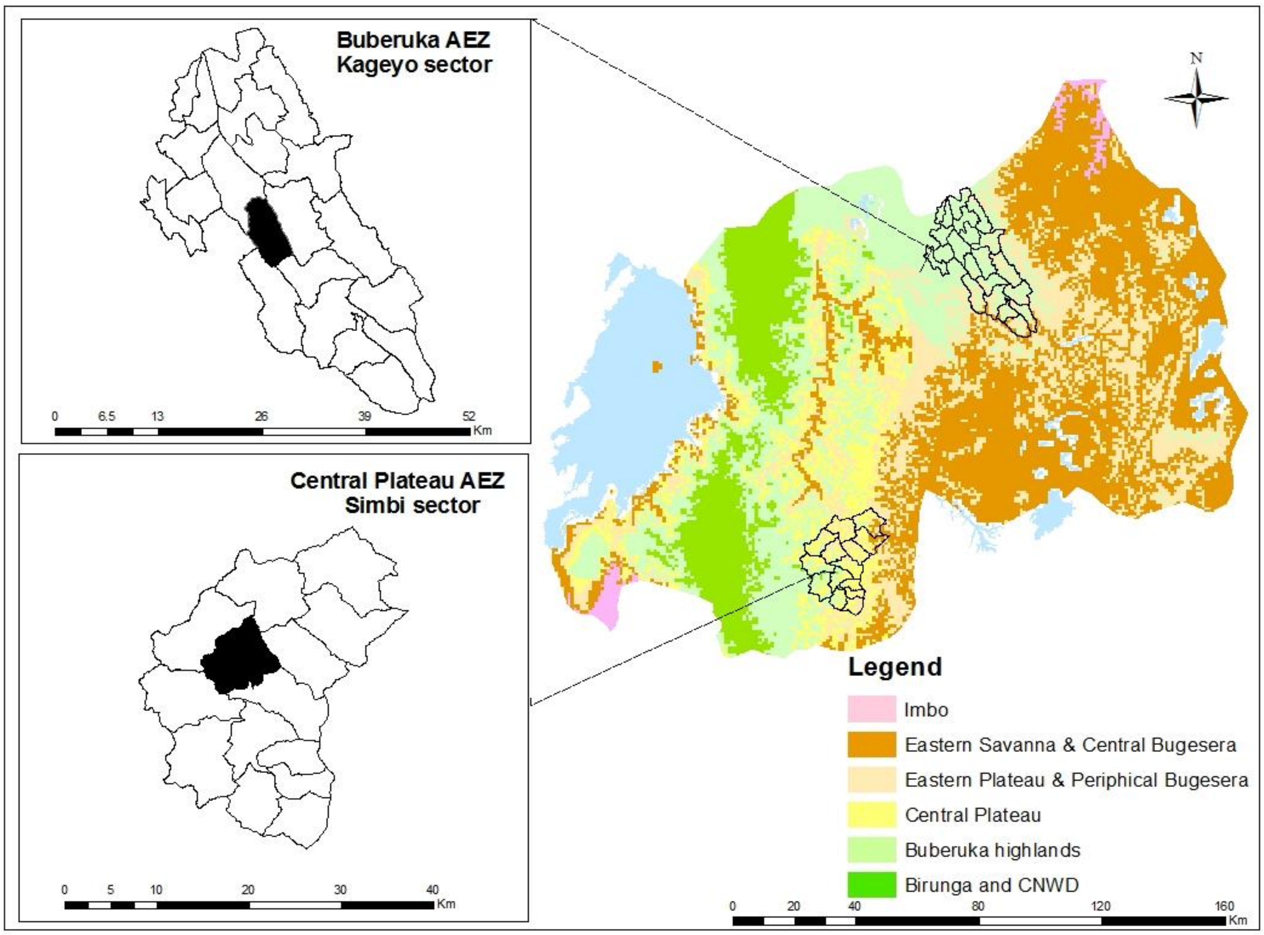


Figure 2.1 Selected study areas within different agro-ecological zones (AEZ)
Source: Agro-ecological map generated by Bucagu et al (2012, unpublished)

A B

Figure 2.2. Landscape view of Central Plateau (A) and Buberuka highlands (B) agro-ecological zones

Selection of study locations based on predominant types of land use

In each AEZ zone, representative sites were selected based on major land use types. The study areas were selected based on consultation with local leaders, agronomists and after touring the two agro-ecological zones. Other criteria were based on the existence of information on the areas where several projects were conducted in the past, availing documentation used in this study. In the Central plateau, Simbi sector (2˚ 30' 28''S and 28˚ 42' 09'' E) was selected to represent the mixed cropping system that is the dominant practice in the farming system in southwest of Rwanda. The main crops are beans (*Phaseolus vulgaris* L.), cassava (*Manihot esculenta* Crantz), and maize (*Zea mays* L.) together with coffee (*Coffea arabica* L.) as a cash crop. In homegarden fields, banana (*Musa* spp.) is intercropped with beans together with other indigenous vegetables (e.g. *Colocasia esculenta* (L.) Schott, *Amaranthus* sp.). Such practice is characterized by a wide spacing between the banana plants, allowing intercropping of several crops. In fields further away from home, beans or maize are commonly mixed with sweet potatoes (*Ipomoea batatas* L.) or cassava that constitute the basic diet for most rural household community. By contrast, coffee is grown as a monocrop in most cases. In Buberuka, Kageyo sector (1^{o} 36'54''S, 30^{o} 04'42''E) was selected to represent the potato (*Solanum tuberosum* L.) and wheat (*Triticum* sp.) based farming system. The main biophysical characteristics of the study zones are reported in Table 2.1. Two villages were selected in each sector. These were Maliza (115 households, 583 people) and Murera (164 households, 1324 people) within Simbi sector, where farms are found on the hill slopes around a large valley-bottom. In Kageyo, Mutobo (94 households, 529 inhabitants) and Musura (98 households, 575 inhabitants) were selected. They form a watershed with a narrow valley representing the general landscape structure of Buberuka agro-ecological zone. These two villages were close to each other and situated at 2 km from the local market and 5 km from the main market of Rukomo (Gicumbi city). In both locations, livestock comprises cattle but also small ruminants (goats, pigs and sheep); poultry is less developed due to diseases outbreak. While cattle are reared for milk and dung production, small ruminants are often kept as living savings that may be converted into cash when any need arises. Cattle are largely local bred cows (Ankole) but there is a shift to cross-bred cattle with the ongoing ‘one cow one family’ policy that aimed at enabling vulnerable households to own an improved dairy cow.

Socio-economic farm characterisation

A series of meetings was held, with first the local leaders and then with household representatives to gather the baseline socioeconomic and biophysical information. For practical reasons, households from the two villages per sector were gathered together in one village. A first meeting held with local leaders aimed to gather the general information (the total number of households, major socio-economic features, population and livestock statistics). Focus group discussions were held with representatives of households to identify criteria they used to classify themselves into resource groups. A participatory wealth ranking allowed categorising local households into three categories based on land size, the number of cattle, the type of house, and the ability of the farmer to hire labour (Table 2.2). Other criteria were not consistently selected across all locations. For instance, the size of the forest or woodlot was an additional criterion in Kageyo. Three farmer categories were identified based on resource endowment: a poor resource group (RG 1), a moderate resource-endowed farmer group (RG 2) and a wealthier resource farmer group (RG 3). The farm typology was later validated by comparing it with a nationwide Ubudehe farmer categorisation (Ansom 2008). Using the list of farmers available at village level, each farmer was then allocated to one farmer group based on the criteria identified for the resource grouping. Farmers were then sampled for a rapid survey for a broader socio-economic characterization. Samples of 164 and 115 in Umurera and Maliza respectively in Simbi and 94 and 98 in Mutobo and Musura villages respectively in Kageyo were then selected following the proportions of farmer groups within the population. A formal survey was conducted using a structured questionnaire to elicit data on major characteristics of household, major grown crops and types of animals.

Table 2.1 Main biophysical characteristics of the selected working sites

Variable	Unit	Sites	
		Simbi	**Kageyo**
Agro-ecological zones		Central Plateau	Buberuka
[1*]Altitude	m a s l	1634	1736
[2*]Geographic coordinates	Degree	2˚ 30' 28''S, 28˚ 42' 09'' E	1° 36'54''S, 30° 04'42''E
[3*]**Rainfall**			
Total annual rainfall	Mm	1050 to 1200	1100 to 1300
Rain distribution			
Short rains		February to May	March to May
Long rains		September to December	September to Mid-December
[4*]**Temperature**			
Annual mean	°C	19	15 - 16
Annual maximum	°C	30	20
Annual minimum	°C	10	12
[5*]**Soil type (dominant)**		Cambisols, Leptisols and Acrisols dominant on uphill while histosols and Vertisols dominant in valley	Cambisols, Nitisols and Leptisols dominant on uphill while histosols and Vertisols dominant in valley
[6*]Population density	# inhab km^{-2}	520	430
[7*]Dominant cropping systems		Mostly intensive crops association with predominance of sweet potatoes, beans, maize, bananas, colocasia and soyabeans	Mostly monoculture with predominace of maize, peas, potatoes, wheat, bananas, beans, sorghum and sweet potatoes

[1*2*]Own data taken at sectors headquater offices; [3*] Verdoodt (2002); [4, 5*] Djimde, 1988; Niang & Styger (1990), [6*]PDD: Plans for Development of Districts of Huye (Simbi, 2007) and Gicumbi (Kageyo, 2007) [7*]Den Biggelaar, C (1996). Geographic coordinates were taken nearby offices of selected villages within districts

Field typology

During the discussion group, farmers indicated that wide variability in soil fertility exists across farms, and that soil fertility is in general decreasing with distance from the home compound. Farm fields were, therefore, categorised into three classes (homefield, close field and outfield) based on the relative distance from the homestead. Homefields were generally next to home compound located at some 10 to 30 m generally under banana crop mixed with beans, vegetables and fruit trees. Close fields are located at some 50 to 100 m from home compound mostly reserved for mixed food crops such as beans, maize for local consumption, sweet potatoes. Some close fields are grown with coffee plantations in Simbi. Outfields were as far as 100 to 800 m from home compounds. In Simbi, some farmers had their outfields in valley-bottom at further distance from their houses. In valley bottom, fields are fragmented and separated by small canals to allow water drainage and irrigation. Fields are cultivated by farmers organized into cooperatives and are allowed to use the wetlands under specific conditions. They have to apply similar management (choice of a single crop, planting date, weeding time, application of agricultural inputs and harvest schedule).

Detailed farm characterisation: estimating on-farm productivity and resources flow

From the farms initially sampled, three case study farms per farm type were selected in the two locations (Simbi and Kageyo) for detailed farm characterisation, totalling 18 farms. The 18 farms were selected in two villages considered as the most representative of the two locations. Case study farms of Simbi were chosen in Murera while those of Kageyo in Mutobo village. Resource flow mapping was implemented during two succesive seasons (2008 Short rain and Long rain seasons). Farms were first visited and information on the family composition, number and arrangement of production units on the farm, components of the farm systems, farm assets and infrastructure, management practices and labour supply were noted using a structured questionnaire. Answers provided by the household heads were cross-checked by asking different family members the same questions in different ways.

The second visit at the beginning of the season aimed at identifying the major crops cultivated and the amount of resources used in each plot. An overview of the arable land use pattern in both locations was made by adding up the total cultivated areas, adding up the total area per crop and calculating the share of the total area allocated to the respective crops in case study farms. Fields were measured using tapes to obtain actual field and farm sizes. In case of various mixed crops within a plot, five 1 m × 1 m squared quadrats (4 in the corners and one in the centre) were demarcated within each field. The average plant spacing and number of plants for main crops were determined. The total number of plants for a crop was then extrapolated to the total field area and the average land allocation was derived by multiplying the number of plants with the average plant spacing. In the case of crops with wider spacing (e.g cassava), the average plant density in the field was assessed. During this visit, information on individual crop management was collected, including inputs and labour allocated to different cropping activities.

Labour used for major tasks on farms (land preparation, manuring, planting, weeding, pesticide application and harvesting was recorded from farmers' reports. Children who worked on the farm outside school hours counted as half a man-day. Labour was estimated per activity and crop on farm. Labour on per unit area (man-days ha^{-1}) basis was obtained by dividing the total labour by the total area allocated to the specific field (homefield, close field and outfield). Overall labour efficiency was assessed by dividing the total annual DM by the total labour invested on the farm on annual basis.

The last visit was done towards the end of the season to assess crop production, both economic yield and residues crop. The amounts are based on farmer estimates of production of grains, pulses, root and tubers on fresh weight basis which were later converted to dry weight basis.

Quantifying nutrients use, output and partial nutrient balance

Nutrient flows were derived from the amount of mineral and organic inputs used for the three case studies per farm type (18 farms in total) and estimates of total biomass (on dry matter basis).

Estimates were derived from the amount of fertiliser applied to the different fields and the total amount of produce harvested for the short and long rain seasons 2008 as reported by farmers. Farmers indicated the amount of fertiliser and harvested products using local units of measurements such as ‘Mironko’ containers (1.5 kg of bean grains), small baskets (Agatebo, weighing 10 to 12 kg when containing root crops) and large ‘baskets’ (Ibitebo weighing 20 to 25 kg when containing root or tuber crops). Cattle dung applied was assessed in terms of number of wheelbarrows and each wheelbarrow full of fresh cow dung would weigh up to 70 kg. Dry matter content, harvest indices and nutrients content in the different crop parts (economic and residues) were obtained from various sources (Palm et al. 1997; Fageria 1992; Azam-Ali and Squire 2002). The information helped in determining the amount of residues from each crop as well as the total nutrient (N, P and K) content in the outputs. Gross DM production was estimated by summing the corresponding DM of all outputs in different forms (Grains, tubers, roots and vegetables). Compost and manure N, P and K content were obtained from the Palm et al. (1997) database. Total fertiliser use (kg) at farm level was obtained by summing up the amounts of fertiliser applied to different fields. The rate of fertiliser (kg ha^{-1}) applied to individual field was calculated considering only the area that received the nutrients. This information helped in determining the total N, P and K inputs applied to different fields. Partial nutrient balance was estimated by subtracting the average nutrient supplied through mineral and organic fertilisers from the nutrient uptake of different crops.

Soil sampling and nutrients analytical procedures

The 18 farms used for resource flow mapping in Simbi and Kageyo were used as test farms for soil properties characterisation. Soil sampling was executed separately on different field types. Areas of discontinuity such as old cattle sheds or termite mounds were avoided. Topsoil (0-20 cm) samples were taken with an auger at five spots per parcel from all fields identified in 18 case study farms.

The number of fields varied between farms (between 3 and 12 fields per farm). Two composite soil samples (0-20 cm depth) were taken per field type (homefield, closefield and outfield). From each bulked sample, a sub-sample of about 500 g was then taken to the laboratory for chemical and physical analysis. Soil samples were air-dried, sieved through 2 mm and stored at room temperature prior to analysis. Soil pH was determined in water using a 1: 2.5 soil solution ratio. Soil particle size analysis was done using the hydrometer method. Total N was determined using the Kjeldahl method. Organic carbon was determined colorimetrically after oxidation with sulphuric acid and potassium dichromate mixture at 150^{o}C for 30 min. Available phosphorus in soil was determined by Bray-1 method (Okalebo et al. 2002).

Assessing food self-sufficiency status

Assessment of food self-sufficiency was made based on major food crops produced in the uplands. Crop production from the wetlands was excluded since it is meant for selling to cater for basic household needs (health insurance and children schooling). Traditionally, Rwandan farmers rely on food produced on their own farm and buying of food occurs only in extreme necessity. Also animal products and sale of these was not included in the food self-sufficiency assessment because consumption of animal products (meat and milk) is not a common practice in most rural households in Rwanda. The small amount of milk produced (1 to 2 Litres day^{-1}) is sold to milk collector retailers (at 0.25 US$ L^{-1}) making a modest contribution to the household income. Animal sale occurs in certain circumstances and the income obtained by this is rarely used to purchase food. Total food production and the amount of protein and calories (energy) in this food were used as major indicators of food self-sufficiency. These indicators were estimated following two approaches. First, total dietary energy and proteins consumed per capita was estimated under current conditions. Secondly, food self-sufficiency was assessed under a scenario of maximum maize production. Data was collected on the composition and the quantity of food crops consumption per capita on daily basis. Calories and proteins content for different food commodities were calculated using the averages obtained from several sources. Per capita calories and proteins consumption was calculated by summing up the amount of calories and proteins intake from different food commodities.

To assess food self-sufficiency under a maximum maize production scenario, the total maize yield was calculated from the proportion of land allocated to maize crop in each RG farm using a maximum maize yield of 2 t ha^{-1} in Simbi and 2.5 t ha^{-1} in Kageyo. Using the current fraction of maize consumption (as a percentage of total maize production) in each farm, per capita maize consumption was derived. Using a simplified diet with common daily foodstuffs, we assessed the dietary calories and proteins intake. Total calories and proteins intake were compared against the daily protein requirement of 0.8 g protein kg^{-1} body weight and 2250 kcal $person^{-1}$ for an average body weight of 60 kg (Trumbho et al. 2002) to assess to which extent basic food needs are met at villages and farm scales. Households were food secure when domestic food production exceeded the minimum daily energy requirements.

Data analysis

The results on socio-economical survey were compiled and cross tabulation done using SPSS (SPSS 11.0). All statistical analyses were done using Genstat® Discovery Edition 3 (2009). The statistical significance of the differences between field types, resource group and locations for the soil nutrients, total area cultivated, the total biomass production, nutrients inputs, output and balance and the labour use efficiency was assessed by analysis of variance (ANOVA) using the mixed model (REML) where ‘Location/Resource group’ and ‘field type’ were considered as fixed factors (2 locations, 3 resource groups and 3 field types) and ‘Farm (Location)’ as random factor. Food self-sufficiency indicators were assessed using the mixed model (REML) where ‘Location/Resource group’ was considered as a fixed factor and ‘Farm (Location)’ as random factor. *P* at different significance levels and SED were computed and reported. Only significant main or interaction effects are shown in the results section.

Results

Defining the farmer resource groups

Wealth indicators for different groups were related to land size, the family labour use, animal ownership, labour availability and the number of months of food deficit. In the two study areas, the large majority of farmers surveyed falls within the poor farmer category, between 76 and 86% of all sampled households in Simbi and between 67.5 and 75.3% in Kageyo (Table 2.2). The resource endowments differed between farm types. A poor farmer (referred as RG 1 in the text) is a farmer with limited land size (0.20 ha in Simbi and 0.21 ha in Kageyo) without cattle but with at most 1 goat. He/she is the least endowned of the three RGs, with the smallest family size (4.5 and 5 people household^{-1} in Simbi and Kageyo respectively) (Figure 2.3). Generally, poor household heads are the least educated with 2 to 4 years of schooling and most food insecure of the three farm types, experiencing 4 to 5 months year^{-1} of food deficit. Most female-headed households (generally widows) were found within this category. The head of the household has variable sources of off-farm income and may work casually for other farmers or is employed in wetlands reclamation work under government scheme. A moderately resourced farmer (referred as RG 2 in the text) is intermediate between the poor and the wealthier farmer. Households of this category represented 8.5 to 18.2% of the total number of households in Simbi and 17 to 30.6% in Kageyo.

The head of the household attended at least 3 years of basic education and may own 0.5 to 1 ha of land and 1 cow or 3 goats. Having access to organic manure, she/he is able to invest in food crops, experiencing only 2 to 3 months of food deficit. A wealthy farmer (referred as RG 3 in the text) was identified as a farmer owning 1.98 ha (Simbi) and 2.07 ha (Kageyo) of land, with 2 or more cattle. Family size is the largest in RG 3 with an average of 6 to 7 family members household^{-1}. Generally, the head of the household has the basic education level. Having enough land, RG 3 could comfortably meet the family food needs for at least 10 months year^{-1}. In most cases, RG 3 farmers are more or less older households who have been in farming activities for several years and have therefore accumulated wealth through investing in cash crops (coffee, rice and irish potatoes in Simbi or irish potato and vegetables in Kageyo). In other cases, RG 3 household heads would hold leadership positions in the village or be employed in local institutions (banks, NGOs, schools). Generally, one or two family members (in most cases elder children) may be employed as a primary school teacher or in other local institutions, contributing to the household income. RG 3 category represents the smallest population fraction (4.9 to 5.2% in Simbi and 2.0 to 7.5% in Kageyo). Compared with Ubudehe classification, RG 3, RG 2 and RG 1 farm classes identified in Simbi and Kageyo appeared to match with Umukungu, Umukene wifashije and Umukene categories respectively. Though farm classes were referred to as RG 1, RG 2 and RG 3 in the two locations, they remain specific to each location and therefore were considered as nested within locations in data analyses.

Table 2.2 Wealth indicators and characteristics of the different resource groups in Simbi and Kageyo

Agro-ecological zone	Locations (Sectors/villages)	Resource groups (RG)					
		Resource group I (RG 1)		Resource group II (RG 2)		Resource group III (RG 3)	
Central Plateau	Simbi	Have relatively small land Keep a cow for wealthier farmers May have 1 to 2 goats and/or pigs Have a house with tiled or thatched roof Selling labour to wealthier farmers		Have less than 1 ha of land Have one cow with 2 to 3 goats and or pigs Have a house with tiled roof Produce enough for his own family		Have about 1 ha or more, Have about 2 cattle or more, Have a house with cemented floor cemented, roof in iron. Hire permanent or casual labour for livestock or cropping activities Produces enough and sale surplus	
	Selected villages	*n*	% of total HHs	*n*	% of total HHs	*n*	% of total HHs
	Umurera	142	86.6	14	8.5	8	4.9
	Maliza	88	76.4	21	18.2	6	5.2
Buberuka	Kageyo	Have relatively small land Keep 1 livestock for others with a small ruminant Have few trees or none on farm Have a mud house with thatched roof Selling labour to wealthier farmers for cash income		Have more or less ½ ha of land Have 2 cattle and/or 3 goats Have a woodlot of moderate size Have a mud house with tiled roofed Sometimes hire temporarily labour Produces enough for his family and sometimes sale to the market		Have a large farm of 1 ha or more Have 3 cows or more, Have a large forest/woodlot Have a house with ironed or tiled roof. Hire permanent and/or temporarily labour for livestock or cropping activities. Produces enough and sale surplus on market	
	Selected villages	*n*	% of total HHs	*n*	% of total HHs	*n*	% of total HHs
	Mutobo	71	75.5	16	17.0	7	7.5
	Musura	66	67.3	30	30.6	2	2.0
*Ubudehe classification		**Umukene**: Have land to produce food for their family but no surplus for the market, often work for others, Have no savings.		**Umukene wifashiye** Poor with a bit more land, Have few animals, besides subsistence production, Have a small income to satisfy a few other needs (e.g. school fees for children)		**Umukungu**: Food secured, Have a large farm (often with banana or coffee groves and/or forest) with rich soils, Have some animal s, employ others on own farms, at times get access to paid employment (higher-skilled jobs), Have savings	

*Ubudehe is a community development program initiated by Rwanda Government and integrated within the Poverty Reduction strategic Programme. It was named after an ancient cultural practice whereby people could come together for mutual assistance. Under the program, a local rural community classification was made based on criteria considered as the most relevant to farmers.

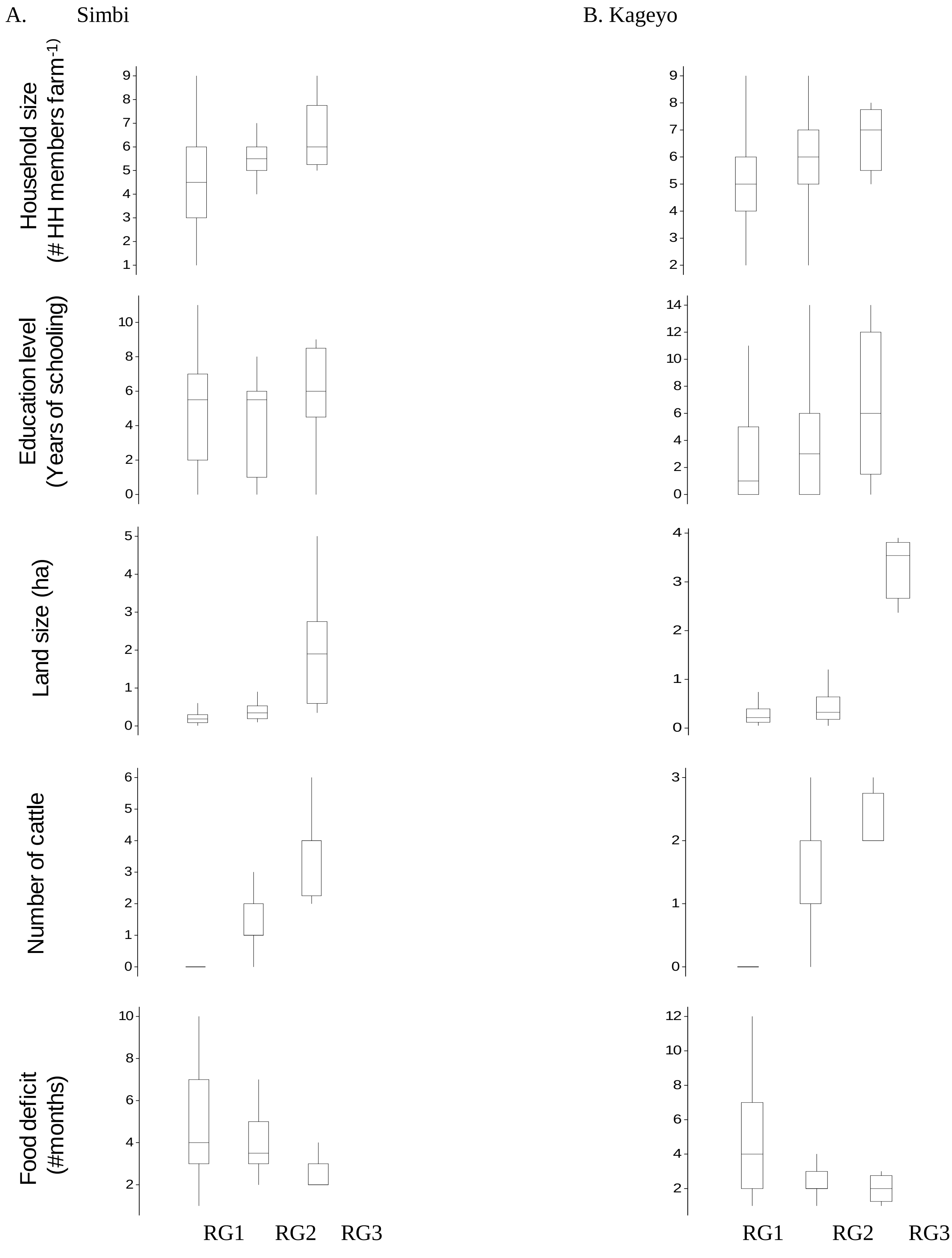


Figure 2.3 Main socio-economical characteristics of farm types within Simbi (a) and Kageyo (b)

Land use

Major crops and land allocation

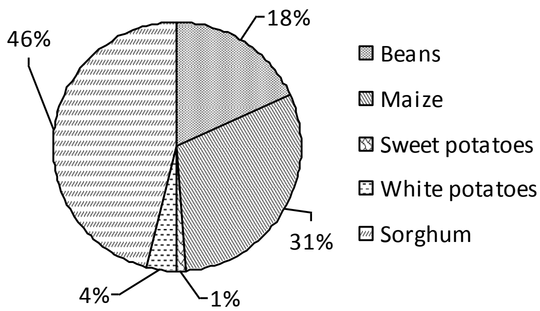
Individual landholdings are fragmented into small pieces of plots ranging from 8 to 10 plots. Land holding patterns varied widely, from farms with a few number of plots concentrated around homestead fields (mostly RG 1 farms) to farms having their fields all scattered and far away (mostly RG 3 farms). In both locations, all farm types show comparable crop diversity but some specific crops dominated in one location relatively to the other over a specific season (Figure 2.4 & 2.5). Beans occupy the major land share in RG 1 (34% of land) against 19% in RG 2 and 30% in RG 3 during short rains 2008. Land share for beans drastically reduced to only 13 to 18% during long rains 2008. Maize occupied 31 to 53 % of land during the 2008 short rains but only 16 to 31% in the 2008 long rains. It was replaced by irish potato during the 2008 long rains. Cassava, an important staple food crop in Simbi, occupied 9 to 15% of cultivated land.

In Kageyo, the most important crops were beans, sorghum, sweet potato, peas and wheat (*Triticum* sp.) (Figure 2.5). Beans occupy a large share of land in least resourced RG (RG 1 and RG 2) with 47 to 67% of land and only 26% in RG 3 during the short rains 2008. Land share for beans was however much lower during long rains 2008, with only 16, 19 and 9% of land share in RG 1, RG 2 and RG 3. Sorghum is the most important staple food during the 2008 long rains season, occupying 76% of land in RG 1 and 21% in RG 3. Peas are an important food and cash crop, especially for RG 3 category, being allocated 48% of land. Though wheat used to be widely produced in the area in the past, land share for this crop was only 7 to 15% in RG 2 and RG 3.

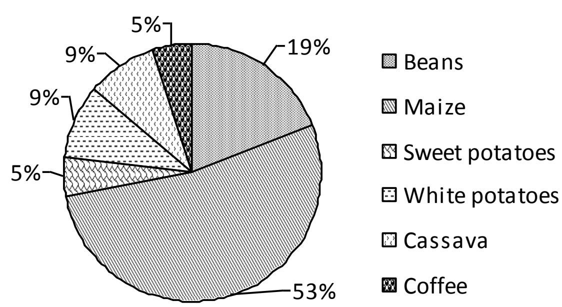
Simbi

2008 Short Rains season

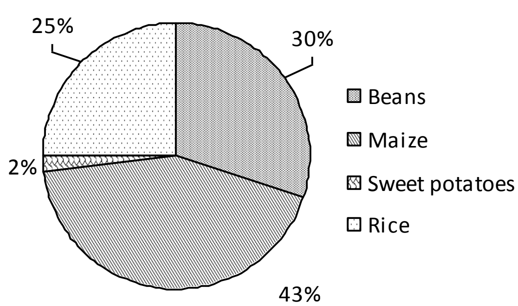
RG 1 (0.17 ha)



RG 2 (0.37 ha)

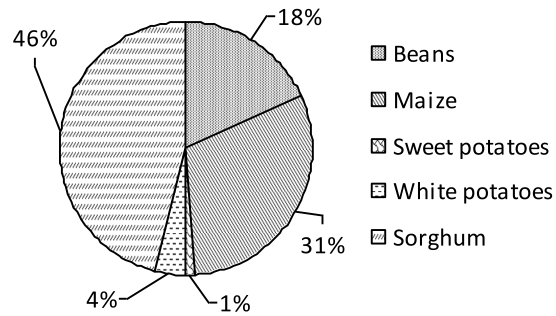


RG 3 (1.14 ha)

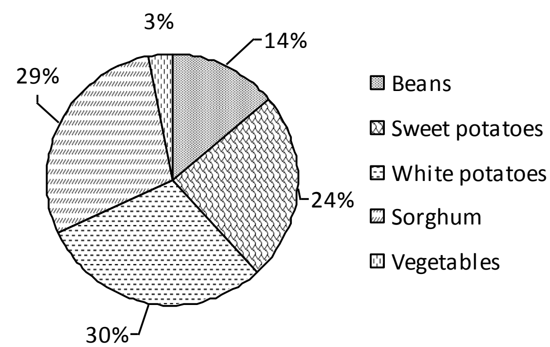


2008 Long Rains Season

RG 1 (0.17 ha)



RG 2 (0.30 ha)



RG 3 (1.23 ha)

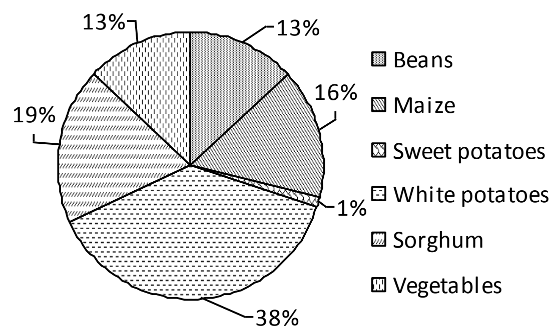


Figure 2.4 Major crops and land allocation in different farming systems during the 2008 short and long rains seasons in Simbi. The total cultivated area varies over seasons due to differences in seasonal land share allocated to each crop

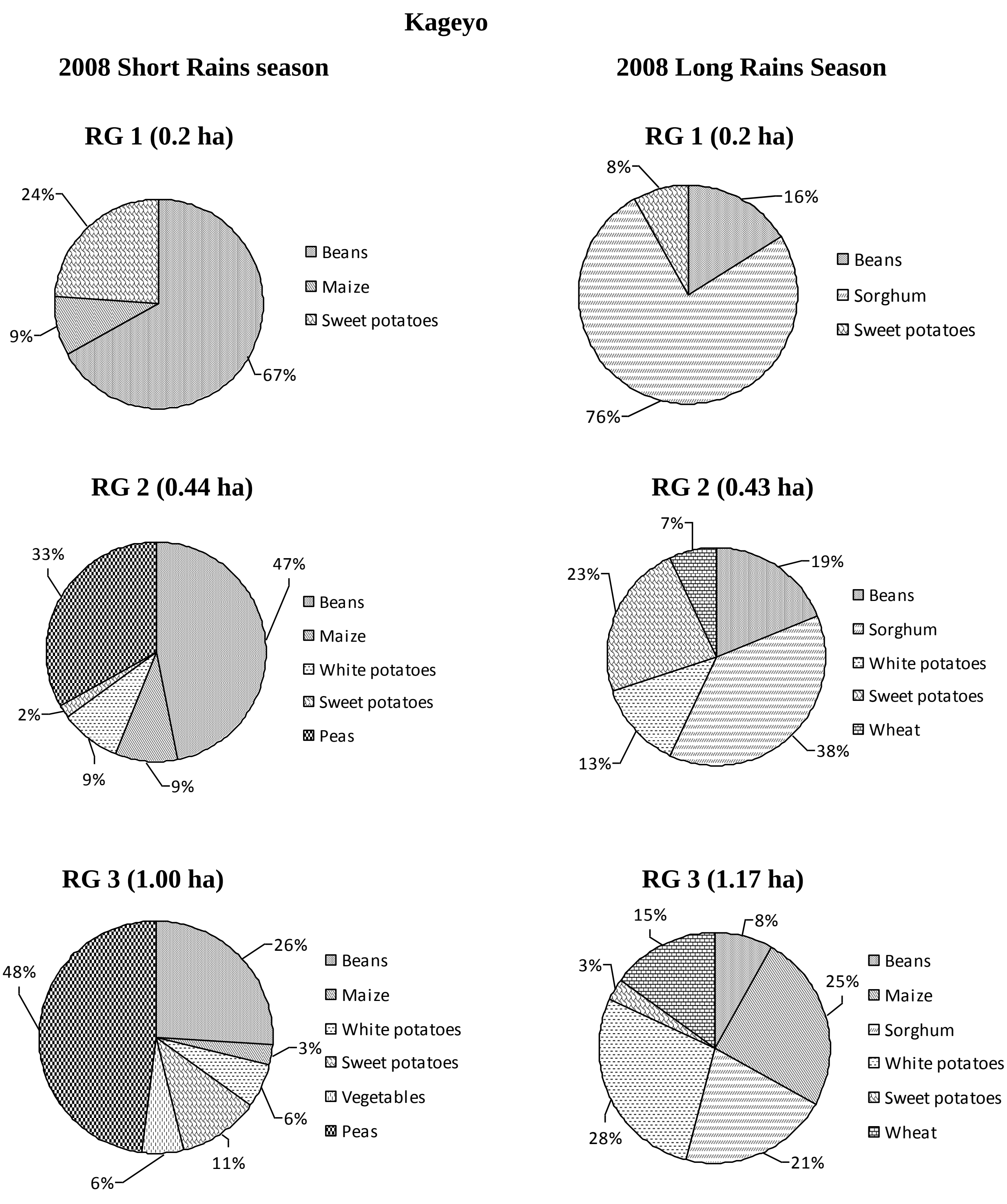


Figure 2.5 Major crops and land allocation in different farming systems during the 2008 short and long rains seasons in Kageyo. The total cultivated area varies over seasons due to differences in seasonal land share allocated to each crop

Soil fertility status for different farms and fields

Soil fertility indicators are reported in Table 2.3. The highly weathered soils of Simbi had lower pH (5.1), reflecting more soil depletion in Simbi. Soil organic carbon (SOC) and total N were the highest in clay soils of Kageyo, wealthier farms and fields closest to home compound (homefields). C/N ratio was comparable between locations, farms and fields. Extractable P was comparable across locations but significantly differed between fields (*P* < 0.001). It was greater in homefields (12.5 mg kg^{-1}) than in close fields (7.9 mg kg^{-1}) and outfields (5.1 mg kg^{-1}). K^+ level was the highest (*P* = 0.02) in RG 3 farms (0.6 cmol $_{(+)}$ kg^{-1}) and homefields (0.7 cmol $_{(+)}$ kg^{-1}). CEC significantly differed between locations (*P* = 0.002) and was higher in the heavier clayey soils of Kageyo (12.3 cmol $_{(+)}$ kg^{-1}). Though soils from the two locations fall within similar or close soil texture classes (sandy loam/sandy clay loam texture), clay was the most dominant fraction in soils of Kageyo (206 g kg^{-1}) while the sand fraction was dominant in soils of Simbi (637 g kg^{-1}). Clearly, nutrient contents decreased with increasing distance from the home compound.

Table 2.3 pH, Soil organic carbon, Total soil N, extractable P and exchangeable K and cation exchange capacity on 18 case study farms at Simbi and Kageyo. Fields in the wetland were not included

	pH (H_2O)	Organic C (g kg^{-1})	Total N (g kg^{-1})	C/N	Extractable P (mg kg^{-1})	K^+ (cmol (+) kg^{-1})	CEC (cmol (+) kg^{-1})	Soil texture (g kg^{-1})			
								Clay	Silt	[1]Sand	Class
Location											
Simbi	5.1	14.9	1.3	11.4	7.5	0.5	9.5	161	202	637	Sandy loam
Kageyo	5.4	25.4	2.5	10.1	9.5	0.5	12.3	206	226	568	Sandy clay loam
Location/Resource group											
Simbi											
(RG 1)	5.1	10.1	1.0	10.1	7.4	0.3	7.47	137	204	659	Sandy loam
(RG 2)	4.9	19.2	1.5	12.8	7.0	0.3	10.20	158	201	641	Sandy loam
(RG 3)	5.1	20.0	1.7	11.7	8.0	0.6	10.76	171	222	607	Sandy loam
Kageyo											
(RG 1)	5.4	27.8	2.2	12.6	10.3	0.3	9.7	183	211	606	
(RG 2)	4.9	27.1	2.2	12.3	10.6	0.6	12.7	217	255	528	Sandy clay loam
(RG 3)	5.9	31.0	3.0	10.3	13.8	0.8	14.3	246	213	541	Sandy loam
Field type											
Homefield	5.5	25.2	2.5	10.0	12.5	0.7	8.6	200	200	600	Sandy loam
Close field	5.2	19.3	1.8	10.1	7.9	0.3	11.4	185	223	592	Sandy loam
Outfield	5.2	16	1.5	10.6	5.1	0.4	12.5	166.7	220	613	Sandy loam
P value											
L	0.005**	< 0.001***	< 0.001***	0.83^{NS}	0.58^{NS}	0.71^{NS}	0.002**	0.01**	0.06^{NS}	0.02**	
L/RG	0.29^{NS}	0.03**	0.02**	0.72^{NS}	0.44^{NS}	0.02**	0.10^{NS}	0.41^{NS}	0.09^{NS}	0.23^{NS}	
FT	0.29^{NS}	< 0.001***	0.009**	0.50^{NS}	< 0.001***	0.02**	0.001**	0.81^{NS}	0.25^{NS}	0.94^{NS}	
SED											
L	0.1	1.2	0.2	1.1	1.2	0.1	0.8	20.8	12.5	23.0	
L/RG	0.2	0.2	0.03	1.8	2.1	0.1	1.4	37.7	21.7	40.9	
FT	0.1	1.5	0.2	1.3	1.9	0.1	1.0	26.7	15.3	28.0	

Area cultivated, crop production and nutrient flows at field level

Area cultivated aggregated over the two cropping seasons (2008 SR and 2008 LR seasons), total annual DM produced and N, P, and K flows are reported in Tables 2.4 & 2.5. The land area cultivated significantly differed among locations, RGs and field types. Cultivated area was the largest in Kageyo (0.60 ha yr^{-1}), in RG 3 farms (1.05 ha yr^{-1}) and outfields (0.24 ha yr^{-1}). The total DM yield differed between locations RG (*P* = 0.03), RG_S within location (*P* = 0.04) and fields (*P* = 0.02). Total annual DM yield was the largest in Kageyo (1.77 t ha^{-1} yr^{-1}) and larger in RG 2 (2.65 t $ha^{-1}yr^{-1}$) than in RG1 in Kageyo. At field level, the total DM productivity was significantly higher in homefields (1.64 t $ha^{-1}yr^{-1}$) than in outfields (0.68 t $ha^{-1}yr^{-1}$).

N and P inputs were the largest in Kageyo (20.28 kg N $ha^{-1}yr^{-1}$; 6.50 kg P $ha^{-1}yr^{-1}$). On the other hand, N and P inputs were smallest in RG 1 but comparable between RG 2 and RG 3 farms. A similar trend was observed for nutrient outputs. Differences between RGs were more clearly expressed in Kageyo than in Simbi. The N balance was more negative in Kageyo (-35.87 kg N $ha^{-1}yr^{-1}$) than in Simbi (-14.20 kg N $ha^{-1}yr^{-1}$). The N and P balance were significantly different between RGs within locations; values were less negative in RG 1. The P balance was negative in close fields (-0.57 kg P $ha^{-1}yr^{-1}$) and outfields (-7.11 kg P $ha^{-1}yr^{-1}$) but positive in homefields (0.43 kg P $ha^{-1}yr^{-1}$). Data on crop productivity and nutrient flows for the wetlands in Simbi (Table 2.5) indicate larger cultivated areas, higher DM biomass production, nutrient inputs and outputs in RG 3 farms but with more negative nutrient partial balance compared with the other RGs.

Table 2.4 Area cultivated on upland fields (ha yr^{-1}), total production (kg DM ha^{-1} yr^{-1}), N, P and K inputs, outputs, and partial balance (kg ha^{-1} yr^{-1}) in different resource groups (RG) and Field types (FT) at Simbi and Kageyo locations (L).

	Cultivated Area (ha yr^{-1})	Total DM (kg ha^{-1} yr^{-1})	Inputs (Inorg. & organic) (kg $ha^{-1}yr^{-1}$)			Outputs (kg ha^{-1} yr^{-1})			Partial Nutrient Balance (kg ha^{-1} yr^{-1})		
			N	P	K	N	P	K	N	P	K
Location											
Simbi	0.53	678	12.11	3.51	10.39	26.38	4.73	28.65	-14.20	-1.22	-18.26
Kageyo	0.60	1770	20.28	6.50	17.13	56.23	9.85	40.93	-35.87	-3.30	-23.80
Location/ Resource group											
Simbi											
(RG 1)	0.20	484	4.49	1.08	9.91	18.39	4.10	11.25	-13.90	-3.02	-1.34
(RG 2)	0.34	500	10.34	2.50	5.80	25.10	4.21	32.19	-14.76	-1.71	-26.39
(RG 3)	1.05	1051	21.49	7.55	15.46	35.65	5.78	42.52	-14.16	1.77	-27.06
Kageyo											
(RG 1)	0.16	874	15.11	2.63	12.74	31.47	5.24	25.20	-16.44	-2.61	-12.46
(RG 2)	0.33	2657	21.92	10.03	19.87	87.69	16.59	60.27	-65.61	-6.52	-40.40
(RG 3)	1.30	1778	23.80	6.83	18.79	49.54	7.71	37.31	-25.55	-0.77	-18.52
Field type											
Homefield	0.14	1636	19.32	5.33	10.18	53.29	4.90	44.07	-33.97	0.43	-33.89
Close field	0.12	1350	17.79	6.20	17.94	36.15	6.77	34.36	-18.36	- 0.57	-16.42
Outfield	0.24	686	11.47	3.08	13.17	30.28	10.19	25.94	-18.81	- 7.11	-12.77
P value											
L	0.02**	0.03**	0.03**	0.01**	0.21	0.02**	0.02**	0.04**	0.04**	0.51 *NS*	0.55 *NS*
L/RG	<0.001**	0.04**	0.04**	0.03**	0.82	0.04**	0.04**	0.01**	0.04**	0.03**	0.15 *NS*
FT	0.02**	0.02**	0.02**	0.04**	0.30	0.04**	0.04**	0.75 *NS*	0.53 *NS*	0.02**	0.35 *NS*
SED											
L	0.06	451.2	3.54	1.4	5.18	14.09	2.07	5.06	10.02	3.76	8.00
L/RG	0.07	596.7	4.02	2.4	8.93	23.01	4.41	8.38	19.37	2.07	13.80
FT	0.04	402.4	3.71	1.5	5.60	10.09	2.16	12.02	26.81	2.02	12.66

Design used Location/wealth group*Field type as fixed factors and location as a random factor

L: Location, S: Season, RG: Resource group, FT: Farm type, * significant at $P < 0.1$ level, ** significant at $P < 0.05$ level, NS: not significant

Cultivated area covers the area cropped averaged over two growing seasons. The area under forest was excluded.

Table 2.5 Area cultivated (ha yr^{-1}), total production (kg DM $ha^{-1}yr^{-1}$), N, P and K inputs, outputs, and partial balance (kg ha^{-1} yr^{-1}) for different resource groups (RG) in wetland outfields in Simbi.

Resource group (RG)	Cultivated Area (ha yr^{-1})	Total DM (kg DM $ha^{-1}yr^{-1}$)	Inputs (kg ha^{-1} yr^{-1})			Outputs (kg ha^{-1} yr^{-1})			Partial Nutrient Balance (kg ha^{-1} yr^{-1})		
			N	P	K	N	P	K	N	P	K
RG 1	0.07	4974	60.65	12.70	55.65	89.95	16.69	73.25	29.30	-3.99	-17.60
RG 2	0.20	3556	45.62	14.88	29.27	143.96	25.05	53.28	-195.58	-10.17	-24.01
RG 3	0.51	6223	64.25	19.29	62.14	241.20	29.15	162.79	-79.71	-9.86	-100.62

Land in valley bottom is not a property of farmers but it is rented on contract basis by farmers organized in cooperatives

*Wetland fields are categorized as outfields since located at distance from home compound.

Labour allocation and use efficiency

Land preparation required the largest labour demand, about 30 to 44% of the total labour demand (Table 2.6). Labour for land preparation was larger in RG 1 (216 man-days $ha^{-1}yr^{-1}$) than in RG 2 and RG 3 (73 and 74 man-days $ha^{-1}yr^{-1}$) in Kageyo. Similarly, labour required for planting and harvesting was significantly larger for RG1 than for the other RGs. Labour for spraying was largest in outfields since it was specifically invested to particular fields (coffee and irish potatoes to combat *Antestia lineaticollis* and late potato blight) usually located away from home. Labour use efficiency was comparable in homefields and close fields (5.19; 4.18 kg DM man-day^{-1}) but was larger than in outfields (1.43 kg DM man-day^{-1}).

Table 2.6 Labour allocation (man-days $ha^{-1}yr^{-1}$) and use efficiency (kg DM man-$days^{-1}$) for different agricultural practices in different farm types in Simbi and Kageyo

	Land preparation (man-days $ha^{-1}yr^{-1}$)	Manuring (man-days $ha^{-1}yr^{-1}$)	Planting (man-days $ha^{-1}yr^{-1}$)	Weeding (man-days $ha^{-1}yr^{-1}$)	Spraying (man-days $ha^{-1}yr^{-1}$)	Harvesting (man-days $ha^{-1}yr^{-1}$)	Total labour (man-days $ha^{-1}yr^{-1}$)	Labour use efficiency (kg DM man-day^{-1})
Location/ Resource group								
Simbi								
RG 1	216	31	87	133	0	82	549	1.59
RG 2	96	32	41	98	3	46	316	8.41
RG 3	164	26	59	104	23	41	417	4.26
Kageyo								
RG 1	238	39	82	102	0	76	537	0.90
RG 2	73	19	34	58	0	41	225	2.22
RG 3	74	10	38	43	3	20	188	5.59
Field type								
Homefield	123	21	51	76	4	40	315	5.19
Close field	141	18	48	71	4	41	323	4.18
Outfield	167	40	72	122	6	72	479	1.43
P value								
L/RG	0.03**	0.76^{NS}	0.03**	0.73^{NS}	0.51^{NS}	0.002**	0.12^{NS}	0.37^{NS}
FT	0.7^{NS}	0.20^{NS}	0.65^{NS}	0.33^{NS}	0.03**	0.5^{NS}	0.51^{NS}	0.02**
SED								
L/RG	60.7	15.2	18.3	63.8	0.7	13.8	147.4	6.10
FT	54.7	11.3	22.5	46.5	13.7	22.0	154.4	1.20

A working day count for 6 hours (7h00 am to 13h00 pm). * significant at P < 0.1 level, ** significant at P < 0.05 level, NS: not significant.
Averages over locations are omitted because no significant differences were detected between locations (sectors)

Food self-sufficiency at farm and village levels

The average calories and proteins contents for different food commodities were obtained from several sources (Table 2.7) and used to estimate food self-sufficiency in both location (Table 2.8). Under the current situation, the dietary calories and proteins intake was much higher in Kageyo (4014 kcal person^{-1}day^{-1} and 136.9 g person^{-1}day^{-1}) than in Simbi (1666 kcal person^{-1}day^{-1} and 50.14 g person^{-1}day^{-1}) due to larger DM production and subsequently more calorific and protein rich food (Table 2.8). In Simbi, the dietary calories intake per capita was short by 26% of the required standards. At farm level, calories needs were only met at 40% and 67% in RG1 and RG 2. In Kageyo, deficit in calories intake was noticed in RG1 where the requirements were only met at 39%. As for the dietary protein consumption, 52.8% and 83.7% of daily needs were met in RG1 and RG 2 in Simbi and about 44.4% in RG1 in Kageyo. Under the scenario of maximum maize production, all RGs could meet both calories and proteins needs in both locations. Food self-sufficiency status was much improved in Kageyo than in Simbi but still RG 3 could access more calories and proteins than RG 1 and RG 2.

Table 2.7 Energy and protein value for major food crops grown in Simbi and Kageyo

	Food quality parameters	
Crops	Energy (kcal/100g DW)	Protein (g/100g DW)
Irish potato[b]	82	2.0
Common beans[a]	333	22.5
Sweet potato[b]	117	1.3
Maize[a]	342	9
Sorghum[b]	335	10.4
Cassava[b]	146	1.2
Soybean[a]	446	36.5
Peas[c]	444	27.6
Rice[b]	384	7.3

[a] The data is adapted from from 'West African Food Composition table' by FAO, Infoods, ECOWAS/WAHO and Biodiversity International, 2012, available from: http://www.fao.org/docrep/015/i2698b/i2698b00.pdf

[b] Okigbo (1980); [c] Brunsgaard et al (1994)

Table 2.8 Food self-sufficiency indicators under current and maximum maize yield scenarios in different farm type of Simbi and Kageyo in 2008

	Current food self-sufficiency indicators				Food self-sufficiency indicators under maximum maize production scenario			
	Total Energy (kcal $person^{-1}day^{-1}$)	Requirements coverage (%)	Total proteins (g $person^{-1}day^{-1}$)	Requirements coverage (%)	Total Energy (kcal $person^{-1}day^{-1}$)	Requirements coverage (%)	Total proteins (g $person^{-1}day^{-1}$)	Requirements coverage (%)
Location								
Simbi	1666	74.04	50.47	105.15	2527	112.31	73.10	152.29
Kageyo	4014	178.40	136.92	285.25	4446	197.60	148.30	308.96
Location/RG								
Simbi								
RG 1	921	40.93	25.36	52.83	2336	103.82	62.60	130.42
RG 2	1518	67.46	40.20	83.75	2393	106.35	63.20	131.67
RG 3	2558	113.68	85.84	178.83	2853	126.80	93.60	195.00
Kageyo								
RG 1	898	39.91	21.35	44.48	2323	103.24	58.90	122.71
RG 2	5513	245.02	156.94	326.96	5441	241.82	155.00	322.92
RG 3	5632	250.31	232.48	484.33	5573	247.68	230.90	481.04
P value								
L	0.01**		< 0.001		0.03**		0.002**	
L/RG	0.02**		<0.001		0.19^{NS}		0.003**	
SED								
L	805.1		19.17		797.9		18.83	
L/RG	1395		33.20		1382		32.62	

Requirements coverage is estimated as a percentage of the available daily energy or proteins requirement of 0.8 g proteins $day^{-1}person^{-1}kg^{-1}$ body weight

For an average body weight of 60 kg (Trumbho et al., 2002) and 2250 kcal $person^{-1}day^{-1}$. * significant at P < 0.1 level, ** significant at P < 0.05 level, NS: not significant

Discussion

Farm typology to identify differences in farm management

The research explored the diversity within farming systems in two contrasting agro-ecological zones of Rwanda. Simbi, located in Central Plateau with erratic rainfall and more depleted soils clearly contrasted with Kageyo, a highlands area with high rainfalls and relatively more fertile soils (Table 2.1). To assess differences between different farming systems, a typology was created to be able to deal with the large variability in individual farm characteristics. Major differences in socio-economic factors could be found between farms (household size, education level, livestock ownership, land size and available labour) and there is a strong link with farm production. Although three similar groups were defined in Simbi and Kageyo, the thresholds between the groupings were different: average land size was smaller in Simbi compared to Kageyo in wealthier farmer groups. In addition, fields within farms were classified according to their relative position from the homestead that relate also to the general management and the intensity of resource use.

This type of classification can sometimes generate poor differentiation between farm types (Tittonell et al 2005a). For that reason and to check the generic applicability of our classification, we checked our classification using the nationwide farmer categorisation made earlier through Ubudehe (Table 2.2). Using key criteria that are specific to some farmer categories (labour allocation, off-farm employment and animal ownership), it was possible to identify three groups (Umukungu, Umukene wifashije and Umukene) out of the six groups from UBUDEHE classes that match with RG 1, RG 2 and RG 3 farm types. For instance Umukene farmer, defined as selling labour to others closely relates to RG 1 and the Umukungu farmer referred as having a paid employment was shown to closely match with RG 3 farmer category.

Resource allocation and use patterns

The arable land represents 53 to 100% of total land in Simbi and 62 to 80% in Kageyo. The fraction of cropping land (as a percentage of total available land) was the highest in poor resource farmers (RG 1), illustrating a higher demand for cropping land on smaller farms. On per capita basis, the available arable land was about 0.04, 0.06 and 0.16 ha for RG 1, RG 2 and RG 3 in Simbi and 0.03, 0.06 and 0.20 ha person^{-1} in Kageyo. The values for RG 1 and RG 2 are smaller than 0.18 ha of land available person^{-1} at national level (de Graaff et al. 2011). The figure is closer to the average in RG 3. This implies that the average at national scale is unlikely to accurately reflect land availability at the farm scale in separate regions.

There was a high diversity of crops in all farms and locations (Table 2.3). There was no systematic allocation of crops to certain fields, contrasting with other countries in sub-Saharan Africa such as Zimbabwe and Kenya (see Tittonell et al. 2005a). This could be due to the extreme shortage of land and predominance of mixed cropping systems. An exception was irrigated rice, a water demanding crop which was exclusively grown in wetland fields. Predominance of different cropping patterns seems to be much more related to the biophysical conditions of the agro-ecological zones. Intensive cassava crop production in Simbi and irish potatoes and wheat in Kageyo were clearly related to the adaptability of these crops to the prevailing climate and soil conditions in the respective agro-ecological zones. Cassava is preferred by farmers in the southwest of Rwanda due to its adaptation to degraded and sloping landscape. Climatic conditions in the Northern Highlands Rwanda allow cultivation of temperate crops. Beans and maize crops are adapted to multiple locations but specific varieties are recommended for specific agro-ecological zones. At the farm/household level, RG 2 and RG 3 may allocate substantial amount of land meant for cash crop production relative to the area allocated to food crops produced for household consumptions. For instance, maize has become a major source of income for farmers in

Simbi where up to 40 to 50% of land is allocated to it by RG 2 and RG 3 farmers. In Kageyo, where irish potatoes and peas are major crops for income generation, more land was allocated to these crops by RG 3 farmers than by RG 1 and RG 2 farmers.

The land area allocated to legumes is smaller than the land allocated to cereals and tuber and root crops. The number of legumes grown is also small: only beans or peas are being produced. Common bean is the most important food grain legume in Rwanda (CIAT 1995). Beans are said to be grown by at least 95% of farmers in the country, providing up to 65% of proteins and 32% of caloric intake (Ministère du Plan 1988). In our study, beans occupy a relatively larger land share in poor resource farmer categories. However, productivity of beans remains poor. The average bean production was about 620 kg ha^{-1}, lower than the average of 750 kg ha^{-1} reported for Rwanda (Karanja et al. 2011). Diverse factors are reported to suppress bean production, including moisture and heat stresses, declining soil fertility, poor crop management practices and limited access to quality seed and markets (Karanja et al. 2011).

Differences in total crop productivity were found between locations (Table 2.4), with more DM produced in Kageyo than in Simbi. Higher crop productivity in Kageyo could be explained by better soil fertility (Table 2.3) but also more nutrient inputs (Table 2.4). At the field level, the higher DM productivity in homefields can be attributed to higher soil fertility (Table 2.4) but also to more N, P and K inputs applied (Table 2.5). Homefields with higher DM (Table 2.4) and greater labour use efficiency (Table 2.6) received the largest amounts of nutrients (Table 2.4), illustrating a farmer strategic allocation of resources seeking to generate higher return. At the scale of individual farms, farmers preferentially allocate the available labour and nutrient resources to certain fields, which contribute to the creation of spatial variability within their farms and this seems to be a general feature in many densely-populated, tropical farming systems (Tittonell et al. 2005b; Crowley and Carter 2000). Several studies have indicated that farmers tend to allocate resources to most productive fields (for instance homefields) at the expense of fields located away from home (Tittonell et al. 2005a; Zingore et al. 2007a). Because of the proximity to the homestead, fields closest to home compound are the first to get household refuse, chicken droppings and livestock manure, increasing the fertility of the soils in these fields. In the current study, wetlands are regarded as ‘special niches’. Resource allocation in these fields does not follow the general trend of inputs allocation in relation to the distance from the homestead. Existence of such special niches within farming systems was also reported in other studies (Mango, 1999; Cowley and Carter, 2000; Tittonell et al 2005a).

Differences between fields within Kageyo were larger than in Simbi. Lack of clear differences between fields within farms in Simbi may be associated with high population density in Simbi (520 inhabitants km^{-2}) as compared with Kageyo with 430 inhabitants km^{-2}. High population growth accelerates the subdivision of landholdings among heirs, and produce increasingly smaller field size. Similar observations are reported in neighbouring Kenya (Emuhaia district) where soil fertility gradients were reported to be much smaller than in other locations, this being attributed to higher population density (Tittonell et al 2005a).

Food self-sufficiency

Food self-sufficiency indicators showed critical levels in RG 1 farms that represent 71 to 81% of the sampled households in both locations and in RG 2 farms of Simbi (13% of sampled households). RG 1 farmers experience a 20 to 25% deficit in proteins and a 54 to 60% deficit in energy (Table 2.8). Low productivity of proteins rich crops greatly affects food self-sufficiency. The situation of protein intake was much better for Kageyo due to the cultivation of more legume crops (beans and peas) with higher protein content (Table 2.8) but also higher total DM (Table 2.4). Low proteins intake in RG 1 farms of Simbi could be related to larger consumption of root crops (sweet potatoes and cassava) that have a lower protein contribution (1.3 and 1.2 g/100g DW respectively against 9 g/100g DW for maize), in agreement with a previous report attributing the decline in food self-sufficiency in Rwanda to a larger consumption of roots and tubers based diet that contains less of proteins (de Graaff et al. 2011). This suggests that strategies to improve on food self-sufficiency should not only consist of increasing crop productivity but should also target commodities with higher caloric and protein value. Achieving food self-sufficiency within a rapidly increasing population and limited resources context means intensifying food production on existing cropland and targeting best options in relation to the specific biophysical and socioeconomic conditions. For instance optimising maize productivity on farm can potentially enhance food self-sufficiency status with additional supply of proteins and calories within poor resource households.

Conclusions

Using various and complementary research tools, the current study highlighted the large diversity among farms and farming systems in Rwanda. The results demonstrate that farms differ in terms of resource endowment, socio-economic characteristcs and resource management. Describing the major socio-economic assets of farms, quantifying resources and their allocation to different farms and fields helped to understand the management of farms that induce differences in soil fertility, food production and food self-sufficiency. Resource allocation trends in Simbi and Kageyo could be explained by the inherent factors (location/agro-ecological zoning), the type of soil, but could also be linked to farm management. This integrated research approach is needed when analyzing strategies or opportunities for better allocation of resources at farm scale.

Food self-sufficiency is a major concern in RG 1 and RG 2 farms in Simbi and RG 1 farms in Kageyo. Poor food self-sufficiency is due to poor food availability/production and utilization to cater for proteins and energy requirements. Optimising maize production on the respective farms could substantially improve food self-sufficiency, suggesting that there is room for manoeuvre in these smallholder systems. Therefore, targeting opportunities for sustainable intensification for enhancing food self-sufficiency status requires an approach that should take on board the effects of biophysical and management aspects and bring the analysis to the livelihood level. Such an approach should allow a broader multidimensional analysis of possible and realistic resource management options.

Chapter 3

Assessing farmers' interest in agroforestry in two contrasting agro-ecological zones of Rwanda

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Abstract

Uptake and management of agroforestry technologies differs among farms in Rwanda and needs to be documented as a basis for shaping future research and development programs. The objective of this study was to investigate current agroforestry practices, farmers' preferences, tree management and perspectives for agroforestry technologies. The study consisted of a combination of a formal survey, a participatory tree testing, farmer evaluation and focus group discussions in the Central Plateau (moderate altitude) and the Buberuka (high altitude zone) agro-ecological zones. A survey and a tree testing exercise with a range of species: (timber species - *Eucalyptus urophyla, Grevillea robusta;* legume shrubs - *Calliandra calothyrsus, Tephrosia vogelii*; and fruit species - *Persea americana* and *Citrus sinensis*) were carried out in Simbi (Central Plateau) and Kageyo (Buberuka) with farmers from different wealth status who received tree seedlings for planting, managing, and evaluating. Simbi had more tree species farm^{-1} (4.5) than Kageyo (2.9). Fruit trees occurred most frequently in Simbi. *Grevillea robusta*, *Calliandra calothyrsus* and *Tephrosia vogelii* were mostly established along contours, fruit trees in homefields and *Eucalyptus urophyla* trees in woodlots. Survival was better on contours for *Grevillea robusta* (58 to 100%) and *Calliandra calothyrsus* (50 to 72%). Tree growth was strongly correlated with the total tree lop biomass in *Eucalyptus urophyla* (R^2 = 0.69). *Grevillea robusta* was most preferred in Simbi and *Eucalyptus urophyla* and *Calliandra calothyrsus* in Kageyo. The study provided information useful for revising the national agroforestry research and extension agenda and has important implications for other countries in the highlands of Africa.

Key-words: Tree species, biophysical factors, farmer resource groups, tree testing, farmer evaluation

Introduction

Agroforestry is an ancient practice in sub-Saharan Africa where farmers deliberately retain and integrate trees into their farmland. It was widely promoted as a sustainability-enhancing practice combining the benefits of both forestry and agriculture (Bene et al. 1977). Agroforestry development has taken place in sub-Saharan African as a response to the major problems, including food shortage in many parts of the developing world and the increasing ecological degradation and the energy crisis at the beginning of the 1970s (King 1989). In Rwanda, food security and land degradation were the major concerns in the early 1990s due to high population pressure, decreased farm size, land encroachment on forested and steeply-sloping landscapes (Ndiaye and Sofranko 1994).

Though agroforestry is a native practice in sub-Saharan rural communities, the formal research in the discipline started much later. Worldwide agroforestry research spearheaded by ICRAF (International Council for Research in Agroforestry) was firstly directed towards the description and characterisation of the farmers' agroforestry systems (Sanchez 1995) with the objective of identifying major constraints and opportunities for designing of adequate solutions. Later, specific practices including intercropping and integrated farming systems were widely investigated (Wilson and Kang 1981) to mainly deal with soil fertility and livestock concerns in the tropics. Agroforestry systems were developed with specific tree species such as *Faidherbia albida* that has shown great potential in providing fodder, other services and ability to fix nitrogen. In Rwanda, integrating legume species within cropping systems was extensively tested using species such as *Sesbania sesban*, *Leuceana leucocephala*, *Calliandra calothyrsus* and *Markhamia lutea* in bean (*Phaseolus vulgaris*), potato (*Solanum tuberosum*), pea (*Pisum sativum*) and wheat (*Triticum* sp.) (Yamoah et al. 1989). The principle underlying the promotion of leafy biomass of agroforestry species lies in the fact that the addition of green manure is important in the tropics where most of the plant nutrients are provided from organic matter (Kang et al. 1981). The most remarkable effect of legume shrubs in livestock production was that related to the use of legume species such as *Calliandra* for milk production (Paterson et al. 1998, Wambugu et al. 2011). Alongside these benefits, agroforestry could supply other basic services including firewood, food, medicine, fodder, timber, boundary markers and windbreaks (Young 1997; Franzel et al. 2002). In most agroforestry trials undertaken in the 1990s, priority was on the investigation of the performance of different species under different biophysical conditions (Nair 1998). Later, agroforestry research has been broadened to include social, anthropological, environmental and economic concepts (Mercer and Miller 1998).

Despite major agroforestry development and achievements in the last two decades, it is important to notice that most of agroforestry species promoted by the research are not necessarily the ones widely adopted by smallholder farmers in sub-Saharan Africa. The uptake of different agroforestry technologies varies across farms and each species seems to be managed as a unique technology in countries such as Rwanda. It appears that farmers design individual systems that respond to their multiple needs depending on the available resources, making the agroforestry systems complex in their arrangement over time and space.

Several authors have recognized that smallholder farmers in the tropics operate under diverse agro-ecological conditions (Tittonell et al. 2005a; Niang and Styger 1990) and within an agro-ecological zone, farm management is rarely homogenous. Variability at regional level, mostly related to agro-ecological conditions, and, at farm level, farm management strategies, significantly influence the establishment and productivity of trees and shrubs. Other authors have stressed the importance of both socioeconomic and agro-ecological conditions in the identification of a window of opportunity that favours particular forms of management (Giller et al. 2006).

There is therefore a need to use innovative approaches to identify potential niches for agroforestry species and to apply these to complex smallholder farming systems. A research approach integrating multidimensional socio-economic and ecological aspects could assist in properly identifying ‘socio-ecological niches’ for agroforestry species (cf. Ojiem et al. 2007). Participatory methods include several techniques, including formal surveys, informal interviews, technology testing and farmer scoring (Raintree 1983; Franzel 2001; De Groote et al. 2010) that would allow speeding up the process of identifying agroforestry technologies appropriate for a specific farming system but these have not been widely applied in Rwanda.

Of the numerous published agroforestry research activities, conducted in Rwanda over the last 20 years (Yamoah and Burleigh 1990; Balasubramanian and Sekayange 1992; Niang et al. 1998; Yamoah et al. 1989; Balasubramanian and Egli 1986; den Biggelaar and Gold 1995; Pinners and Balasubramanian 1991, Ndiaye and Sofranko 1994), only few have engaged with farmers through the use of participatory research methods.

This study was designed to assess the interest of smallholder farmers in agroforestry technologies in Rwanda. Specifically, the study aimed to: (i) assess the current agroforestry situation by describing the type of tree species, tree density and diversity in the targeted agro-ecological zones, (ii) evaluate the preferred species by farmers on the basis of tree management, growth and productivity; and (iii) identify constraints faced by farmers, farmers’ perceptions and perspectives with regards to tree planting in the different locations.

Materials and Methods

Biophysical characteristics of the research sites and socioeconomic characteristics of households

Two agro-ecological zones were compared, namely the Central Plateau (average altitude of 1500 to 1700 m a.s.l and annual rainfall of 1160 mm) and the northern Buberuka highlands (average altitude of 1800 to 2650 m a.s.l and annual rainfall of 1560 mm rainfall) both of which are considered to have good potential for agroforestry (Yamoah et al. 1989). The Central Plateau agro-ecological zone (AEZ) is located in south-west of Rwanda contrasting with the Buberuka highlands agro-ecological zone (AEZ) located in Northern part of the country. In the Central Plateau, Histosols and Cambisols are dominant in valleys and Cambisols, Acrisols and Leptosols dominant on hills. In the Buberuka highlands, soils are dominated by Cambisols, Nitisols and Leptosols in uphill areas and Histosols and Vertisols in wetland areas (Djimde 1988; Niang and Styger 1990). The Simbi sector was selected in the Central Plateau agro-ecological zone to represent a mixed cropping system with dominance of *Phaseolus vulgaris*, *Manihot esculenta* Crantz, *Zea mays* together with coffee (*Coffea arabica*) as a cash crop. Simbi is located at 1634 m a.s.l with an average temperature of 20^{o}C. Umurera village (164 households, 1324 inhabitants) was selected as a representative study site. Umurera village shares much of biophysical and socioeconomic variability with the central agro-ecological zone. Information collected through our own measurement or District official documents (Huye DDP 2007) indicate that population density, farm size, cattle ownership and other socio-economic features are comparable to those reported for the Central Plateau AEZ (Verdoodt 2002; Yamoah et al. 1989). Total rainfall averaged 1061 and 1044 mm in 2007 and 2008 respectively. In Buberuka highlands, Kageyo sector was selected to represent the typical farming system with dominance of wheat (*Triticum* sp.) and Irish potato (*Solanum tuberosum*). Kageyo is located at 1736 m a.s.l with an average temperature of 15 to 16^{o}C, and average precipitation of 737 and 1015 mm in 2007 and 2008, respectively. Mutobo village (94 households, 529 inhabitants) was purposely selected as study site because it has similar biophysical and socioeconomic features found in Buberuka (Gicumbi DDP 2007), be it in terms of population density, land use and most socio-economic indicators. In both locations, the periods from September to October and November to December 2007 season were exceptionally dry (Figure 3.1).

In the two locations, wealth ranking allowed categorising local households into classes based on local farmer criteria including land size, the number of cattle, the type of house, the ability of the farmer to hire labour (Grandin 1988). Four farmer groups were identified: a wealthier farmer group, a moderately resourced farmer group, a poor farmer group and a landless farmer group. Wealthier farmers accounted for 2 to 7% of the households, moderate farmers 8 to 30%, poor farmers 66 to 84% and landless farmers 1 to 2%. The landless farmer group was not included in the study due to the fact that they had no land which they manage on their own. Table 3.1 gives an overview of the main socioeconomic characteristics of households at the two sites.

Inventory of current trees grown on farms

Before starting the inventory exercise, it was important to clearly define what “a tree” is. In an earlier study, a tree was defined differently depending on whether one uses the western or the Rwandan epistemology (den Biggelaar 1994). From the definition given by Kagame (1958 cited in den Biggelaar 1994) the term “tree” is understood as all plants that are not grasses (referred to as Rwandan-Bantu epistemology). The definition clearly differs from the western conception of a “tree” that only encompasses trees and shrubs. In the current study, we considered “a tree” based on the western epistemology, meaning woody and shrub vegetation excluding herbaceous species.

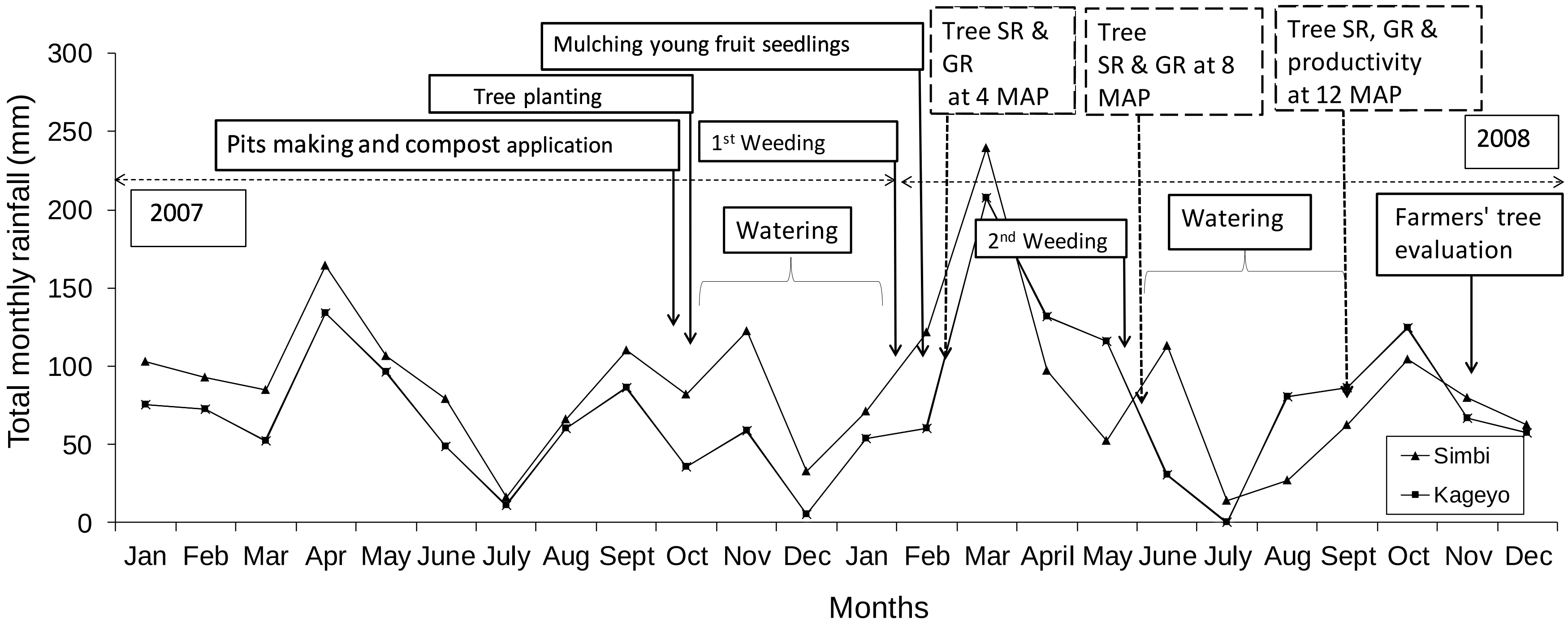

Figure 3.1 Total monthly rainfall (mm) and different tree management activities executed by farmers (solid squares) and tree evaluation activities by the researcher (dotted squares) in 2007and 2008 in Simbi and Kageyo. Total rainfall in 2007 was 1061 and 734 mm in Simbi and Kageyo respectively. In 2008, it was 1045 and 1016 mm in both locations respectively. SR & GR: Survival rate and growth measurement, MAP: Months after planting.

Sources for rainfall data: Ministry of Infrastructure/Meteorological Unit, Rwanda (2009)

Table 3.1 Main socioeconomic characteristics of households in Simbi and Kageyo

	Simbi (*n* = *65*)				Kageyo (*n* = *78*)			
	Wealthier (*n* = *12*)	Moderate (*n* =*19*)	Poor (*n* = *34*)	Means	Wealthier (*n* = *11*)	Moderate (*n* = *25*)	Poor (*n* = *42*)	Means
Family size	6.6 (0.8)	5.9 (1.1)	4.5 (1.8)	5.6	6.0 (2.3)	6.1 (1.8)	4.7 (2.0)	5.6
Education level † (% HH heads with basic education)	66	47	37	40	66	34	18	26
Cattle owned (number)	3.5 (1.3)	1.3 (0.9)	-	2.4	3.3 (1.0)	1.5 (1.0)	-	2.4
Livestock (number)	7.4 (3.7)	4.5 (3.3)	1.2 (1.0)	4.3	5.6 (2.5)	3.6 (1.3)	2.2 (1.0)	4.1
Land size (ha)	1.9 (1.6)	0.5 (0.2)	0.3 (0.1)	0.8	3.2 (0.8)	0.5 (0.3)	0.30 (0.2)	1.3
Area under woodlot/forest (ha)	0.16 (0.05)	0.05 (0.03)	0.005 (0.001)	0.05	0.34 (0.2)	0.07(0.05)	0.02 (0.0)	0.1

†Household with basic education refers to a household who has at least completed primary school; the overall mean was calculated over the total sampled households per location. Values in parentheses are standard deviation (SD)

A formal survey was conducted with 65 farms in Simbi and 73 farms in Kageyo to identify which, where and to what extent different types of trees are currently grown on farm. The data were gathered separately for woodlots and croplands on individual farm types using a pre-tested and pre-coded questionnaire. Data included household characteristics such as farm identification and location, household status, education level, land area, the type and number of animals reared, and source of firewood. The second set of data related to farmer's preferences for specific species and their management. Since the local language (Kinyarwanda) was used during the interview, tree names were given in local names and translated into scientific names. Names were cross-checked with a tree expert from ISAR/Agroforestry Department. The frequencies of the presence of tree species were recorded and used a proxy for identifying the most preferred tree species that were selected afterward for tree testing. Species richness (i.e. the total number of trees species on farm and tree density (the total number of trees per unit area) were recorded.

Testing farmers' preferences

Farmers categorized into the three wealth categories were listed and 25 farmers per wealth group were selected based on a systematic sampling procedure by picking every second farmer on the list of farmers belonging to each wealth category. The trial was discontinued on 5 farms in Simbi and 3 farms in Kageyo due to various reasons including death, or farmers who had not planted any tree. A tree evaluation exercise was finally conducted with 20 farmers in Simbi and 22 farmers in Kageyo. Two species belonging to each of the most important tree classes were selected: timber trees (*Eucalyptus urophyla*, *Grevillea robusta*), legume shrubs (*Calliandra calothyrsus* and *Tephrosia vogelii)* and fruit trees *(Persea americana* and *Citrus sinensis*). Tree seedlings were obtained from the agroforestry nursery of the Rwanda Agricultural Research Institute, ISAR). *Eucalyptus urophyla* seedlings were supplied by ISAR (Rwanda Agricultural

Research Institute/Forestry and Agroforestry Department). *Grevillea*, *Calliandra* and *Tephrosia* seeds were from Gisagara provenance (Southern Rwanda) and seedlings were produced by ISAR (Forestry and Agroforestry Department). Grafted fruit tree seedlings (*Persea americana* and *Citrus sinensis*) were produced and supplied by ISAR/Rubona station (Horticultural Department). A total of 60 trees (10 *Eucalyptus urophyla*, 10 *Grevillea robusta*, 10 *Calliandra calothyrsus* and 10 *Tephrosia vogelii*, 10 *Persea americana* and 10 *Citrus sinensis*.) were made available to each farmer for planting. A total of 2520 tree seedlings were distributed across the two locations. Seedlings were 15 to 25 cm height at planting time. Farmers were free to choose which tree species to plant and where to plant them. Before planting, best tree planting practices were discussed. Farmers were advised to plant in pits of about 40 x 40 x 40 cm and apply manure and watering regularly for best results. Tree seedlings were planted at the start of the rainy season in September 2007. Trees, especially those planted on contours and home fields were weeded when this was done for adjacent crops. Fruit trees were mostly planted under banana crops near home compounds and were mulched. Some farmers watered trees at planting when a drought occurred. The chronological sequence of different farmer activities is provided in Figure 3.1.

Data collection

The number of trees effectively planted by each farmer was recorded after planting by counting the number of planted trees and expressing this as a percentage of the trees the farmer had received. Management practices were recorded and expressed in percentage of farmers that had conducted primary management practices for individual tree species. Height measurement was done using measuring poles. The tree survival rate and height were assessed at 4, 8 and 12 MAP (months after planting) in different tree niches on different farms. Only data at 12 MAP are reported. Assessment of productivity was limited to *Eucalyptus urophyla*, *Grevillea robusta*, *Calliandra calothyrsus* and

Tephrosia vogelii since there was no fruit production recorded at 12 MAP. Tree productivity was expressed in terms of dry biomass of above-ground prunings, including leaves and twigs or sticks of or less than 2 m length. Tree species were carefully pruned and the fresh biomass was determined at 12 months after planting on a sample of 10 trees selected on each farm type and in each niche. *Eucalyptus* trees planted in woodlots were pruned and dry matter reported per unit area. For the tree species planted along contours or along paths, productivity per unit area was obtained by estimating the total biomass on 100 m contour length and squaring to estimate biomass on a per ha basis. To determine biomass dry matter content, a 1 kg sample of fresh leafy and twigs parts was collected for each species from the different farms and the average dry matter content determined after oven-drying at 103^{o}C to constant weight and weighted for dry matter content (Anderson and Ingram 1993).

A farmer evaluation was conducted through an inventory of the problems encountered during the tree testing exercise using a formal survey. The questionnaire used was designed after a focus group discussion with participant farmers. Farmers also evaluated the trees for a range of attributes. For this, a focus group discussion was conducted with farmers involved in the study together with randomly selected tree users (carpenters and charcoal makers) to identify key criteria farmers considered important for tree evaluation. Sampled farmers included a broad range of farmers: wealthier, moderate and poor farmers with both household sex groups fairly represented. Female households were 30 to 40% of the participants. A total of 70 to 80 farmers and other tree users were involved at each study location. Farmers used different criteria for different tree species. For timber species, criteria were the ability of the tree species to provide poles, straightness, tree diameter, compatibility with other crops and coppicing ability. For legume species, the palatability for livestock, the ability to supply poles, the ability to coppice and the compatibility with other crops were the most important criteria for both locations. Other criteria were specific to sites. For instance, the durability of fire (the ability of firewood to keep burning for longer period), was an important criterion for the evaluation of timber species while the ability to contribute to soil fertility improvement was an additional important criterion to evaluate legume species in Simbi. For fruit trees, farmers focused on branching ability, adaptability to the site and growth vigour. Fruit trees were also assessed based on the early growth performance. Based on these criteria, an evaluation sheet was designed and only farmers who had planted trees as part of the study were asked to assess tree species using a scoring technique (Franzel 2001). The technique involves moving seeds or stones among pockets to score tree species on a scale of 1 to 5. In addition, an informal survey helped to assess the farmers' future plans for agroforestry.

Data analysis

Data on the number of tree species, total number of trees per farm and per unit area basis were subjected to ANOVA using the mixed model procedure with site, farm type and farm location as fixed factors and farm (site) as the random factor in the Genstat statistical package (GENSTAT release 7.22 2009). Data on the number of trees planted expressed as percentage of the total trees received per species, tree management activities, growth and productivity and farmers' evaluation were presented as means over sites or tree species as no clear relationship with farmer resource status could be found.

Results

Tree species diversity and density

Tree species were more diversified in Simbi (4.5 tree species farm^{-1}) than in Kageyo (2.9 tree species farm^{-1}), and, were more diversified in cropland (6.2 tree species farm^{-1}) than in woodlots (1.0 tree species farm^{-1}) (Table 3.2). There was a significant interaction between site and location for the number of tree species. The number of tree species farm^{-1} in woodlots was comparable in both sites with averages of 1.1 and 1.2 tree species farm^{-1} in Simbi and in Kageyo respectively, but was much greater in cropland in Simbi (7.8 tree species farm^{-1}) than in Kageyo (4.6 tree species farm^{-1}). There was a significant interaction between site, location and farm types for the number of trees farm^{-1}.

The average number of trees on farm was comparable in woodlots and croplands in wealthier and moderate farms in Simbi. On average, 164 and 149 trees farm^{-1} were recorded in woodlots and cropland respectively on wealthier farms and 135 and 105 trees farm^{-1} in woodlot and cropland respectively on moderate farms. In Kageyo, the number of trees was significantly larger in woodlots than in croplands in wealthier and moderate farms. On average, wealthier farms had 709 and 125 trees farm^{-1} in woodlot and cropland, respectively, and moderate farms had 160 and 48 trees farm^{-1} in woodlots and croplands, respectively. The interaction between site and farm type was significant for the number of trees per unit area. In both locations, poor farms had the largest number of trees ha^{-1} compared with wealthier and moderate farms.

Table 3.2 Tree diversity and density on farms from different wealth categories recorded during a formal survey in 2007 in Simbi and Kageyo

Site (S)	Farm type (FT)	Sample size (n)	Location (L)	† Number of tree species (farm^{-1})	Number of trees (farm^{-1})	Number of trees (ha^{-1})
Simbi (*n = 65*)						
	Wealthier	12	Woodlot	1.2[a]	164[a]	1025[b]
			Cropland	8.3[c]	149[a]	135[a]
	Moderate	19	Woodlot	0.8[a]	135[a]	2700[b]
			Cropland	7.7[c]	105[a]	331[a]
	Poor	34	Woodlot	1.3[a]	99[a]	19800[d]
			Cropland	7.6[c]	22[a]	1743[b]
Kageyo (*n = 78*)						
	Wealthier	11	Woodlot	1.7[a]	709[b]	2085[b]
			Cropland	5.1[b]	125[a]	230[a]
	Moderate	25	Woodlot	1.1[a]	160[a]	2286[b]
			Cropland	4.8[b]	48[a]	210[a]
	Poor	42	Woodlot	0.9[a]	130[a]	6500[c]
			Cropland	3.9[b]	34[a]	205[a]
P values						
S				< .001***	0.663*NS*	0.373*NS*
FT				0.437	< .001***	0.121*NS*
L				< .001***	< .001***	< .001***
S*FT				0.130 *NS*	0.101*NS*	0.04**
S *L				< .001***	0.004**	0.30*NS*
FT* L				0.706*NS*	0.118*NS*	0.50*NS*
S*FT*L				0.516*NS*	< .001***	0.89*NS*

*** P < 0.001,** P < 0.05.*NS* not significant

S: Site, FT: Farm type, L: location

† In woodlots, only dominant *Eucalyptus* species were counted (The most commonly found were *E. camaldulensis* Dehnh, *E. globulus* Labill, and *E. saligna* Sm), hybrid species were excluded since they could not be recognised and differentiated

a,b Values within columns with the same letter are not significantly different at the 5% level

Number of trees planted on different farms

Farmers from different wealth groups differed in their preferences for tree species. More timber trees (*Grevillea robusta* and *Eucalyptus urophyla*) were planted by wealthier and moderate farmers than poor farmers (Table 3.3). Wealthier farmers planted all *Grevillea robusta* (100% of the trees they received) while moderate and poor farmers planted between 70 to 88%. For *Eucalyptus urophyla*, wealthier farmers planted only 60% of the trees in Simbi and 70% in Kageyo. As for legume species, a higher percentage of *Calliandra calothyrsus* was planted by poor farmers in Simbi (88% of seedlings received) than by moderate farmers (70%) and wealthier farmers (66%). In contrary, the largest proportion (95%) of *Calliandra calothyrsus* shrub was planted on wealthier farms of Kageyo. In the fruit trees category, all (100%) of the *Persea americana* and *Citrus sinensis* were planted in Simbi. In Kageyo, 60 to 70% of *Persea americana* and 30 to 70% of *Citrus sinensis* respectively were planted.

Table 3.3 Percent of distributed trees planted in different farm types in Simbi and Kageyo. The *n* = the number of farmers per category who planted different tree species in each location. Each farmer was given 10 tree seedlings of each tree species.

	Simbi (*n* = *20*)			Kageyo(*n* = *22*)		
	Wealthier (*n* = *6*) %	Moderate (*n* = *6*) %	Poor (*n* = *8*) %	Wealthier (*n* = *5*) %	Moderate (*n* = *8*) %	Poor (*n* = *9*) %
Grevillea robusta	100	88	87	100	84	70
Eucalyptus urophyla	60	70	36	70	70	100
Calliandra calothyrsus	66	88	72	95	80	77
Tephrosia vogelii	53	51	36	50	44	20
Persea americana	100	100	100	70	73	62
Citrus sinensis	100	100	100	76	31	30

Number of trees planted in different niches and tree survival

Grevillea robusta was in most cases established on contours (Table 3.4). The number of *Grevillea robusta* on contours was the smallest on wealthier farms (60%) in Simbi and largest on poor farms (89% and 78% respectively in Simbi and Kageyo). Some 10 to 20% of *Grevillea robusta* were allocated to other niches (farm boundaries or along paths). The survival rate was much better on contours, an average of 57.5 to 100 % whereas it ranged from 44.9 to 72 % in other niches (Table 3.5). *Eucalyptus* sp. trees were exclusively established in woodlot on wealthier farms but allocated to different niches on moderate and poor farms, and mainly to niches away from the farm (along paths). The average survival rate of *Eucalyptus urophyla* was much higher in woodlots (60 to 65%) and was the lowest (40 to 56%) along paths. On wealthier farms, *Calliandra calothyrsus* shrubs were established on contours or alternatively along paths. On moderate and poor farms, they were generally established in niches close to the croplands (contours or farm boundaries). *Calliandra calothyrsus* survived best on contours (50 to 72%) compared with other niches (30 to 40%). *Tephrosia vogelii* was exclusively planted on contours in Kageyo but in Simbi 33% of the shrubs were established along paths on wealthier farms. *Persea americana* and *Citrus sinensis* were planted either in homefields or in food crop fields, but with more than 50 % of trees close to homesteads. The survival rate for fruit trees was the largest in the homestead.

Table 3.4 Percent of trees planted in different farm locations by farm types in Simbi and Kageyo. The n = the number of farmers per category who planted different tree species in each location. Each farmer was given 10 tree seedlings of each species.

	Simbi (*n = 20*)			Kageyo (*n = 22*)		
	Wealthier (*n = 6*) (%)	Moderate (*n = 6*) (%)	Poor (*n = 8*) (%)	Wealthier (*n =5)* (%)	Moderate (*n = 8*) (%)	Poor (*n = 9*) (%)
G. robusta						
Along paths	-	-	-	40	-	21.7
Farm limits	40	20	10.5	-	40	-
Contours	60	80	89.5	60	60	78.3
E. urophyla						
Along paths	-	40	18.5	-	-	50
Contours	-	-	-	-	-	-
Woodlot	100	60	81.5	100	100	50
C. calothyrsus						
Along paths	25	-	-	-	-	-
Farm limits	-	-	19.3	-	60	-
Contours	75	100	80.7	100	40	100
T. vogelii						
Along paths	33	-	-	-	-	-
Contours	67	100	100	100	100	100
P. americana						
Homefield	100	50	81.5	100	100	80.7
Food crop field	-	50	18.5	-	-	19.3
C. sinensis						
Homefield	51.7	57.2	87.9	80	75	85.7
Food crop field	48.3	42.8	12.1	20	25	14.3

Table 3.5 Survival rate (%) of tree species planted in different farm locations in different farm types in Simbi and Kageyo. The *n* = the number of farmers per category who planted different tree species in each location. Survival rate was calculated based on the number of trees that were effectively planted (Table 4)

	Simbi (*n = 20*)			Kageyo(*n = 22*)		
	Wealthier (*n = 6*) (%)	Moderate (*n = 6*) (%)	Poor (*n = 8*) (%)	Wealthier (*n = 6*) (%)	Moderate (*n = 6*) (%)	Poor (*n = 9*) (%)
G. robusta						
Along paths	-	-	-	73.0	-	60
Farm limits	44.9	50	50	-	53	-
Contours	57.5	68.2	65	92.0	100	60.9
E. urophyla						
Along paths	-	56.4	40	-	-	48.8
Contours	-	-	-	-	-	-
Woodlot	65	66.1	65	62.1	60	55.0
C. calothyrsus						
Along paths	30	-	-	-	-	-
Farm limits	-	-	40.0	-	31.6	-
Contours	50	66.7	66.2	72	60.0	60.0
T. vogelii						
Along paths	20.6	-	-	-	-	-
Contours	41.5	40.2	30.6	21.1	20.4	46.7
P. americana						
Homefield	100	73.2	80	80	66.7	70.6
Food crop field	-	79.3	82	-	-	70
C. sinensis						
Homefield	100	100	100	60.3	100	100
Food crop field	87.5	80.8	93.7	50.0	66.7	72.2

Tree management practices

Farmers were selective in which of the management practices such as compost application at planting, watering and weeding they used with each species (Table 3.6). Weeding was the most common management practice for *Eucalyptus urophyla* and *Grevillea robusta* seedlings. About 90% and 62.5% of farmers weeded the seedlings of *Eucalyptus urophyla* in Simbi and Kageyo, respectively. The same practice was carried out by 78% and 95% of farmers on *Grevillea robusta* in Simbi and Kageyo respectively. Fruit trees received much more care. They benefited from compost application and were weeded and watered. Watering was more common in Simbi than in Kageyo. A smaller number of farmers applied compost on *Persea americana* in Kageyo. Weeding was the only management practice carried out for legume shrubs, but much more weeding was done with *Calliandra calothyrsus* than with *Tephrosia vogelii*. *Calliandra calothyrsus* is more valued than *Tephrosia* by farmers, *Calliandra* is fed to animals and provides stakes for climbing beans in the area. *Tephrosia* has less uses, mainly used as fish trap.

Table 3.6 Primary management carried out by farmers (% farmers) for different tree species during the tree testing in Simbi and Kageyo.

	Eucalyptus urophyla		*Grevillea robusta*	
	Simbi (*n = 11*)	Kageyo (*n = 12*)	Simbi (*n = 14*)	Kageyo (*n = 22*)
None	-	37.5	21.4	4.3
Watering	10	-	14.3	-
Weeding	90	62.5	64.3	95.7
Compost application	-	-	-	-
	Persea americana		*Citrus sinensis*	
	Simbi (*n = 19*)	Kageyo (*n = 22*)	Simbi (n = 19)	Kageyo (*n = 22*)
None	5.7	5.0	5.0	4.9
Watering	20.1	5.0	15.9	-
Weeding	52.2	85	68.5	95.1
Compost application	22	5.0	10.6	-
	Calliandra calothyrsus		*Tephrosia vogelii*	
	Simbi (*n = 20*)	Kageyo(*n = 20*)	Simbi (*n = 18*)	Kageyo(*n = 6*)
None	33.4	10	55.5	66.6
Watering	-	-	-	-
Weeding	66.6	90	44.5	33.4
Compost application	-	-	-	-

Height and biomass production

Tree growth and productivity did not differ significantly between wealth classes of farmers (Table 3.7). *Grevillea robusta* height was comparable in both sites and attained 4.4 to 4.5 m at 12 months after planting. The production was slightly larger in Simbi with 7.8 t ha^{-1} than in Kageyo with 7.3 t ha^{-1}. Tree height and productivity of *Grevillea robusta* was greater on contours compared to other niches. *Eucalyptus* trees were 4.1 to 5.5 m high in woodlots with DM production much larger in Simbi (9.2 t ha^{-1}) than in Kageyo (7.1 t ha^{-1}). *Eucalyptus* trees planted along paths exhibited slow growth and hardly reached 2.5 m in both sites. The associated productivity was in the range of 2 to 4 t ha^{-1}. Generally, growth and production of *Calliandra calothyrsus* was much better on contours than in other niches. Productivity of *Calliandra calothyrsus* on contours was two and three times greater compared to that along paths in Simbi and Kageyo, respectively. In Simbi, *Tephrosia vogelii* grew faster on contours with an average of 3.0 m at 12 months after planting as compared to 2.8 m high along paths. Tree height was closely related to the total lopped biomass with a linear relationship with a correlation coefficient greater than 50% for all the tree species (Figure 3.2). The relationship was much stronger in *Eucalyptus urophyla* (R^2 = 0.69) than in other species, and was weakest in *Grevillea robusta* (R^2 = 0.51).

Table 3.7 Height (m) and DM prunings (leafy and twigs) yield (t ha^{-1})[a] for different tree species at 12 months after planting in Simbi and Kageyo

	Simbi (*n = 20*)		Kageyo (*n = 22*)	
	Height (m)	DM yield (t ha^{-1})	Height (m)	DM yield (t ha^{-1})
G. robusta				
Along paths	-	-	3.1 (1.6)	5.1 (0.1)
Farm limits	3.7 (1.0)	5.5 (0.9)	3.2 (1.2)	5.4 (0.3)
Contours	4.5 (1.2)	7.8 (3.9)	4.4 (0.8)	7.3 (2.7)
E. urophyla				
Along paths	2.6 (1.1)	4.0 (0.9)	1.4 (0.2)	2.0 (0.1)
Woodlot	5.5 (1.9)	9.2 (5.1)	4.1 (0.9)	7.1 (1.8)
C. calothyrsus				
Along paths	1.9 (0.6)	4.1 (1.7)	-	-
Farm limits	2.1 (1.2)	4.6 (0.7)	2.5 (1.0)	5.3 (2.6)
Contours	2.8 (0.9)	5.8 (3.8)	3.1 (1.2)	6.5 (3.8)
T. vogelii				
Along paths	2.8 (0.7)	8.1 (0.2)	-	-
Contours	3.0 (0.6)	8.0 (4.3)	3.2 (0.7)	8.3 (2.8)

[a]Yield for fruit species was not assessed since there were no fruits yet
Values in parentheses are SD

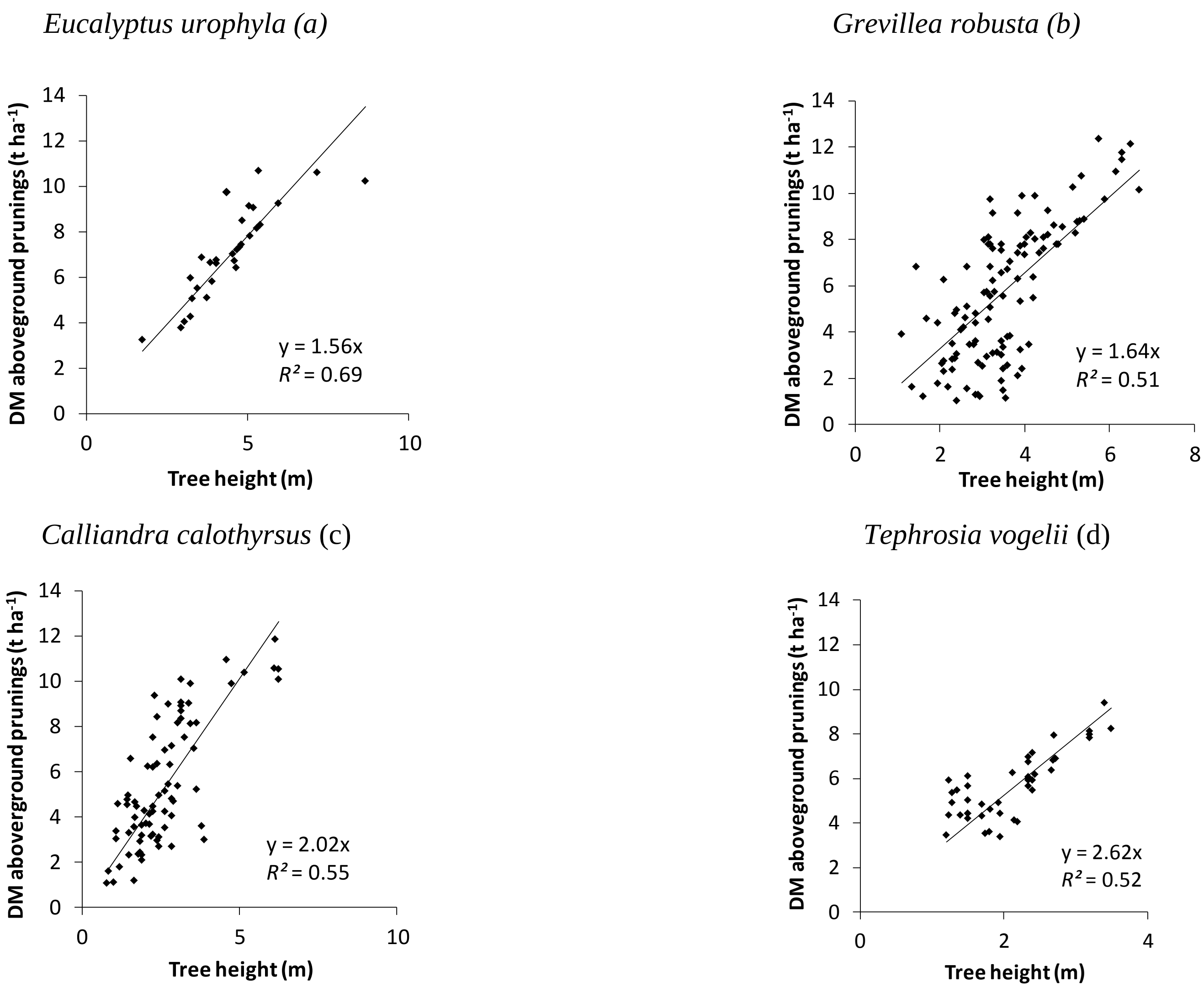

Figure 3.2 Relationship between tree height and total DM aboveground prunings for *Eucalyptus urophyla* (a), *Grevillea robusta* (b), *Calliandra calothyrsus* and *Tephrosia vogelii* (d) established in Simbi and Kageyo in September 2007.

Farmers' tree evaluation

The constraints that the farmers identified were aggregated into major categories (Table 3.8). For timber trees, major constraints were termite damage, competition with *Pennisetum* spp., water stress, poor adaptation and animal browsing. Termite damage on *Eucalyptus urophyla* trees was reported in Simbi but not in Kageyo. Water stress was reported as a serious constraint to *Eucalyptus urophyla* establishment by 39% of farmers in Simbi and 50% in Kageyo. Only 17% of farmers in Simbi and 21% in Kageyo reported the same problem with *Grevillea robusta*. *Pennisetum* competition suppressing *Grevillea robusta* was reported by a large number of farmers of Simbi. Poor adaptation of *Grevillea robusta* was reported in 5% of cases in Kageyo. In fruit trees, major problems reported were water stress mainly reported in Kageyo (51% of farmers), poor adaptation that was reported in 9-10% of cases for *Persea americana* and 21-24 % of cases for *Citrus sinensis*. Damage due to animal browsing was reported by 12-15% of farmers for *Persea americana* and 23% of farmers for *Citrus sinensis* in Kageyo. For the legume species, major constraints reported were the poor adaptation in 13% of cases for *Calliandra calothyrsus* in Simbi and 17% of cases for *Tephrosia vogelii* in Kageyo. Water stress was reported in 14% of cases in Simbi, and in 42% and 54% of cases for *Calliandra calothyrsus* and *Tephrosia vogelii* in Kageyo, respectively.

Table 3.8 Primary problems expressed by farmers (% of farmers) during the tree species evaluation in Simbi and Kageyo.

	Eucalyptus urophyla		*Grevillea robusta*	
	Simbi (*n = 11*)	Kageyo (*n = 12*)	Simbi (*n = 14*)	Kageyo (*n = 23*)
No problem	28	50	62	54
Termites	5	-	8	-
Competition for *Pennisetum* sp.	-	-	13	5
Water stress	39	50	17	21
Poor adaptation	-	-	-	5
Animal browsing	28	-	-	10
Soil compaction	-	-	-	5
	Persea americana		*Citrus sinensis*	
	Simbi (*n = 17*)	Kageyo (*n = 22*)	Simbi (*n = 19*)	Kageyo (*n = 20*)
No problem	40	28	79	36
Water stress	35	51	-	17
Poor adaptation.	10	9	21	24
Animal browsing	15	12	-	23
	Calliandra calothyrsus		*Tephrosia vogelii*	
	Simbi (*n = 20*)	Kageyo (*n = 20*)	Simbi (*n = 18*)	Kageyo (*n = 6*)
No problem	73	50	89	13
Poor adaptation	13	-	-	17
Water stress	14	42	-	54
Diseases	-	-	11	16
Animal browsing	-	4	-	-
Competition for *Pennisetum* sp.	-	4	-	-

Farmer scoring and perspectives for tree planting

Farmer criteria for evaluating tree species were related to different tree attributes including growth patterns (straightness, trunk diameter, growth speed), tree productivity and product quality (poles, firewood and wood quality) and the compatibility with other crops (competition aspect) (Table 3.9). *Eucalyptus urophyla* was rated good to very good for the ability to provide poles. *Grevillea robusta* was rated good in Simbi but poor in Kageyo. The most striking differences in farmers' scores for *Eucalyptus urophyla* and *Grevillea robusta* were observed on tree compatibility with other crops and coppicing ability attributes. *Eucalyptus urophyla* was rated poorly than *Grevillea robusta* on tree compatibility attribute and vice versa on coppicing ability. A large number of farmers showed interest in planting more *Grevillea robusta* in Simbi and *Eucalyptus urophyla* in Kageyo.

Fruit tree species were rated very well in Simbi but poorly in Kageyo with regards to the adaptability to different locations. Growth vigour was more highly rated in Simbi than in Kageyo. All farmers in Simbi and Kageyo expressed an interest to plant more *Persea americana*, while 80% of them interested in planting more *Citrus sinensis*. In the legume species category, *Calliandra calothyrsus* scored well for its ability to provide poles, palatability, coppicing and compatibility with other crops. In addition, *Calliandra calothyrsus* was rated good to very good for its potential to improve soil fertility. This attribute was only reported in Simbi probably due to trials that were previously conducted in the area. The overall appreciation of legume species indicated that farmers in both locations were much more interested to plant more *Calliandra calothyrsus* but especially so in Kageyo.

Table 3.9 Farmers' mean rating of species, using the Bao game*, on criteria important to farmers and preferences for future planting, 12 months after planting (minimum and maximum values in parentheses)

	Eucalyptus urophyla		*Grevillea robusta*	
	Simbi (*n* = *20*)	Kageyo (*n* = *22*)	Simbi (*n* = *20*)	Kageyo (*n* = *22*)
Poles supply	3.2 (3-4)	4.0 (4-5)	3.0 (2-4)	2.6 (2-3)
Straightness	4.3 (3-5)	4.3 (3-5)	2.2 (2-3)	2.3 (2-3)
Trunk thickness	4.7 (4-5)	4.0 (3-5)	3.0 (2-4)	3.2 (3-4)
Compatibility	1.5 (1-2)	1.2 (1-2)	3.5 (2-4)	3.2 (2-4)
Coppicing	4.0 (3-5)	3.3 (2-4)	1.5 (1-2)	1.6 (1-2)
Durability of fire	4.9 (4-5)	-	2.3 (2-3)	-
Wood quality	-	4.4 (4-5)	-	2.2 (1-2)
**% farmers rating 4 to 5 for future planting	42.2	85.2	81.6	74.4
	Persea americana		*Citrus sinensis*	
	Simbi (*n* = *20*)	Kageyo (*n* = *22*)	Simbi (*n* = *20*)	Kageyo (*n* = *22*)
Branching	1.7 (1-3)	2.1 (1-2)	3.5 (3-4)	4.3 (2-5)
Adaptability	4.2 (3-5)	1.9 (1-3)	4.0 (3-5)	2.0 (2-3)
Growth vigour	2.3 (2-3)	1.9 (1-2)	3.8 (3-4)	2.1 (2-3)
Early growth	3.8 (2.4)	-	2.0 (1-3)	-
Productivity	4.4 (4-5)	-	2.1 (1-3)	-
% farmers rating 4 to 5 for future planting	100	100	81.6	82.5
	Calliandra calothyrsus		*Tephrosia vogelii*	
	Simbi (*n* = *20*)	Kageyo (*n* = *22*)	Simbi (*n* = *20*)	Kageyo (*n* = *22*)
Poles supply	3.6 (2-5)	3.2 (2-3)	2.6 (2-4)	2.0 (2-3)
Palatability	3.7 (3-4)	4.8 (4-5)	1.8 (1-3)	1.0 (1-2)
Coppicing	3.6 (3-4)	4.1 (3-5)	1.9 (1-3)	1.6 (1-2)
Compatibility	5.0 (5-5)	4.4 (3-5)	3.2 (3-4)	2.9 (2-4)
Soil fertility improvement	3.9 (3-5)	-	1.2 (1-2)	-
% farmers rating 4 to 5 for future planting	80.2	95.8	28.3	11.1

*Scale ranging from 1 to 5: 1: very low score, 2: low score, 3: high score, 4: very high score and 5: Best score,

**Percent of farmers rating higher to very higher probably for a given species to be planted in future.

Discussion

Comparing socio-economic characteristics between the two locations

The average family size was comparable between similar farm types in the two locations (Table 3.1). The overall number of household heads with primary education level in moderate and poor farmer categories was larger in Simbi (40%) than Kageyo (26%), but was comparable in wealthier category in the two areas. On average, 66, 47 and 37 % of household heads in wealthier, moderate and poor farm categories, respectively, had basic education in Simbi while 66, 34 and 18% of household heads in the corresponding farm groups had the same education level in Kageyo. The average number of cattle reared was similar across farm types. On average, a wealthier farmer had 3 cattle and a moderate farmer 1 cow in both locations. However, wealthier and moderate farmers in Simbi had a larger number of livestock than farmers from similar resource groups in Kageyo. The average woodlot was larger on wealthier farms in Kageyo (0.34 ha) compared to the corresponding farm type of Simbi (0.16 ha). Agroforestry is more diversified in Simbi than in Kageyo. The reasons for differences in tree diversity are of biophysical and socio-economic nature (Table 3.2). The agro-ecological conditions, such as the altitude and temperature may have considerable influence on growth and development of different tree species. Higher altitude associated with low temperature limit the development of some tree species in the Buberuka Highlands, explaining why fruit trees such as papaya (*Carica papaya*) or mangoes (*Mangifera indica*) were not found there. The number of trees per farm differed between sites and wealth groups. Tree density was much higher on wealthier farms than on moderate and poor farms. This was mainly due to the large number of trees in woodlots and cropland on wealthier farms (Table 3.2). Wealthier farmers own larger farms (Table 3.1) and therefore have flexibility to plant a relatively larger number of trees in cropland. Woodlot/forest area was three to four times greater on wealthier farms than on moderate farms and twenty to thirty times more than on poor farms, contributing to a greater number of trees on farm (Table 3.1). The smaller number of tree species and density in Kageyo could also be related to the lower population density compared with Simbi. The population density was about 520 inhabitants km^{-2} in Simbi (Huye DDP 2007) and 430 inhabitants km^{-2} in Kageyo (Gicumbi DDP 2007). The high population density in Simbi may have contributed in increasing the tree density and diversity since specific tree species are needed for construction (*Ficus thonninghi* and *Vernonia amygdalina* used for fences around the house), daily needs (*Vernonia*, *Erythrina abyssinica*, *Euphorbia tirucalli* used as medicines) or to protect the inhabitants from danger (*Erythrina abyssinica*). Despite having the least number of trees on per farm basis, resource-limited farms had the highest density of trees per unit area basis, confirming an inverse correlation between land holding size and tree density previously reported by den Biggelaar and Gold (1996) in Simbi.

Types and number of tree planted on farm and survival

In general, wealthier farmers planted most of the timber trees (*Eucalyptus urophyla* and *Grevillea robusta*). More *Eucalyptus urophyla* was planted in Kageyo (Table 3.3). A stronger preference for *Eucalyptus urophyla* by wealthier farmers was due to the fact that these farmers have a large woodlot area (Table 3.1) where *Eucalyptus* was exclusively established (Table 3.4). Poor farmers who did not have enough land for woodlots planted *Eucalyptus urophyla* trees in other niches. The strong preference for *Grevillea robusta* in Simbi was due to the fact that it is less competitive and may be grown in niches close to crops (e.g. contours) (Table 3.4). Also, *Grevillea robusta* is a fast growing tree producing relatively larger biomass and stakes with tolerance to poor degraded soils of southwest of Rwanda (König 1992). *Grevillea robusta* produced slightly more biomass in Central plateau than in Buberuka, probably due to the limiting effect of cooler temperature at higher altitude (Kalinganire 1996).

The results indicated that legume shrubs were preferentially established on niches close to the home compounds (contours of cropland or farm boundaries) on moderate and poor farms while wealthier farmers allocated *Calliandra calothyrsus* to niches located further from the homestead such as along paths. The reasons that moderate and poor farmers chose niches closer to home compounds could be related to the importance they attach to *Calliandra calothyrsus* as an important source of firewood, stakes/poles and animal feeds. Based on our informal discussions with farmers, it appears that farmers prefer having *Calliandra* closer to cropping fields so that they may easily collect firewood sticks, stakes at the planting time and leafy biomass for animal feeding. In addition, *Calliandra* shrubs together with *Grevillea robusta* may offer possibility for soil conservation on sloping landscape threatened by severe soil erosion.Wealthier farms have several options including use of the large number of trees from the *Eucalyptus urophyla* woodlots.

The higher survival rate of fruit trees in homesteads was attributed to them being planted in more favourable growing conditions. Previous studies conducted in sub-Saharan Africa have shown that home fields are generally richer than fields further away from home. In most cases, both organic and inorganic fertilizers are preferably allocated to the fields closer to home compound at the expense of those located further away (e.g. Tittonell et al. 2005a; Zingore et al. 2007a). In addition, fruit trees grew under banana and benefited from shade, reduced evapo-transpiration and better soil moisture conditions. Fruit trees were regularly watered during the severe drought in September 2007 (Table 3.8). Fruit trees received more care than other tree species, indicating their importance for farmers. Farmer preferences for fruit species were also highlighted by the larger number of farmers willing to plant more of them on their farms (Table 3.9). Young fruit tree seedlings are less competitive than the fast growing timber trees (e.g. *Eucalyptus* sp, Table 3.9) so farmers can plant them in cropland (Table 3.4). More interest for *Persea americana* trees was also related to the possibility to use it for purposes other than fruit production. Some farmers without woodlots use all possible alternatives for firewood including old *Persea americana* trees. Farmers' strong preference for fruit trees was reported earlier in Rwanda (Balasubramanian and Egli 1986;

Pinners and Balasubramanian 1991). Farmer investment in fruit trees appears to be common in low-input farming systems in tropical regions with similar biophysical configurations as Rwanda such as in Central Kenya highlands (Cleaver and Schreiber 1994). High-value trees including fruit-tree based agroforestry are popular in highland areas and play a complementary role with other activities in the subsistence farming system, contributing in increasing the total productivity and food security in the communities. Highland regions are known to have favourable climate conditions comparable to temperate conditions that would favour production of several fruit species that can be sold to other regions. This suggests that fruit species will continue to be one of the most preferred and planted tree species on resource-limited farms in Rwanda. However, more research attention, access to planting material and fruit marketing development should be promoted to ensure that smallholder farmers benefit from the full potential of the fruit tree species.

Tree growth and productivity

Better tree growth and productivity on contours (Table 3.7) could be attributed to several factors. Firstly, trees and shrubs established together with crops may benefit from fertiliser and compost applied to the crops (Table 3.6). Secondly, the trees receive much more care since they are established closer to the home compound. Management practices such as weeding, watering were mostly done for trees established near homesteads or on contours and less for trees away from home. Trees planted on contours were planted at higher density (data not shown), resulting in more biomass production per unit area.

Generally, tree survival and productivity were much poorer than observed on the research station. For instance, the survival rate of *Grevillea* was 44 to 68 % in southwest Rwanda, much lower than the average of 95.9 % reported from on station trials in Ruhande (Kalinganire and Zuercher 1996). *Calliandra calothyrsus* hedges yielded 4 to 5.8 t ha^{-1} of biomass only half the 9.7 t $year^{-1}$ ha^{-1} on experimental plots in southwest of Rwanda as reported by König (1992). Poor survival and productivity was partly due to the large variability among locations/niches where the trees were planted (Table 3.4), tree management (Table 3.6) and constraints faced during the tree establishment (Table 3.8). The strong linear relationship between tree growth and the above-ground productivity found with *Eucalyptus urophyla* (R^2 = 0.69) was partly because most *Eucalyptus urophyla* trees were established in one niche (woodlot), which significantly reduced variability. The relationship between tree growth and biomass productivity may be used to estimate tree productivity on-farm.

Farmers' perceptions and perspectives for agroforestry

Farmers'scoring reflected farmers' perceptions on the main attributes and potential uses of different tree species. Tree utility and locational flexibility are important criteria for farmer preferences as earlier reported by den Biggelaar and Gold (1996). For instance *Eucalyptus urophyla* was the most preferred by wealthier farmers in Kageyo due to the fact that the species is used for several daily needs: firewood, construction, stakes, but also because farmers still have available land. In Simbi, on the other hand, *Eucalyptus urophyla* was not among the most preferred species due to the critical land shortage (Tables 3.1 & 3.9). All of the farmers planted *Persea americana*, although they already have many fruit species in the homestead niche. Farmers planted fruit trees in the food crop fields (Table 3.4) despite potential competition with food crops. A higher score for the ability to supply poles was expected for timber trees. However, *Eucalyptus urophyla* was blamed for its competitiveness (Table 3.9), a reason for the farmers planting it away from home for fear of competition with other food crops (Table 3.4). Farmer perceptions of *Eucalyptus urophyla* competitiveness were similar to that reported in western Kenya (Franzel et al. 2002). *Calliandra calothyrsus* was equally regarded as source of stakes and animal forage in Simbi (Table 3.9). In Kageyo, *Calliandra calothyrsus* scored well for the supply of poles but very high for palatability, suggesting a greater relative importance for livestock feeding compared with the staking of beans. Palatability was one of the important attributes used by farmers in the evaluation of tree forage. This criterion is related to the effect of feeds on animal nutrition (Roothaert and Franzel 2001). *Calliandra* biomass is given in smaller quantities (mostly a third of the diet) together with other feeds (e.g. grasses such as *Setaria* sp. or *Pennisetum* sp.).

Besides animal feeding, *Calliandra calothyrsus* is also appreciated for the supply of stakes for climbing bean. Climbing beans are widely grown in the highlands zone of Rwanda where they give about twice the yield of the local bush beans and are key for food security. One of the major challenges for bean production is the lack of staking material (den Biggelaar personal communication).

Tephrosia was the least preferred species. Only 28 % of the farmers in Simbi and 11% in Kageyo showed interest in growing it, which was related to the few uses they had for it. *Tephrosia vogelii* is used for catching fish or protecting stored grains against pest (Barnes and Freyre 1965). During our focus group discussion, it was observed that especially older farmers were more knowledgeable about *Tephrosia vogelii* and have been consistently using and managing it over a longer period of time. The species was tested by some farmers for feeding goats.

Conclusion

By using a variety of participatory approaches, we gained insight into the interest of farmers in different types of agroforestry that address a variety of their needs. The combination of surveys of existing practices, following farmers' preferences for planting and the way they managed different agroforestry species, as well as the farmers' own evaluations allowed us to identify on-farm niches for agroforestry for farmers of different wealth classes. Participatory approaches offer major advantages. First, they provide the opportunity for farmers to share their valuable knowledge of their agroforestry systems which can help to identify key opportunities, problems and constraints. Second, they allow researchers and farmers to jointly share results, to design agroforestry interventions and in doing so refine the development of agroforestry systems.

We found that farmers from different agro-ecological zones had preferences for different tree species. Tree performance (survival and growth) differed between the two agro-ecological zones. The tree management and performance appear to be similar across farm types, implying that farmers learn from each other.

Our results have important implications for setting priorities for future investment in agroforestry research. Fruit trees received little attention in the past research and development priority setting. The focus was largely on timber and legume species to deal with soil erosion and soil fertility problems (ICRAF/ISAR/ECA 2001). Our results suggest that a revision of research priorities should consider extending attention to agroforestry species that match farmer preferences and include those options that have a direct potential for generating income. This fits with the current Government policy aimed at moving from subsistence to market-driven agriculture (MINAGRI 2009). Similarly, *Calliandra calothyrsus*, found to be popular with wealthier farmers owning dairy cattle appears to have a special role. Under the 'One cow, one poor farmer' programme, (a current government programme aimed at donating a cow to each vulnerable household), it is expected that the increasing number of dairy cattle will translate into a strong demand for quality feeds to maintain and increase milk production of cross-breed cattle. *Calliandra calothyrsus* prunings are a suitable feed for cross-bred cows (Tuwei et al. 2003) that have been widely-adopted in the highlands of East Africa (Wambugu et al. 2011). Whilst soil conservation and soil fertility remain to be important issues for agricultural development in the highlands of East and Central Africa, other entry points need to be sought for agroforestry-based approaches to these problems. For example, provision of staking material for climbing beans could be an entry point for introduction of multi-purpose legume trees into the farming system, which could provide multiple benefits.

Chapter 4

Managing Tephrosia *mulch* and fertilizer to enhance coffee productivity on smallholder farms in Eastern African Highlands

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Abstract

In Maraba, Southwest Rwanda, coffee productivity is constrained by poor soil fertility and lack of organic mulch. We investigated the potential to produce mulch by growing *Tephrosia vogelii* either intercropped with smallholder coffee or in arable fields outside the coffee, and the effect of the mulch on coffee yields over two years. Two accessions of *Tephrosia vogelii* (ex. Gisagara, Rwanda and ex. Kisumu, Kenya) were grown for six months both within and outside smallholder coffee fields in the first year. Experimental blocks were replicated across eight smallholder farms, only a single replicate per farm due to the small farm sizes. The accession from Rwanda (*Tephrosia vogelii* ex. Gisagara) grew more vigorously in all experiments. Soils within the coffee fields were more fertile those outside the coffee fields, presumably due to farmers' long-term management with mulch. *Tephrosia* grew less well in the fields outside coffee, producing only 0.6-0.7 Mg ha^{-1} of biomass and adding (in kg ha^{-1}) 19 N, 1 P and 6 K in the mulch. By contrast, *Tephrosia* intercropped with coffee, produced 1.4-1.9 Mg ha^{-1} of biomass and added (in kg ha^{-1}) 42-57 N, 3 P and 13-16 K in the mulch. Coffee yields were increased significantly by 400-500 kg ha^{-1} only in the treatments where *Tephrosia* was intercropped with coffee. Soil analysis and a missing-nutrient pot experiment showed that the poor growth of *Tephrosia* in the fields outside coffee was due to soil acidity (aluminium toxicity) combined with deficiencies of P, K and Ca.

In the second year, the treatments in fields outside coffee were discontinued, and in the coffee intercrops, two *Tephrosia* accessions were grown in treatments with and without NPK fertilizer. *Tephrosia* grew well and produced between 2.5 and 3.8 Mg ha^{-1} biomass for the two accessions when interplanted within coffee fields, adding 103-150 kg N ha^{-1}, 5-9 kg P ha^{-1} and 24-38 kg K ha^{-1}. *Tephrosia* mulch increased yields of coffee by 400 kg ha^{-1}. Combined use of NPK + *Tephrosia* mulch increased *Tephrosia* biomass production and in turn yielded an additional 300-700 kg ha^{-1} of coffee. Over the two years, this was equivalent to a 23-36% increase in coffee yield using *Tephrosia* intercropping alone and a further 25-42% increase in coffee yield when

NPK fertilizer was also added. Agronomic efficiency (*AE*) of nutrients added were 30% greater when the *Tephrosia* mulch was grown *in situ* and the two cultivars of *Tephrosia* did not differ in *AE*. The *A*E of *Tephrosia* mulch was 87% that of NPK fertilizer, reflecting the rapid mineralization of *Tephrosia* mulch. There was a synergistic effect of *Tephrosia* mulch on the efficiency with which NPK fertilizer was used by coffee. The increase in coffee yields was positively related to the amount of nutrients added in the *Tephrosia* biomass. *Tephrosia* intercropping required 30 man-days ha^{-1} less than current farmer management due to reduced labour required for weeding, and benefit-cost ratios ranged between 3.4 and 5.5. The *Tephrosia*-coffee intercropping system offers great potential for agroecological intensification for smallholder farmers in the East African highlands.

Keywords: Organic mulching. Economic evaluation. Intercropping. Limiting nutrients. Agroecological intensification.

1. Introduction

Coffee is a major cash crop in the Eastern African highlands and is important for national economies, accounting for 60% of exports in most countries (USAID 2006; de Graaff 1986; Van Asten et al. 2011). Coffee is grown on large estates, but the majority is produced by smallholder farmers, who are often grouped into cooperative societies. For instance, smallholder coffee farmers were reported to contribute for about 60% of the national coffee production in Kenya (de Graaff 1986). Most coffee production is concentrated in the highlands (> 1500 m asl) with favourable climate conditions that coincide with higher human population densities. Coffee quality differs among the countries depending both on production and processing methods. While the Kenyan coffee (90% fully washed) has long been recognized as high quality (de Graaf 1986), Rwandan coffee was classified largely as ordinary grade category (semi-washed coffee) and could not compete with other coffees on the international market. In 1999, Government laid down strategies aimed at shifting from intensive production of ordinary grade coffee towards improving quality to target specialty coffee markets with premium prices. However, average annual coffee production is estimated at 0.33 kg of dry parchment coffee per tree, far less than the 0.7 to 1.15 kg per tree obtained in the region (Loveridge et al. 2002). Their poor production capacity compromises the ability of smallholder coffee growers to venture into the specialty coffee market, as they cannot assure sufficient and regular coffee supplies.

In the coffee producing area of Maraba (Southern Rwanda), soils on steeply sloping cropland are strongly depleted and susceptible to the erosion. Over 50% of the coffee fields receive no mulch (Nkeshimana 2008). In densely coffee areas, fallow land is scarce and additional land required to produce organic material for mulch is scarce or unavailable. Therefore, mulch is collected from food crop fields, including grass species (*Hyparrhenia filipendula*, *Eragrostis* sp.), cereals (*Sorghum bicolor* thatch), banana leaves and pseudo-stems and this could in the long-run induce a decline in soil fertility of these fields and a reduction in food crop yields (Balasubramanian and Egli 1986).

Mulching with leguminous cover crops is a proven option for increasing crop production and providing N to crops in tropical farming systems (Armstrong et al. 1997; Thonnissen et al. 2000). *Tephrosia* species are widely used as multipurpose legumes in agroforestry, well known for the insecticidal properties of the leaves and their use for stunning and catching fish (Giller 2001). They grow well at high altitudes in the tropics. Substantial research has been done on the use of *Tephrosia* for soil fertility improvement (Ikpe et al. 2003; Mafongoya et al. 2003; Rutunga et al., 2003). *Tephrosia vogelii* is among the most promising fast-growing legume trees for agroforestry in Rwanda (Balasubramanian and Sekayange 1992; Drechsel et al. 1996). Though legume residues can contribute to soil fertility (Vanlauwe et al. 1997), the expected benefits may not be generated on poor soils because of limited biomass and N accumulation due to deficiencies of other nutrients such as P and K (Houngnandan et al. 2001; Baijukya et al. 2005).

Tephrosia mulch for coffee can be produced in two ways: by intercropping the shrubs between the bushes of coffee that are typically planted 2 to 2.5 m apart, or by growing the shrubs on fields outside the coffee and using the mulch in a ‘biomass transfer’ or ‘cut-and-carry’ system. The ecological advantages of intercropping can include reduced risks of pests and diseases, improved use of production factors, greater total production per unit area and more effective use of labour (Vandermeer 1990). Yet the governments of Papua New Guinea and Rwanda have respectively restricted or discouraged intercropping in coffee (Bourke 1985; Balasubramanian and Egli 1986), arguing that inter-species competition for nutrients and water may reduce coffee yield. The recommendations may result from previous policy by the colonial ruling power which was more interested in coffee than in other crops and the fear that farmers could not be in the position to manage complex farming systems where coffee production could be hampered by strong competition (Van Asten et al. 2011).

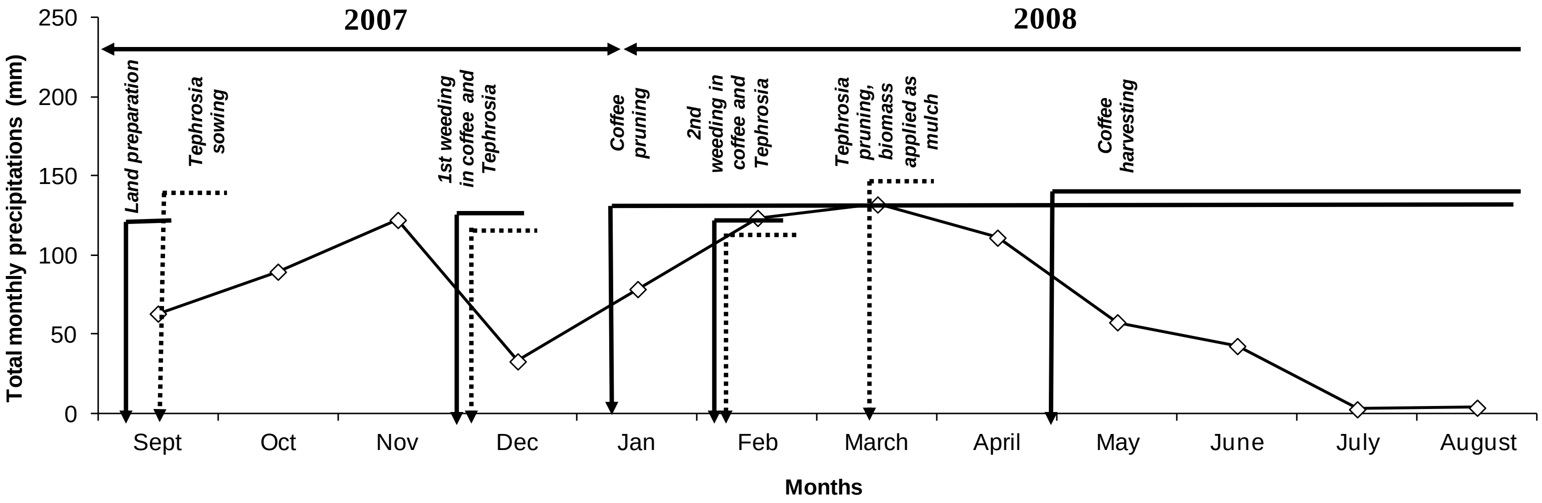
We evaluated growth and biomass production of two *Tephrosia vogelii* accessions (*Tephrosia vogelii* ex. Gisagara, Rwanda and *Tephrosia vogelii* ex. Kisumu, Kenya) and their use as mulch in smallholder coffee plantations. Our overall hypothesis was that growing organic matter *in situ* could address the shortage of mulch for coffee production. Different approaches of growing *Tephrosia* were tested with and without fertilizer: interplanting rows of *Tephrosia* between the rows of established coffee fields; and growing *Tephrosia* as a sole crop on separate fields outside the coffee. The specific objectives were: 1) to quantify *Tephrosia* biomass production and nutrient accumulation when intercropped with coffee or grown in pure stands, and the effects on coffee production; 2) to assess the effects of NPK fertilizer on production of *Tephrosia* mulch, and the resulting effects of the fertilizer and mulch on coffee production; 3) to identify through a pot experiment which nutrients limited growth of *Tephrosia* in the soils of the Maraba area; and 4) to evaluate the economics of using *Tephrosia* to improve coffee production by performing a cost-benefit analysis.

2. Materials and Methods

2.1 Study site

The study was conducted in Maraba sector (2° 30' 54" S, 29° 40' 47" E) located in the central plateau agro-ecological zone of Rwanda during the 2007/2008 and 2008/2009 seasons. The area is hilly, being situated close to the Western Rift Valley and the Nyungwe Forest, with altitude ranging between 1,650 and 2,000 m (Nkeshimana 2008), and mean annual temperature of 19^{o}C. The dominant soils are gleysol and acrisols in the uphill areas, and histosols and vertisols in the valleys. Rainfall follows a bimodal trend, divided over the long rainy season from February to May/June and short rainy season extending from September to December (Drechsel et al. 1996). The total rainfall was 881 mm in the 2007/2008 season, with a pronounced dry spell in December while it was 1089 mm in the 2008/2009 season (Figures 4.1a & b).

(a)



(b)

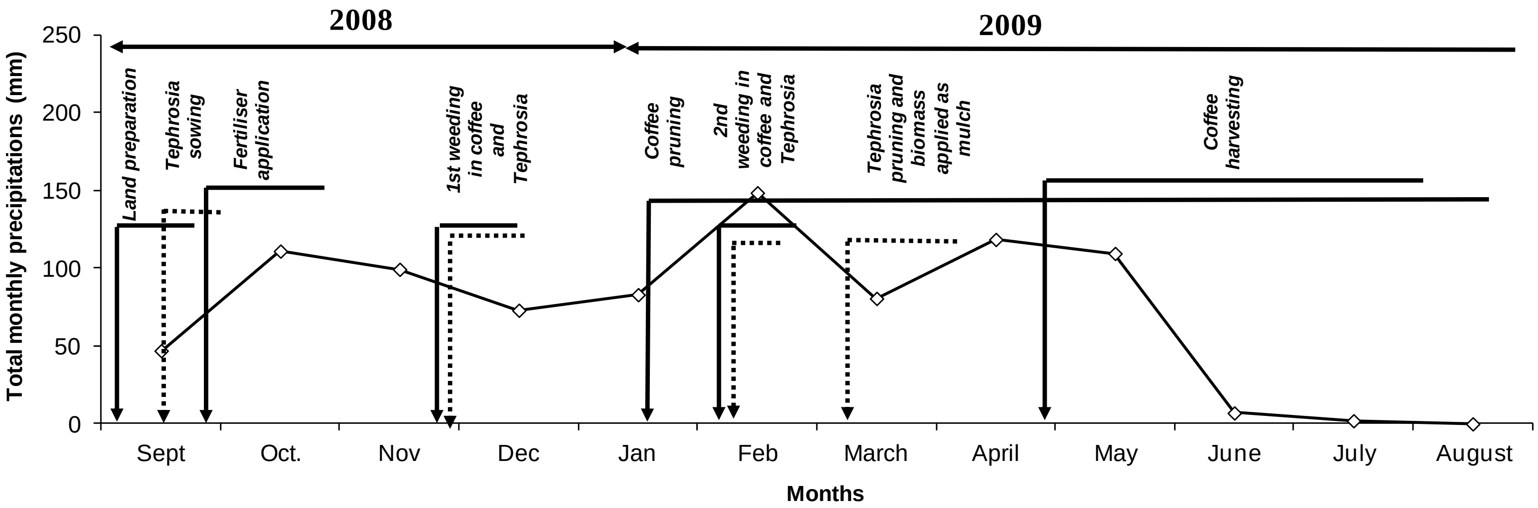


Figure 4.1 Total monthly rainfall (mm) and different coffee (solid line) and *Tephrosia* (dotted line) activities during 2007/2008 (a) and 2008/2009 (b) seasons. Total rainfall was 881 mm in the 2007/2008 season and 1089 mm in the 2008/2009 season. Source: ISAR Weather Unit (2009)

Eight smallholder coffee farms were selected for the trials each with 100 to 400 coffee trees, in fields measuring 400 to 1600 m^2. In all farms, the coffee bushes (*Coffea arabica* L.) were 20 to 30 years old, spaced roughly 2 m × 2.5 m apart. The fields received annually 4 to 5 t ha^{-1} of mulch with varying composition, roughly consisting of 30 to 50% *Eucalyptus* branches and litter, 20 to 30% of *Grevillea* branches, and 20 to 50% of sorghum and other cereal residues mixed with various grasses (e.g. *Pennisetum clandestinum, Hyparrhenia filipendula*). None of the coffee fields had received fertilizer in the previous five years.

2.2. Field trials

A field experiment was conducted during the 2007/2008 season to compare growth, biomass production and nutrient uptake of two accessions of *Tephrosia* planted within coffee or outside coffee, and the impact of their use as mulch in coffee fields. Two accessions of *Tephrosia vogelii* (Hook. f.) were compared: one collected in Gisagara, Rwanda (Lot number: 430/2008) obtained from the agroforestry seed bank of Ruhande station of The Institute of Agricultural Research of Rwanda (ISAR); the other was collected in Kisumu and obtained from the Seed Laboratory of World Agroforestry Centre (ICRAF, Nairobi, Kenya) and was designated as *Tephrosia candida* (ICRAF 03116). As both are confirmed to be *T. vogelii* (P. Stevenson, personal communication 2011), we refer to them as *Tephrosia* ex. Gisagara and *Tephrosia* ex. Kisumu. Thus the following treatments were compared: (i) coffee fields in which single rows of *Tephrosia* ex. Gisagara or *Tephrosia* ex. Kisumu were intercropped between rows of coffee, and where *Tephrosia* biomass was applied as mulch in the same plot in addition to the farmers' mulch; (ii) coffee fields to which mulch of the aboveground biomass of the two *Tephrosia* accessions grown in fields close to the coffee fields was applied in addition to the farmers' mulch; and (iii) coffee fields maintained under farmers' mulch practice as a control treatment. No fertilizer was applied to any of the plots. The experiment was established with single replicates of all treatments on eight farms where the farms served as individual replicate blocks as the farmer plots were too small to accommodate more plots.

Because *Tephrosia* productivity was poor when grown outside the coffee fields in the 2007/2008 season, this treatment was discontinued. In the 2008/2009 season a separate trial was established to test whether addition of fertilizer would improve biomass production of *Tephrosia* and coffee yield when intercropped. The following treatments were tested, all with and without NPK fertilizer: (1) farmers' mulch practice, (2) *Tephrosia* ex. Gisagara and (3) *Tephrosia* ex. Kisumu both intercropped between coffee with the *Tephrosia* mulch recycled *in situ*. As in the first season, all plots received the standard farmers' mulch. The same eight farms served as complete replicate blocks, but different plots were used. The same procedure for planting and management was followed in the 2008/2009 season as in the 2007/2008 season.

Land in the plots outside coffee was tilled by hand by the farmers, within coffee there was minimal soil disturbance (Figure 4.1). The equivalent amount of 5.5 t dry matter ha^{-1}, comprising 50% of *Eucalyptus* sp., 20% *Grevillea robusta* prunings, 10% of *Hyparrhenia filipendula*, 10% *Sorghum bicolor* thatch, and 10% of banana leaves and pseudo-stems was applied uniformly to all the experimental plots. In the second season, NPK fertilizer (20-10-10) was applied in the relevant treatments at the rate of 100 g tree^{-1} (200 kg ha^{-1}) broadcast uniformly over the experimental plot, providing 40 kg N ha^{-1}, 8.8 kg P ha^{-1} and 16.6 kg K ha^{-1}.

Experimental plots were 6 m × 7.5 m both outside the coffee fields and in the coffee fields where four trees in the centre formed the net plot for harvesting coffee. *Tephrosia* seeds were soaked in water for 24 hours to break dormancy and sown directly in or outside coffee fields using a spacing of 50 × 30 cm (4 rows of 30 plants each equivalent to 66,000 plants per ha^{-1}). Thus there were two rows of *Tephrosia* plants in each alley between the coffee. Gaps were filled at two weeks after planting using seedlings to maintain a uniform plant density. The seedlings were watered by hand during the drought of December 2007. All plots were weeded at two and four months after planting. Coffee bushes were pruned in January after the short rain season and thereafter, removing secondary and tertiary and other weak branches.

Prior to sowing and mulch application, soil samples were taken from the 0-20 cm horizon, air-dried in the laboratory, and ground to pass a 2 mm sieve for chemical and physical analysis. At six months after establishment, when the plants were approximately 1 m tall, the *Tephrosia* shrubs were cut to the ground and the mulch was chopped into pieces (< 10 cm) and applied in the corresponding plots. Plant height of *Tephrosia* was recorded on 30 plants randomly selected in each plot. *Tephrosia* grown in plots adjacent to coffee was pruned following the same procedure and applied on plots where *Tephrosia* had not been grown. Five samples of *Tephrosia* and farmers' mulch were collected from each plot, dried and ground for analysis. Coffee was harvested from April to July. Four centered coffee trees were marked and harvested on weekly basis in specific jute bags per each plot. Fresh coffee berries were manually depulped, washed and dried to obtain coffee parchment.

2.3. Nutrient omission greenhouse trial with Tephrosia

A nutrient omission pot trial was established to identify nutrients limiting growth of *Tephrosia* ex. Gisagara, in soils (0-20 cm) from one of the farms used for the field experiments. The farm selected had *Tephrosia* production close to the average over all farms in the 2007/2008 season. Treatments included lime ($CaCO_3$) applied at two rates (0 and 2.08 g pot^{-1}), 2 soil locations (soil inside and outside the coffee field) and seven nutrient solutions: Full solution (FS), without N, without P, without K, without Ca, without Mg and a control with no nutrients added. There were five replicate pots for each treatment. Pots were filled with 3 kg of air-dried and sieved (9.5 mm mesh) soil. Adequate liming rate was applied to neutralise exchangeable Al^{3+} in the soil (Brady and Weil, 2002). Half of the pots were limed before application of the nutrient solutions. Rates of nutrients were calculated based on plant requirements suggested by Mutwewingabo and Rutunga (1987). Nutrients were applied in forms and at rates as follows (amounts calculated on a volume basis): 1 g N pot^{-1} as NH_4NO_3, 0.16 g P pot^{-1} as KH_2PO_4, 0.23 g K pot^{-1} as K_2SO_4, 0.8 g Ca pot^{-1} as $CaSO_4$ and 0.32 g Mg pot^{-1} as $MgSO_4$. Twenty seeds of *Tephrosia* ex. Gisagara were sown in each pot and thinned after establishment to leave five plants. Plants were allowed to establish for two weeks before receiving 75 ml of the nutrient solutions. Pots were monitored for moisture loss every 2nd day and watered to maintain moisture at 40 to 50 % of field capacity. Shoot length (cm), total dry weight and nutrient accumulation at 16 weeks after planting (16 WAP), were measured.

2.4. Plant and soil analysis

To determine dry matter and nutrient contents, 0.5 kg samples of chopped above ground *Tephrosia* biomass and farmer mulch were oven-dried at 75^{o}C to constant weight, weighed, and ground. Total N was analysed after Kjeldahl digestion, available P using the ascorbic acid method and K was analysed by flame photometry. Ca and Mg were determined using atomic absorption spectrometry (AAS) (Anderson and Ingram 1993).

The soil samples were air-dried in the laboratory and ground to pass a 2 mm sieve. Soil particle distribution was determined using standard hydrometer method. Soil pH was determined in a 1: 2.5 soil: H_2O and 0.01 M KCl suspension. Organic C was determined by the Walkley-Black method, total nitrogen using Kjeldahl digestion method, available phosphorus using the Bray-1 method (Anderson and Ingram 1993). Exchangeable cations (K, Ca, Mg) were extracted in 1 M ammonium acetate and estimated as above. Exchangeable acidity (Al^{3+}; H^+) was determined by extraction with 1.0 KCl followed by titration with NaOH and HCl. Effective cation exchange capacity (ECEC) was calculated by summing exchangeable cations, K, Ca, Mg, H^+ and Al^{3+} (Anderson and Ingram 1993).

2.5. Data analysis

Nutrient recovery in *Tephrosia* and farmer mulch was measured and used to calculate nutrient use efficiencies separately for *Tephrosia* mulch and NPK fertilizer applied. Due to the fact that we could not estimate N captured through N_2-fixation, the calculation of nutrient use efficiencies for the total nutrients from the three sources (*Tephrosia* + farmer mulch + NPK fertilizer) could generate errors due to double counting. We calculated net NPK fertilizer as:

$$\text{net NPK fertilizer added} = \text{TM} + \text{NPK} - \text{TM (NPK)} \qquad [1]$$

where TM, NPK and TM (NPK) are the nutrient quantities in *Tephrosia* mulch, NPK fertilizer and in the mulch of *Tephrosia* that had received fertilizer NPK, respectively.

Agronomic nutrient use efficiency (*AE*) was calculated as

$$AE\ (\text{kg ha}^{-1}) = (Y_F - Y_C)/(F_{app}) \qquad [2]\ \text{(Vanlauwe et al. 2011)}$$

where Y_F and Y_C refer to the coffee yield in the treatment where nutrients were applied and in the control plot respectively, and F_{app} is the amount of fertilizer and/or organic nutrients applied.

For inorganic nutrient sources, it holds that the agronomic nutrient use efficiency (*AE*) is the product of the uptake nutrient use efficiency (*UE*) or recovery fraction (*RF*) and the internal use efficiency or physiological efficiency (*PhE*):

$$AE\ (\text{inorg}) = RF \times PhE \qquad [1]$$

In the case of organic nutrient sources also the mineralization efficiency (ME) should be considered as organically bound nutrients cannot be taken up:

$$AE\ (\text{org}) = ME \times RF \times PhE \qquad [2]$$

We ascribe differences between *AE* (inorg) and *AE* (org) to *ME*.

Because the yield responses were brought about by the combinations of NPK in the applied mulch and fertilizer, it was not possible to allocate the yield increases to individual nutrients. The sum of N, P and K expressed in kilo of crop equivalent nutrient (kCNE) to be able to express the total nutrient content in mulch or fertilizer (Janssen 1998 2011) where for coffee, 1 kCNE equals 1 kg N, 0.175 kg P and 0.875 kg K (Janssen 2007). A kCNE represents the quantity of the nutrient that would result in a same yield increase as 1 kg of nitrogen under conditions of balanced nutrition.

Soil data from the field experiments were compared using t-tests. Data from the field experiments for *Tephrosia* and coffee yield, and for nutrient uptake were subjected to analysis of variance (ANOVA) using a general linear model (GLM). A one-way analysis was used for the 2007/2008 season where the treatments were unbalanced, for season 2008/2009 a two-way analysis with factors of mulch treatments and NPK fertilizer. The ANOVA for the pot experiment tested effects of soil location, lime and nutrient treatment. Linear regression was used to test the relationship between *Tephrosia* DM yield and the soil chemical parameters and the total nutrients (expressed in kCNE units) applied to the coffee yield. All analyses were conducted using GENSTAT version 7.22 (GenStat® Discovery Edition 3 2009).

2.6. Economic evaluation

Labour used for land preparation, *Tephrosia* sowing, weeding, mulching and coffee harvesting was recorded at plot level. For tasks such as coffee pruning, labour used was calculated from farmer’s reports. Work done by children was counted as half the normal work done by an adult. Labour cost was valued at 400 Rwandese Francs (RwF) day^{-1}, equivalent to US$ 0.72 day^{-1}. Prices for coffee and different inputs (*Tephrosia* seed, fertilizers, pesticide) were estimated based on the current market rates. The local price for coffee fluctuates depending on the world market and the average price was used for the current analysis. Revenues included income from coffee parchments sold at current price, 500 RwF (0.90 US $ kg^{-1}). Since mulching in coffee is often paid back in kind, the total cost was then estimated per unit area and converted in a monetary value. The cost of mulch was estimated at 100 RwF (0.18 US$) a bunch, resulting in a total cost of 70 US $ ha^{-1}, assuming that a total of 380 bunches of 25 kg were required per ha. All monetary values were converted to US$ 1.0 = RwF 550.

Net margins were derived from the difference between the total income from the coffee sale and the total costs incurred. The total income consisted of revenues earned by selling coffee. Operating costs were related to the purchase of *Tephrosia* seed, fertilizer, pesticide, mulch and labour costs. Returns to labour were estimated by dividing the total coffee yield by the number of man-days per ha for each treatment over the different seasons. The benefit-cost ratio was obtained by dividing the total benefits by the total costs for a particular season.

3. Results

3.1. Physical and chemical characteristics of soils

The soil outside the coffee fields was strongly acidic with higher exchangeable Al^{3+} contents and low pH (Table 4.1). The pH (H_2O), organic C, total N, available P and the effective cation exchange capacity (ECEC) were all substantially greater in the soils from the coffee plots. Exchangeable Ca^{2+} and Mg^{2+} concentrations were twice and K^+ concentration five times larger in the soils from the coffee plots. The soils from plots outside the coffee fields contained more sand and less clay likely reflecting the effects of erosion. All soils belonged to the sandy clay loamy texture class based on the USDA Soil Taxonomy key (Soil Survey Staff 1998). The statistical tests indicated strongly significant differences between the soils for almost all of the parameters tested, the only exceptions being exchangeable H^+ and silt. The soils used for the glasshouse trial were similar to those in the field for most soil parameters.

Table 4.1 Chemical and physical characteristics in soil from the field plots (n = 8) and the glasshouse experiment (n = 3)

	Field							Glasshouse						
	Within coffee			Outside coffee			*P*	Within coffee			Outside coffee			*P*
	Mean	Range	SE	Mean	Range	SE		Mean	Range	SE	Mean	Range	SE	
$pH_{(H2O)}$	4.6	4.1-5.2	0.1	4.3	4.0-4.7	0.1	**	5.2	5.1-5.3	0.01	4.4	4.4-4.5	0.01	***
$pH_{(KCl)}$	4.1	3.9-4.6	0.1	4.0	3.9-4.1	0.03	NS	4.6	4.6-4.7	0.03	4.0	4.0-4.0	0.004	***
OC (g kg^{-1})	12.7	6.5-21.5	1.7	7.8	1.0-17.5	2.3	**	16.8	9.0-23.0	3.2	5.7	4.0-8.0	0.85	**
Total N (g kg^{-1})	1.2	0.8-1.6	0.1	0.9	0.6-1.4	0.1	*	1.4	1.1-1.7	0.1	1.1	1.1-1.2	0.02	*
P (mg kg^{-1})	7.3	4.4-11.7	0.8	5.1	3.6-7.9	0.6	**	11.7	9.7-13.1	0.8	7.7	5.8-8.7	0.6	**
Exchangeable cations ($cmol_{(+)}$ kg^{-1})														
Ca^{2+}	2.2	1.2-3.7	0.3	1.3	0.8-2.3	0.2	**	3.6	3.0-4.1	0.2	1.2	1.0-1.5	0.1	**
K^{+}	0.5	0.1-1.1	0.1	0.1	0.0-0.3	0.03	**	0.6	0.4-0.8	0.1	0.1	0.1-0.2	0.01	**
Mg^{2+}	0.8	0.2-1.4	0.1	0.4	0.2-1.0	0.1	**	1.4	1.3-1.4	0.02	0.4	0.3-0.5	0.05	***
ECEC	5.4	4.5- 6.3	0.2	4.6	3.5-5.5	0.2	**	5.58	5.0-6.0	0.2	1.7	1.4-2.1	0.1	**
Exchangeable acidity ($cmol_{(+)}$ kg^{-1})														
Al^{+++}	1.2	0.0-2.5	0.3	2.1	1.2-2.8	0.1	**	1.0	0.0-2.0	0.2	2.4	2.3-2.5	0.04	***
H^{+}	0.7	0.3-0.8	0.1	0.7	0.5-1.0	0.0	NS	0.6	0.5-07	0.05	0.9	0.8-1.0	0.03	NS
Particle distribution (g kg^{-1})														
Sand	508.6	460-580	14.6	550.0	460-640	20.7	**	5.5	500-550	11.0	640	630-650	4.1	**
Silt	205.0	180-220	4.9	195.7	160-220	7.0	NS	210	190-240	10.8	200	190-210	3.1	NS
Clay	286.4	200-340	16.4	254.3	160-320	19.9	**	262	260-270	2.5	160	150-170	4.0	***

NS: not significant, SE: Standard error of the mean, ECEC: Effective cation exchange capacity

*significant at P < 0.05, **: significant at P < 0.01, ***: significant at P < 0.001

3.2. Tephrosia growth, nutrient concentration, and total nutrient accumulation

Tephrosia established and grew vigorously when planted between coffee trees, but appeared stunted and yellow when planted outside coffee. Growth of all plants was retarded due to drought during the short dry season. Plant height (0.7-1.0 m) and biomass production (1.4-1.9 Mg ha^{-1}) of *Tephrosia* grown within coffee were significantly greater than in the fields outside coffee (0.4-0.6 m; 0.6-0.7 Mg ha^{-1}; Table 4.2). *Tephrosia* ex. Gisagara and *Tephrosia* ex. Kisumu accumulated similar amounts of biomass. The concentrations of N, P and K in the two *Tephrosia* accessions were similar when grown within or outside coffee fields. Because of the larger amount of biomass produced, the total N (104.7-120.1 kCNE of N ha^{-1}) and K (118.4-121.7 KCNE of K ha^{-1}) accumulated and applied in *Tephrosia* mulch harvested within coffee fields was significantly larger than that applied when the *Tephrosia* mulch was harvested from sole *Tephrosia* grown outside coffee (79.7-83.2 kCNE of N ha^{-1}, 109.7-110.2 kCNE of K ha^{-1}). By contrast only 62.7 kCNE of N ha^{-1} and 103.1 kCNE of K ha^{-1} was applied in the farmers' mulch. The total P accumulated and applied was similar across the *Tephrosia* treatments which all provided significantly more than the farmer mulch. *Tephrosia* interplanting reduced weed invasion substantially but the amount was not quantified.

Table 4.2 *Tephrosia* height, shoot dry matter and nutrient accumulation in six month old plants established within coffee and outside coffee fields, in Maraba sector harvested in February 2008 (2007/2008 season). Farmer mulch (FM) consisted of 50% of *Eucalyptus* sp., 20% *Grevillea robusta* prunings, 10% of *Hyparrhenia filipendula*, 10% *Sorghum bicolor* thatch and 10% banana stems.

	Plant height (m)	Dry matter (Mg ha^{-1})	Nutrient concentration (%)			Nutrients added from *Tephrosia* (kg ha^{-1})			Total nutrients added in plots (*Tephrosia* and/or farmer mulch) and 'Net NPK' (kCNE ha^{-1})			
			N	P	K	N	P	K	N	P	K	SUM
Treatments												
Tephrosia ex. Gisagara within coffee fields	1.0	1.9	3.02	0.18	0.86	57.4	3.4	16.3	120.1	48.0	121.7	289.8
Tephrosia ex. Kisumu within coffee fields	0.7	1.4	3.00	0.18	0.96	42.0	2.5	13.4	104.7	42.9	118.4	266.0
Tephrosia ex. Gisagara. outside coffee fields	0.6	0.7	2.93	0.13	0.89	20.5	0.9	6.2	83.2	33.7	110.2	227.1
Tephrosia ex. Kisumu outside coffee fields	0.4	0.6	2.84	0.16	0.96	17.0	1.0	5.8	79.7	33.7	109.7	223.1
Farmer mulch	-	5.5	1.14	0.09	1.64	-	-	-	62.7	28.0	103.1	193.8
SED	0.1	0.5	0.15	0.03	0.08	8.2	0.8	2.3	8.2	4.5	2.6	15
P	*	***	*	*	***	**	**	**	**	**	**	**

SED: Standard error of difference of the mean

*significant at $P < 0.05$, **: significant at $P < 0.01$, ***: significant at $P < 0.001$

NPK applied in coffee improved *Tephrosia* ex. Gisagara and *Tephrosia* ex. Kisumu growth by 21% and 33% respectively (Table 4.3). Biomass production of *Tephrosia* ex. Gisagara was increased by 52% and *Tephrosia* ex. Kisumu by 14% through addition of NPK. With NPK applied, *Tephrosia* ex. Gisagara produced 3.8 Mg ha^{-1} and *Tephrosia* ex. Kisumu 3.1 Mg ha^{-1}. In the case of *Tephrosia* ex Gisumu, the 'net' fertilizer N was assumed to be zero; actually it was negative N (-7 = 165.2 + 40 – 212.4 kg, see Table 4.3), suggesting that at least 7 kg more N was fixed in TM (NPK) than in TM. A remaining fraction of P and K that was not used by *Tephrosia* was assumed to be used by coffee trees.

The larger N concentration in the *Tephrosia* mulch led to larger amounts of N added (>100 kg ha^{-1}), which were greatest when the *Tephrosia* was grown with added NPK. The amounts of P returned to the soil were similar with *Tephrosia* or farmer mulch, but significantly more was returned in the *Tephrosia* mulch where NPK was added. The larger K concentration in the farmer mulch led to much more K added (90 kg ha^{-1}) than in the *Tephrosia* mulch (< 40 kg ha^{-1}). Amounts of K returned by the *Tephrosia* mulch were also significantly larger where the *Tephrosia* had received NPK fertilizer. For the same fertilizer treatment, the total nutrients added did not differ between *Tephrosi*a cultivars but were much greater in treatments where NPK was added. The total 'net NPK' was significantly larger in *Tephrosia* with NPK treatments but was similar across *Tephrosia* cultivars. It was least in the FM treatment. In all treatments the quantities of applied nutrients expressed in kCNE were smallest for P, largest for K in FM and largest for N in *Tephrosia.*

Table 4.3 *Tephrosia* height, shoot biomass and nutrients returned to the soil by six month old *Tephrosia* species intercropped with coffee without or with NPK, applied as 40 kg N ha^{-1}, 8.8 kg P ha^{-1} and 16.6 kg K ha^{-1}, harvested in February 2009 (2008/2009 season) Maraba sector. Farmer mulch (FM) consisted of 50% of *Eucalyptus* sp, 20% *Grevillea robusta* prunings, 10% of *Hyparrhenia filipendula*, 10% Sorghum bicolor thatch and 10% banana pseudo-stems and was applied in all cases.

	Tephrosia height (m)	*Tephrosia* or FM DM (Mg ha^{-1})	*Tephrosia* or FM mulch nutrient mass fraction (%)			Nutrients added from *Tephrosia* (kg ha^{-1})			[1]Nutrients added in *Tephrosia* and/or FM and 'Net NPK' (kCNE ha^{-1})			
			N	P	K	N	P	K	N	P	K	Sum
Mulch and fertilizer use												
Tephrosia ex. Gis.	1.4	2.5	4.10	0.21	0.96	102.5	5.3	24.0	165.2	58.3	130.5	354.0
Tephrosia ex. Kis.	1.2	2.7	3.91	0.20	0.97	105.6	5.4	26.2	168.3	58.9	133.0	360.2
Farmer mulch	-	5.5	1.14	0.09	1.64	-	-	-	62.7	28.6	103.1	194.4
Tephrosia ex. Gis. with NPK	1.7	3.8	3.94	0.23	0.99	149.7	8.7	37.6	212.4	109.1	149.5	471.0
Tephrosia ex. Kis. with NPK	1.6	3.1	3.95	0.22	1.02	122.5	6.8	31.6	208.2	109.7	152.0	469.9
Farmer mulch with NPK	-	5.5	1.14	0.09	1.64	-	-	-	102.7	78.9	122.1	303.6
SED	0.1	0.4	0.08	0.004	0.06	8.1	1.4	2.4	13.1	10.7	7.4	49.9
P	*	***	***	*	*	***	NS	**	***	***	***	***

SED: Standard error of difference of the mean

*significant at $P < 0.05$, **: significant at $P < 0.01$, ***: significant at $P < 0.001$and NS: not significant

3.3. Coffee yield and N, P and K agronomic efficiency (AE)

Coffee yield in the 2007/2008 season was significantly greater (1.80-1.92 t ha^{-1}) with *Tephrosia* mulch grown *in situ* within the coffee fields than on the fields amended with *Tephrosia* mulch collected from outside the coffee fields (1.53-1.55 t ha^{-1}) or with farmer mulch (1.41 t ha^{-1}) (Table 4.4). With NPK, fields with *Tephrosia* mulch yielded 2.4-2.8 t ha^{-1} compared with 2.1-2.1 t ha^{-1} without NPK. With NPK application, the larger amounts of *Tephrosia* ex. Gisagara mulch gave significantly greater increases in coffee yield compared with the *Tephrosia* ex. Kisumu mulch. NPK combined with farmer mulch did not improve coffee yields significantly (Table 4.4).

The fraction of P was the smallest in the total applied NPK nutrient, ranging from 14 to 17% in 2007/2008 season and 15 to 23% in 2008/2009 season. During the 2007/2008 season, agronomic efficiencies of nutrients added were 30% greater with the *Tephrosia* mulch grown *in situ* within the coffee fields compared with *Tephrosia* mulch grown outside coffee. In the 2008/2009 season, agronomic efficiencies of the *Tephrosia* mulches grown *in situ* were smaller than the previous season. The two cultivars of *Tephrosia* did not differ in *AE*. *AE* of *Tephrosia* mulch grown with NPK was greater than that with *Tephrosia* mulch grown alone and the difference was larger for *Tephrosia* ex. Gisagara. *AE* of *Tephrosia* mulch was about 86 to 88 % of *AE* of NPK fertilizer, reflecting the mineralization efficiency of *Tephrosia* mulch. The results indicated that the application of NPK improved nutrient use efficiency of *Tephrosia* mulch.

Table 4.4 Coffee yield in both seasons and agronomic nutrient use efficiencies (*A*E) of *Tephrosia* mulch and of NPK fertilizer, and their ratio

Treatments	Coffee yield (t ha^{-1})	Fraction of sum of applied NPK (%)			Agronomic Efficiency (*A*E) (kg coffee/ kCNE nutrient)		
		N	P	K	*Tephrosia* mulch[1]	NPK fertilizer[2]	*Tephrosia* : NPK (ME)
2007/2008 season							
Mulch management							
Tephrosia ex. Gisagara within coffee	1.92	41	17	42	5.31		
Tephrosia ex. Kisumu within coffee	1.80	39	16	45	5.40		
Tephrosia ex. Gisagara outside coffee	1.55	37	15	49	4.20		
Tephrosia ex. Kisumu outside coffee	1.53	36	15	49	4.09		
Farmer mulch (FM)	1.41	32	14	53			
SED	0.14						
P	**						
2008/2009 season							
Tephrosia ex. Gisagara without NPK	2.13	47	16	37	2.51		
Tephrosia ex. Kisumu without NPK	2.09	47	16	37	2.17		
Farmer mulch without NPK	1.73	32	15	53	-		
Tephrosia ex. Gisagara with NPK	2.81	45	23	32	5.02	5.81	0.86
Tephrosia ex. Kisumu with NPK	2.45	44	23	32	2.89	3.28	0.88
Farmer mulch with NPK	1.97	34	26	40	-	2.20	
SED	0.15						
P	**						

SED: Standard error of difference of the mean.

*significant at $P < 0.05$, **: significant at $P < 0.01$, ***: significant at $P < 0.001$. NS: not significant,

[1]For the calculation of AE of Tephrosia mulch, control was farmer mulch treatment

[2]For the calculation of AE of NPK fertilizer, controls were the treatments without NPK

3.4. Nutrients limiting Tephrosia growth and biomass production

Tephrosia plants grew considerably better on the soil from within the coffee field than on soil collected from outside the coffee field, with the exception of the control (Table 4.5). In the soil from within the coffee field, *Tephrosia* biomass was significantly reduced by omission of P, K, Ca and Mg in the soil without lime. Lime improved biomass production by 5.5 to 53% relatively to the treatments without lime and alleviated all nutrient deficiencies except P in the soil outside coffee. In the soil from outside the coffee field, *Tephrosia* biomass was limited by omission of P and K, and to a lesser extent by omission of Ca and Mg. Adding lime alleviated only the effect of N omission. The accumulation of N was drastically reduced by omission of P and K in both soils and the effects were overcome to some extent by addition of lime. P accumulation was improved substantially by nutrient addition compared with the controls, and lime appeared to improve P uptake in the soil from within coffee (Table 4.5).

Table 4.5 *Tephrosia vogelii* biomass production and nutrient accumulation grown on soils sampled within coffee or outside coffee as influenced by omission of different nutrients and lime in the glasshouse

	Biomass DM (g pot^{-1})		N accum. (mg pot^{-1})		P accum. (mg pot^{-1})		K accum. (mg pot^{-1})		Ca accum. (mg pot^{-1})		Mg accum. (mg pot^{-1})	
	- L	+ L	- L	+ L	- L	+ L	- L	+ L	- L	+ L	- L	+ L
						Within Coffee						
FS	4.3	4.9	150.5	191.1	8.6	14.7	98.9	127.4	98.9	127.4	12.9	19.6
FS - N	3.7	4.4	118.4	145.2	5.7	13.2	81.4	105.6	81.4	96.8	14.8	17.6
FS - P	2.2	3.1	70.4	111.6	2.2	12.2	44.0	102.0	41.8	118.2	8.8	14.4
FS - K	3.1	4.4	89.9	145.2	6.2	11.8	71.3	101.2	55.8	101.2	15.5	22.0
FS - Ca	3.3	4.7	105.6	183.3	5.3	14.1	66.0	141.0	72.6	122.2	13.2	18.8
FS - Mg	3.4	5.2	112.2	182.0	10.2	15.6	98.6	166.4	81.6	140.4	10.2	20.8
Control	1.1	1.4	38.5	53.2	1.1	1.4	20.9	37.8	19.8	32.2	2.2	2.8
						Outside Coffee						
FS	2.3	2.6	71.3	91.0	4.6	5.2	41.4	57.2	43.7	72.8	6.9	7.8
FS - N	1.6	2.5	49.6	35.0	1.6	5.0	27.2	90.0	24.0	65.0	4.8	7.5
FS - P	1.0	1.0	24.0	37.0	1.0	1.0	19.0	21.0	17.0	28.0	3.0	3.0
FS - K	0.8	1.0	21.6	35.0	0.8	2.0	12.8	23.0	14.4	30.0	2.4	3.0
FS - Ca	1.8	1.9	48.6	49.4	1.8	3.8	27.0	26.6	27.0	58.9	5.4	5.7
FS - Mg	1.9	2.1	41.8	71.4	1.9	2.1	49.4	27.3	36.1	67.2	5.7	6.3
Control	0.9	1.0	20.7	34.5	0.9	1.8	13.5	15.4	15.3	17.0	1.8	2.0
SED *S x L x T*	0.3		18.0		1.4		14.0		12.4		2.5	
P	***		**		**		**		**		**	

FS: Full solution, FS - N: Treatment with full solution without N, FS - P: Treatment with full solution without P, FS - K: Treatment with without K, FS - Ca: Treatment without Ca, FS - Mg: Treatment without Mg, Control: Treatment without any nutrient added. Data are averaged over 5 plants harvested from each pot. Data were analysed as a randomized complete block design with soil type, nutrient solutions and lime status as factors with five replicates. The plants were harvested four months after planting.

- L means no lime applied, + L means 2.08 gr $CaCO_3$ applied pot^{-1}

SED *S* x *L* x *T:* SED: Standard error of difference of the mean for the interaction Soil type x Lime status x nutrient treatment

DM: Dry matter

: significant at $P < 0.01$, *: significant at $P < 0.001$

Tephrosia biomass production increased strongly with increases in nearly all the measured soil parameters and was negatively related to exchangeable Al^{3+} contents (Figure 4.2). Soil N and P concentrations explain 60-82% of the variation in *Tephrosia* biomass produced, whilst cations such as K and Ca explained 54-65%. With NPK, at least 61% of the variability in *Tephrosia* biomass was explained by the soil N, P, K and Ca concentrations. Without NPK, the percentage variance explained ranged from 50 to 55%. Coffee yield improvement was positively related to the total nutrients added in the *Tephrosia* biomass and farmer mulch. Total N, P and K nutrients added expressed in total kCNE of N, P and K explain 56, 74 and 64 % of the variation in coffee yield increment during 2007/2008 season, 2008/2009 season without NPK and 2008/2009 season with NPK respectively (Figure 4.3). The results indicate a strong effect of N, P and K nutrients on coffee yield which is substantially increased when *Tephrosia* mulch is applied. The stronger relationship during the 2008/2009 season could partly be attributed to the relatively high and well distributed rainfall (Figure 4.1).

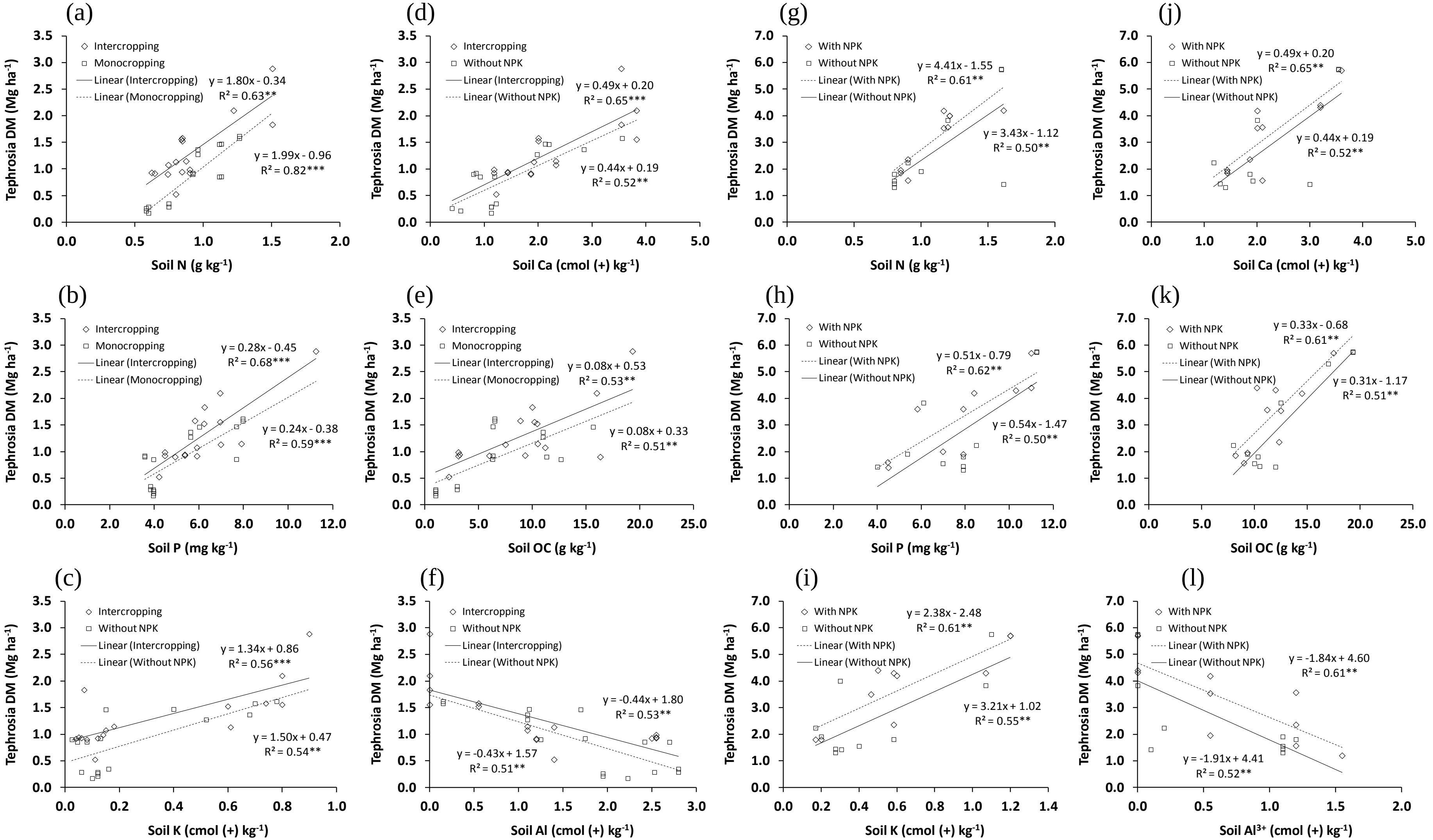


Figure 4.2 Relationship between initial soil N (a), P (b), K (c), Ca (d), Organic C (e) and exchangeable Al^{3+} (f) and *Tephrosia* dry biomass harvested outside coffee fields (dotted lines) and within coffee fields (solid lines) in February 2008 (2007/2008 season) and between initial soil N (g), P (h), K (i), Ca (j), Organic C (k) and exchangeable Al^{3+} (l) and *Tephrosia* dry biomass harvested from within coffee fields with NPK (dotted line) or without NPK (solid line) in February 2009 (2008/2009 season).

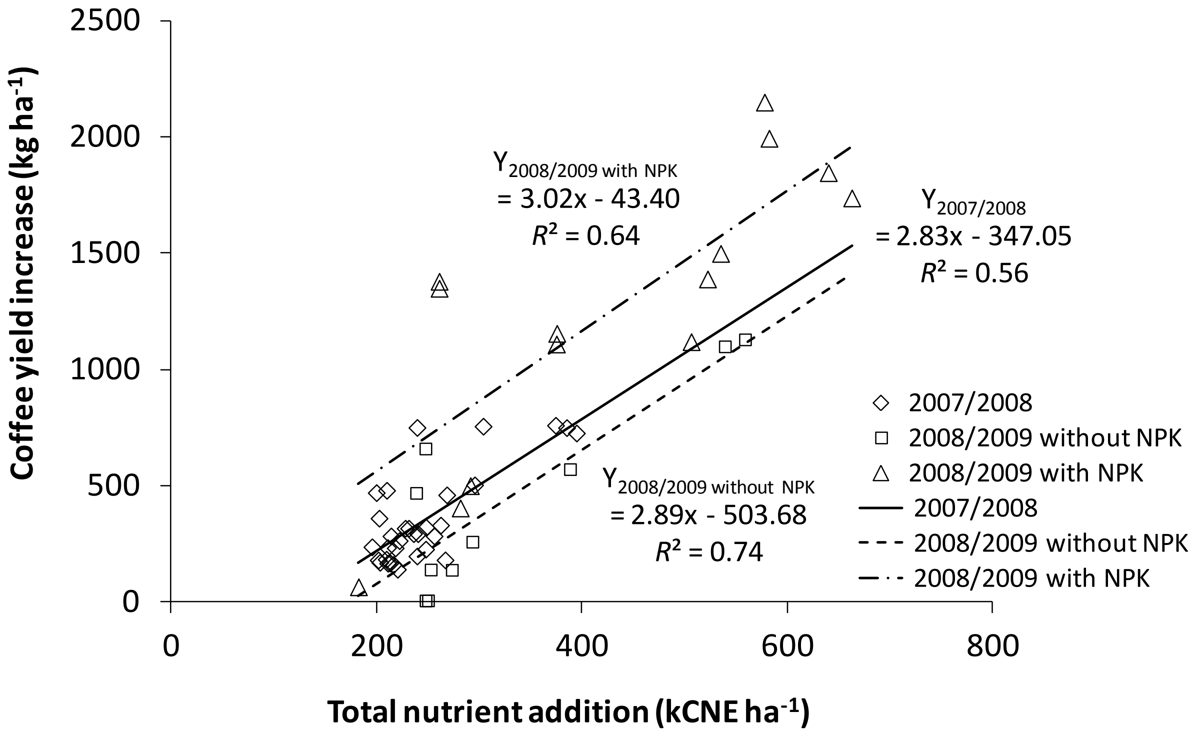


Figure 4.3 Relationship between the total N, P and K nutrients applied (kCNE ha^{-1}) and the increase in coffee yield during 2007/2008 season and 2008/2009 season with and without NPK.

3.5 Assessing economic profitability

Labour cost represented 59 to 82% of total costs (Table 4.6). In the 2007/2008 season, the highest labour cost was incurred by collecting *Tephrosia* mulch from outside coffee fields. Establishing *Tephrosia* outside coffee and transfer of the mulch required 90 more man-days ha^{-1} compared with *Tephrosia* production within coffee and 30 man-days ha^{-1} more than the farmer mulch practice. The biomass transfer treatment resulted in the highest operating costs amounting to US\$519 ha^{-1}. The total operating costs were least in fields maintained with farmer mulch (US\$397 ha^{-1}). Gross margins and returns to labour were the largest with *Tephrosia* mulch produced within coffee and gave the most favourable benefit-cost ratio (5.5).

In the 2008/2009 season, labour demand for weeding in the farmer mulched fields, averaged 457 to 461 man-days ha^{-1}, resulting in the largest labour costs (US\$329-332 ha^{-1}). The labour

Table 4.6 Annual revenues, operating costs and economic profitability for different coffee intercrops in Maraba (US $ ha-1with 1 US $ = 550 Rwandan francs)

	2007/2008 Season			2008/2009 Season			
	Treatments			Treatments			
	Tephrosia mulch within coffee	*Tephrosia* mulch from field outside coffee	Farmer mulch	Treatment with *Tephrosia* mulch within coffee		Farmer mulch	
				- NPK	+ NPK	- NPK	+ NPK
Gross revenues (ha^{-1}**)**							
Yield (t ha^{-1})	1.86	1.54	1.41	2.11	2.63	1.73	1.97
Value (US $)[a]	1711	1452	1271	1899	2368	1557	1775
Operating costs (ha^{-1}**)**							
Tephrosia seed costs (US $ kg^{-1})	44.5	44.5	-	44.5	44.5	-	-
Fertilizer (kg ha^{-1})	-	-	-	-	200	-	200
Fertilizer cost (US $ ha^{-1})[b]	-	-	-	-	90	-	90
Pesticide (L ha^{-1})	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Pesticide cost (US $ ha^{-1})[c]	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Mulch cost (US $ ha^{-1})[d]	70.0	70.0	70.0	70.0	70.0	70.0	70.0
Total labour (man-days)	420	512	454	420	420	457	461
Labour costs (US $ ha^{-1})[e]	303	404	327	302	302	329	332
Total operating costs (US $ ha^{-1})	418	519	397	418	508	400	492
Returns to labour (kg coffee man-day^{-1})	3.9	2.7	2.8	5.0	5.6	3.4	3.9
Gross margin (US $ ha^{-1})	1257	864	873	1597	1860	1157	1282
B/C ratio	5.5	3.4	3.8	3.8	4.7	3.9	3.6

[a]Average price for parchment coffee was 0.90 US $ kg^{-1} (500 RwF)

[b]The cost for fertilizer was fixed at 250 RwF kilo^{-1} (0.45 US $, based on the cooperative price).

[c] 2 ml of Sumithion diluted into 20 l water required to spray on 50 coffee trees for the control of *Antestia lineaticollis*

[d] Cost for mulch estimated at 100 RwF (0.18 US$) a bunch, 380 bunches of 25 kg each were required per ha, implying a total cost of 70 US $ ha^{-1}

[e] Labour cost was estimated at 400 RwF/day, equivalent to US$ 0.72 day^{-1}

cost was less at where *Tephrosia* was intercropped with coffee (US$303 ha^{-1}). Although the total costs were the greatest in the fertilized *Tephrosia* mulch treatments (US$508 ha^{-1}), it gave the best return to labour (5.6 kg coffee man-day^{-1}) and the largest benefit-cost ratio (4.7).

4. Discussion

4.1. Tephrosia mulch production

Tephrosia growth and biomass production was better when intercropped into coffee fields than when grown in outside coffee fields. The soil within coffee fields was richer in organic matter, N, available P, and K and Ca (Table 4.1), presumably due to past farmer mulch management. This was consistent across all of the eight smallholder farms. *Tephrosia* growth was extremely poor in fields outside coffee and only produced 0.6-0.7 t ha^{-1} of biomass (Table 4.2). As a rule of thumb, legumes producing less 2 t ha^{-1} of biomass (~50 kg N ha^{-1}) are unlikely to provide substantial improvements in yield of other crops. This was demonstrated in an experiment with increasing amounts of *Tephrosia* mulch on maize yields in north-west Tanzania (Baijukya et al. 2005). Despite the small size of most smallholder farms in Rwanda, land is fallowed which is why we tested the possibility of producing *Tephrosia* mulch on such fields. It became clear from the study that the soils in these unused fields are extremely degraded. Farmers are unlikely to invest in these soils to improve *Tephrosia* productivity. The results reflect the effect of farmers' past management on the response to fertilizer inputs and crop productivity. In these regions of Rwanda, farmers collect all available organic matter – including collecting *Eucalyptus* leaves, and climbing up to 6 m in *Grevillea* trees to prune branches – and apply all of this mulch to their coffee plots. At present, farmers in this region use virtually no mineral fertilizer. Several studies across sub-Saharan Africa have produced evidence of diversity in soil fertility within smallholder farms (e.g. Tittonell et al. 2005b) and that the historical field management practices are key determinants of the response to fertilizer (Vanlauwe et al. 2006; Zingore et al. 2007b).

Tephrosia growth was strongly and positively related to the soil C and N and concentrations of available P, K and Ca, and negatively correlated with exchangeable aluminium (Figure 4.3). The nutrient omission experiment confirmed that soil taken from coffee fields was much more fertile, presumably due to the past management with mulch and that *Tephrosia* productivity was limited particularly by P and K deficiencies, although there were indications that Ca and Mg were also deficient (Table 5). Adding lime alleviated N deficiency in *Tephrosia* (Table 4.5), probably by allowing effective nodulation and nitrogen fixation.

More *Tephrosia* mulch was produced in the second year (Table 4.3), when more rainfall fell and was better distributed (Figure 4.1). Fungameza (1991) and Dreschsel et al. (1996) reported that *Tephrosia* biomass production in Rwanda was influenced strongly by soil fertility and rainfall. *Tephrosia* ex. Gisagara appears to be better adapted to the high altitudes in Rwanda and consistently produced more biomass than *Tephrosia* ex. Kisumu (often incorrectly referred to as *T. candida*) although the differences were not large. The *Tephrosia* ex. Kisumu accession grows much more vigorously at lower altitudes in Western Kenya where it was collected. Intercropped *Tephrosia* responded strongly when NPK fertilizer was applied to the coffee, resulting in greater production of *Tephrosia* mulch (Table 4.3, Figure 4.2).

4.2.Impacts on coffee production

Coffee yields were significantly improved with *Tephrosia* mulch in all cases and the yield increases were larger with higher *Tephrosia* mulch application rates (Table 4.4). *Tephrosia* mulch resulted in substantial increases in coffee yields compared with the farmers' mulch although the differences were only statistically significant in the first season. Addition of NPK fertilizer together with *Tephrosia* mulch gave much stronger increases – increasing coffee yields by more than 1 t ha^{-1} (Table 4.4). The effect was much stronger than when NPK fertilizer was added together with farmers' mulch, due to the stimulation of *Tephrosia* biomass production by the fertilizer (Table 4.3), and increases in the agronomic efficiency of NPK (Table 4.4). Because of the low N mass fraction in farmer's mulch (high C:N ratio), part of the fertilizer N may be immobilized by the mulch. Higher coffee yields could largely be attributed to the higher nutrients (N, P and K) added through *Tephrosia* biomass and farmer mulch since coffee strongly responded to these nutrients (Fig. 4.3).

Agronomic nutrient use efficiencies indicated somewhat larger values for *Tephrosia* ex. Gisagara than for *Tephrosia* ex. Kisumu (Table 4.4). It is possible *Tephrosia* ex. Gisagara mineralized faster than *Tephrosia* ex. Kisumu. The method of estimating nutrient use efficiency using the sum of crop nutrient equivalents made it possible to compare the agronomic nutrient use efficiencies of *Tephrosia* and fertilizer. *Tephrosia AE* was 87% that of fertilizer *A*E, probably because the *Tephrosia* mulch was not yet completely mineralized at the end of the season. Baijukya et al. (2006) showed that *Tephrosia* residues had a higher Lignin+polyphenol-to-N ratio and released N more slowly than *Crotalaria grahamiana, Desmodium intortum, Macroptilium atropurpureum,* or *Mucuna pruriens.* However, in field experiments maize yields were greater with *Tephrosia* green manure treatments as the total amount of N returned in the mulch was greater. Our results suggest that N, P and K are nutrients determining coffee productivity in soils of Maraba and therefore should be supplied through fertilizer and mulch application to sustain long-term coffee production.

Although intercropping with coffee is strongly discouraged, due to fears of competition for nutrients and moisture (Balasubramanian and Egli 1986) we observed no such effects. Coffee yields were significantly greater when intercropped with *Tephrosia* (Tables 4.2 and 4.3), due to the beneficial effects of the *Tephrosia* mulch. As well as the nutrient effects, the thicker mulch produced could be partly due to other factors such as weed suppression (Baligar et al. 2001) and moisture conservation.

4.3.Economic benefits

The results demonstrate significant potential to improve coffee production by using *Tephrosia* intercropping to provide mulch. The 'cut and carry' system of growing *Tephrosia* on fields outside coffee not only produces less mulch as described above, but also incurs greater labour costs for transport of the mulch (Table 4.6). Net benefits and benefit-cost ratios were much more favourable for the *Tephrosia*/coffee intercropping systems. The better returns with *Tephrosia* intercropping are partly due to reduced labour demand due to better weed control. Different variants of the *Tephrosia* technology may be attractive to coffee growers depending on their ability to invest. Coffee farmers who cannot afford to buy mineral fertilizer can achieve a 20 to 36% in coffee yield by using *Tephrosia* intercropping. Although the cost of *Tephrosia* seed is included in our economic analysis, *Tephrosia* shrubs produce prolific quantities of seed that could be grown on field boundaries. Wealthier coffee farmers who regularly apply mineral fertilizer would expect a further increase of 33% in coffee yield by intercropping *Tephrosia* in the plantation. Wealthier farmers are known to take greater risks and more readily venture into new technologies (Shepherd and Soule 1998a).

5. Conclusions

Intercropping *Tephrosia* in existing coffee plantations shows great promise for increasing coffee production. The mulch produced *in situ* gives substantial increases in coffee yields, while reducing labour demands for weeding. Benefits are realized even without mineral fertilizer, but intercropping with *Tephrosia* had a synergistic effect on coffee yields when NPK fertilizers were added. The system provides an excellent example of the added benefits of an integrated soil fertility management approach (Vanlauwe et al. 2011). The added P and K alleviated constraints on biological nitrogen fixation (Giller 2001) leading to greater amounts of *Tephrosia* mulch produced, which in turn can increase the amount of nutrients available for coffee. This intercropping system with coffee has great potential for agro-ecological intensification of smallholder farms in the East African highlands where farm sizes are small and nutrients and mulch are scarce.

Maize response to applied *Calliandra calothyrsus* **residues and P fertilizer in different fields and farms in two agro-ecological zones in Rwanda.**

This chapter is to be submitted as:

C Bucagu, B. Vanlauwe, M.T. van Wijk and K.E. Giller. Maize response to applied *Calliandra calothyrsus* residues and P fertilizer in different fields and farms in two agro-ecological zones in Rwanda. *Experimental Agriculture*

Abstract

Smallholder farms in Rwanda are characterised by soil depletion due to continuous cultivation without nutrient replacement. Mineral and/or organic fertilizers are required to reverse this trend but are in scarce supply. There is a need to identify the best combinations of inorganic and organic fertilizers. A study was conducted in two field types (infield and outfield) selected within two farm types belonging to farmers differing in resource endowment (Resource groups (RG) 1 and 3) in two agro-ecological zones: Central Plateau (Simbi) and Buberuka (Kageyo) in Rwanda. The effects of different *Calliandra calothyrsus* prunings rates (equivalent of 0, 30, 60 and 90 kg N ha^{-1}) combined or not with different P rates (0 and 44 kg P ha^{-1}) as triple super phosphate on maize grain yield, nutrient use efficiency and economic returns. Experiments were run for three seasons in Simbi (Short rainy season (SR) 2008, Long Rainy season (LR) 2008 and SR 2009) and two consecutive seasons in Kageyo (SR 2009 and LR 2009). Soils were richer in organic C and available P in Kageyo than in Simbi, in RG 3 than in RG 1, and in infields than in outfields. Variability in soil fertility between fields and farms had a significant influence on the productivity of maize. Maize yield was greater in Kageyo than in Simbi. Net returns and the ratio between gross margin and costs of inputs were greater in Kageyo than in Simbi and were improved by P application. N recovery and agronomic efficiency were the highest in infield rather than in outfield plots. Maize yield calculated using the QUEFTS model strongly correlated with maize yield measured during the best seasons in the two locations. *Calliandra* residues may equally be used to improve soil fertility in smallholder farms where other resources are lacking. Our results suggest that 60 kg N ha^{-1} would be sufficient for maize cropping. Fertilizer application rates should be tailored to areas whose specific soil fertility status determines responsiveness to fertilisers.

Keywords: Farmer resource endowment, field type, Nutrient use efficiency, Economic profitability

Introduction

In many parts of the tropics, severe soil nutrient depletion occurs due to continuous cropping of land without compensation through inputs (Tittonell et al. 2007a, Stoorvogel and Smaling 1990; Van der Zaag 1982). In highland areas, nutrient losses may be aggravated due to soil erosion (Yamoah et al. 1989). N and P are reported to be the most limiting nutrients in sub-Saharan Africa (SSA) and particularly in the East African highlands (Shepherd et al. 1996b; Wanda et al. 2002). Several alternative options to deal with soil fertility problems and sustain production systems including use of mineral fertilizer, organic farming and use of agroforestry technologies were suggested for Rwanda (Drechsel et al. 1996).

Mineral fertilizers are used sparsely by smallholder farmers due to limited purchasing power and the unfavourable macroeconomic environment (Wopereis et al. 2006; Heisey and Mwangi 1996). A combination of organic and mineral fertilizer is considered to be a better option to reverse the cycle of perpetual depletion of nutrients and improve soil fertility (Vanlauwe et al. 2002; 2011). Use of leafy biomass of several agroforestry shrubs has shown potential to reverse the declining soil fertility in sub-Saharan Africa (Gachengo 1996; Drechsel et al. 1996). Particularly N_2-fixing species may provide additional N to the farming systems. *Calliandra calothyrsus* is one of the most commonly grown leguminous multi-purpose agroforestry trees on smallholder farms in Rwanda. The shrub is valued for its high leaf production for fodder, production of stakes for climbing beans, and it is grown on contours where it contributes to stabilizing the soil against erosion. Its foliage can be used as green manure, yet an important practical question for smallholder farmers is what is the best combination of organic and mineral fertilisers.

Smallholder farms in Africa operate under diverse biophysical conditions and have marked spatial heterogeneity in soil fertility (Scoones and Toulmin 1999; Prudencio 1983; Tittonell et al. 2005a). Diversity in biophysical conditions occurs at the region scale and mostly determined by the climate and soil type among other factors (Tittonell et al. 2005a). In Rwanda, rainfall distribution and temperature vary strongly between agro-ecological zones, with abundant rainfall and low temperature predominating in the northern highlands with moderate rainfall and high temperatures in the southwest part (Niang and Styger 1990). Within a specific agro-ecological zone, soil fertility varies widely. Factors underlying this heterogeneity are related to natural processes (e.g parental material and topography) and differential farmer management through concentrating resources in specific fields, mostly the infields and coffee fields (see Chapter 4) at the expense of fields further away from the homestead (Tittonell et al. 2007a). This creates soil fertility gradients within smallholder farms (Tittonell et al. 2005b; Zingore et al. 2007b) that have strong impacts on crop production and resource use efficiencies (Zingore et al. 2007b; Wopereis et al. 2006).

In most tropical countries, fertilizer applications are often based on blanket recommendations formulated long ago (Vanlauwe and Giller 2006). For instance, in Rwanda, recommendations for fertiliser application were formulated based on the information collected from database obtained from FAO and the FRSP (Farming Systems Research Project) that operated in the northern part of the country in the 1990s (Kelly and Murekezi 2000). Given the variable soil fertility context within smallholder farms, application rates should be tailored to the particularities of agro-ecological zones (soils and climate), nutrient uptake requirements and socio-economic circumstances of farmers. Testing crop response to fertilizers in varying soil fertility conditions is facilitated by use of simple models. The QUEFTS (Quantitative Evaluation of the Fertility of Tropical Soil) approach integrates N, P and K together and their interactions when predicting maize response to fertilisers (Janssen et al. 1990; Smaling and Janssen 1993). The model was developed for maize in Kenya (Janssen et al. 1990). It predicts maize yield and nutrient uptake based on chemical soil parameters and estimates of the NPK supply from soils and fertilizers.

Our hypothesis was that fields on farms differing in resource endowment and management may respond differently to fertilisers. The objectives were to evaluate the effects of different N rates supplied through *Calliandra calothyrsus* biomass combined or not with different rates of P on (1) maize grain yield and (2) nutrient use efficiency and (3) economic profitability of maize crop in different farms and fields in two agro-ecological zones (Simbi in Central Plateau AEZ and Kageyo in Buberuka AEZ).

Materials and methods

Study sites

The study was conducted in two villages representing contrasting areas with high population density and soil degradation. Sites were selected in Umurera village (314 households, 1324 inhabitants), Simbi sector (2˚30'28''S and 28˚ 42' 09'' E, 1634 m a.s.l,), 17 km south of Butare city and in Mutobo village (94 households, 529 inhabitants), Kageyo sector (1^{o} 36.9' S and 30˚ 4.7'E, 1736 m a.s.l,), 5 km from the main market of Rukomo (Gicumbi city). Simbi is located in Central Plateau Agro-ecological zone (AEZ), southwest of Rwanda. The topography of the Central Plateau zone is dominated by hills and valleys with annual rainfall of about 1200 mm. Major soil types are Histosols and Cambisols in valleys and Cambisols, Acrisols and Leptosols on hills. Simbi sector was selected due to its cropping system being typical to that encountered in Central Plateau AEZ, with dominance of *Phaseolus vulgaris* L., *Manihot esculenta* Crantz, *Zea mays* L. together with coffee (*Coffea arabica* L.) as a cash crop. Kageyo is found in Buberuka AEZ in the north of the country, an area of high altitude plateaus traversed by quartzitic chains, receiving up to 1200 to 1400 mm rainfall annually and the mean temperature ranges from 15 to 16^{o}C. Cambisols, Nitisols and Leptosols are the dominant soil types in uphill areas and Histosols and Vertisols in wetland areas (den Biggelaar 1996). Kageyo sector represents the typical farming system with dominance of wheat (*Triticum* sp.) and irish potato (*Solanum tuberosum* L.). Cumulative rainfall recorded over three seasons in Simbi and two seasons in Kageyo show low rainfall in Simbi compared with Kageyo. Rainfall levels were 295 mm, 255 mm and 198 mm during SR 2008, LR 2008 and SR 2009 seasons in Simbi and 329 mm and 418 mm during SR 2009 and LR 2009 seasons in Kageyo (Fig. 5.1).

Selection of experimental farms

Farms and fields for the experimental work were selected recognising differences among smallholder farms based on socio-economic criteria (Ansoms 2008; Musabyimana 2008). Farms were categorised into three categories; poor resource group (RG 1), moderate resource group (RG 2) and wealthier resource group (RG 3) based on farmer cattle ownership, land size and available family labour among other factors. Only poor and wealthier resource groups (RG 1 & RG 3) were considered for this study. Characteristics for farmer categories were site-specific. RG 1 farms had fewer family members (4.5 and 5.0 in Simbi and Kageyo respectively) compared with RG 3 (6.5 and 6.0 respectively in Simbi and Kageyo). Household heads were the most educated in RG 3 (5.8 and 6.6 years of schooling in Simbi and Kageyo respectively) compared with their counterparts in RG 1 (4.5 and 2.4 years of schooling in Simbi and Kageyo respectively). Households in RG 1 were the most vulnerable in terms of food security (experiencing 3 to 4 months of food deficit in the year) while RG 3 farmers were food deficient only for 2 months in the year. In terms of resource endowment, RG 3 farmers had larger farms (1.9 and 3.2 ha in Simbi and Kageyo respectively) compared with RG 1 farmers holding 0.20 and 0.21 ha of land respectively in Simbi and Kageyo. RG 3 farmers had 3.5 and 2.3 cattle in Simbi and Kageyo while RG 1 farmers had no cows, mostly keeping 2 goats or pigs. Three farms were selected to represent each of the two farm categories.

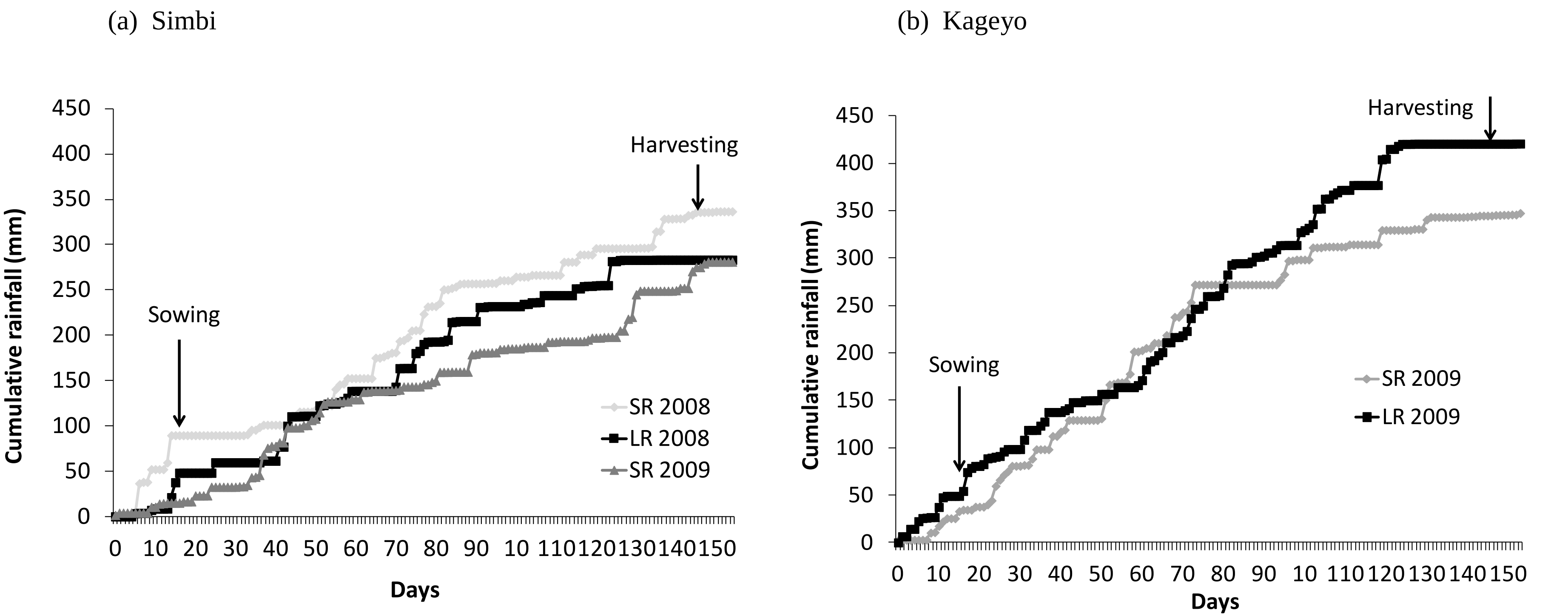


Figure 5.1 Cumulative rainfall at Simbi during SR 2008, LR 2008 and SR 2009 seasons (a) and Kageyo during SR 2009 and LR 2009 seasons (b)

Sources for rainfall data: Ministry of Infrastructure/Meteorological Unit, Rwanda (2009), unpublished data

Two field types, infield and outfield were demarcated on each farm. Infields are closest to home compound (3 to 80 m from the homestead) next to banana crops and cultivated with various crops and vegetables (*Colocasia esculenta* L., *Phaseolus vulgaris* L.) and fruit trees species. Outfields are located further away from home (100 to 800 m from homestead). Valley bottom fields were excluded as these are managed collectively.

Field experiments and agronomic measurements

The experiment was run for three consecutive seasons SR 2008, LR 2008 and SR 2009 in Simbi and SR 2009 and LR 2009 in Kageyo. Plots of 4.5 m by 3.75 m were used and the experiment was laid out following a one farm one-replicate design with 8 treatments (4 N rates equivalent in *Calliandra* biomass and 2 P rates) applied in each of the two fields. Treatments were replicated on three farms from each farm category. Maize (variety ZM 607 in Simbi and variety Pool 9A in Kageyo) was established at 75 cm x 25 cm spacing between and within rows and thinned to one plant per hill, to give 90000 plants ha^{-1}. *Calliandra calothyrsus* fresh leaf prunings was collected from *Calliandra* hedgerows grown *ex-situ* (cut and carry) in Tonga Research Station (Faculty of Agriculture, National University of Rwanda, Rwanda) and subsamples were randomly collected for analysis for dry matter content and N concentration. Prunings of *Calliandra* (60% dry matter content, 2.7% N, 0.19% P and 1.3% K on DW basis) were cut at 50 cm, chopped and spread evenly before incorporating with hand hoes. Mineral fertiliser phosphorus in the form of triple super phosphate (TSP, 46 % P_2O_5) was added at planting and incorporated in the top 20 cm of the soil. The plots were hand weeded twice during the growing season. Different *Calliandra calothyrsus* biomass rates corresponding to 0, 30, 60 and 90 kg N ha^{-1} and two rates of mineral P (0 and 44 kg P ha^{-1}) were applied in each of the seasons. P requirements were earlier estimated at 44 kg available P ha^{-1} for soils in Rwanda (Van der Zaag 1982). The treatments in all six plots were:

i. Control
ii. 44 kg P ha^{-1}
iii. *Calliandra* biomass equivalent to 30 kg N ha^{-1} (1.1 t DW/ha, 1.8 t fresh biomass ha^{-1})
iv *Calliandra* biomass equivalent to 60 kg N ha^{-1} (2.2 t DW/ha, 3.6 t fresh biomass ha^{-1})
v *Calliandra* biomass equivalent to 90 kg N ha^{-1} (3.3 t DW/ha, 5.4 t fresh biomass ha^{-1})
vi. *Calliandra* biomass equivalent to 30 kg N ha^{-1} + 44 kg P ha^{-1}
vii. *Calliandra* biomass equivalent to 60 kg N ha^{-1} + 44 kg P ha^{-1}
viii. *Calliandra* biomass equivalent to 90 kg N ha^{-1} + 44 kg P ha^{-1}

Pesticide (Sumithion: 20 cc/20 L water for 0.1 ha of maize) was applied in the funnels of the maize leaves to control maize stalkborer (*Busseola fusca* Fuller) that attacks maize during the short dry season in Simbi. Maize was harvested at about 20 weeks after planting from an area of 4 m by 2.25 m (four lines of 4 m long, containing 17 plants each), excluding one border row on each side of the harvested area. Maize cobs were manually separated from the stover, sun-dried and packed in paper bags before threshing. Grain fresh weight was measured and grain moisture content determined using a moisture meter and grain weight adjusted to 12% moisture.

Soil and plant analysis

Soils were sampled before the start of the experiments in the first season to characterise different fields in each of the two farms both in Simbi and Kageyo. Topsoils (0-20 cm) samples were taken with an auger at the four corners per field from the two fields chosen within each farm. Samples were mixed and a composite sample of approximately 0.5 kg taken for laboratory analysis. The soil samples were air-dried in the laboratory, crushed and ground to pass a 2 mm sieve and analysed for particle size distribution, soil organic carbon, total nitrogen, available P, cation exchange capacity (CEC) and pH. Soil particle distribution was determined using hydrometer method. Soil pH was determined on a 1: 2.5 soil: H_2O using a glass electrode pH meter. Organic C was determined using the Walkley-Black method and total nitrogen by Kjeldahl digestion. Available phosphorus was determined using Bray method. Exchangeable cations (K, Ca, Mg) were extracted with 1M ammonium acetate and measured using an atomic absorption spectrophotometer (Anderson and Ingram, 1993). *Calliandra* biomass, maize stover and grain samples were dried and ground to less than 0.5 mm. N in maize stover and grain was measured after Kjeldahl digestion.

Mathematical calculations

N use efficiency was estimated using two indices: Agronomic use efficiency (*A*E) and apparent recovery efficiency (RE) that were calculated for different farms and fields types. Agronomic N use efficiency (AE_N) was expressed in kg grain produced per kg N applied. Apparent N recovery (RE_N) was calculated as N uptake per amount N applied using the following formula:

$$AE_N = \frac{Y_N - Y_0}{F_N}$$

$$RE_N = \frac{U_N - U_0}{F_N}$$

Where Y_N is the yield at a particular rate of N and Y_0 is the yield for the plots without N. F_N is the amount of N applied. U_N is the total N taken up by the crop at a particular N rate, U_0 is the crop N taken up in plots without N added.

Using QUEFTS to simulate maize response to fertilisers

Model calibration

The calibration of QUEFTS was based on soil data and fertilizer rates used for trials in Simbi and Kageyo. QUEFTS differentiates organic and mineral nutrients inputs. Organic sources were nutrients from *Calliandra*. Based on N, P and K content in *Calliandra* biomass (N = 2.7%, P = 0.18% and K = 1.2%), the amount of N, P_2O_5 and K_2O were derived and entered into QUEFTS. From the total amount of *Calliandra* biomass, mass fractions for different nutrients, and relative effectiveness (0.4 for N, 0.6 for P and 1 for K as suggested by Janssen (2011), input 'fertilizer' nutrients were estimated. QUEFTS uses maximum fertilizer recovery (Janssen and Guiking

1990). For instance nitrogen recovery is calculated as the difference in N uptake between an experimental unit receiving NPK and a unit receiving PK, divided by the amount of applied N. Since we had no paired (NP, PK, NK) and NPK treatments in our trial, we could not calculate our own maximum nutrient recovery fractions and standard recovery fractions of 0.5 for N and K, and 0.1 for P were used (Janssen and Guiking 1990). Soil parameters for different field types were the averages measured over the three farms and field types. Available P assessed using Bray-1 was converted into P-Olsen using P-Olsen/P-Bray-1 ratio of 0.75 (Mowo et al. 2006). Since the potential supply of N, P and K nutrients was found to relate to pH in different ways, correlation factors (f_N, f_P and f_K) for pH values were defined for different nutrients, f_N, f_P and f_K taking values ranging from 0 to 1 for pH (H_2O) ranging from 4.5 to 7 (Janssen et al. 1990). Crop parameters for N and P (a and d for PhEN and PhEP under accumulation and dilution phases) were derived from maize grain yield and nutrient uptake. For N, a and d were 19 and 68.6 kg maize grain kg^{-1} N uptake respectively. For P, a and d valued 172.7 and 562.5 kg maize grain kg P $uptake^{-1}$. For K, a and d values were derived from the following relations:

CNEK (Crop Nutrient Equivalent for K) = PhENmed/PhEKmed = 0.67 (1)

PhEKmed = m = PhENmed/0.67

For K: d/a = 4 and m= (d+a)/2 (Smaling and Janssen, 1993) (2)

Where CNEK is the Crop Nutrient Equivalent for K, PhENmed and PhEKmed are the medium physiological N and K use efficiency respectively, a and d stand for constant values of PhE under accumulation and dilutions for different nutrients

The maximum yield was fixed per agro-ecological zone. Maize yield potential was estimated at 2.5 t ha^{-1} in Simbi and at 4.5 t ha^{-1} at 12% moisture in Kageyo (ISAR 2011). Yield potential for Kageyo is greater because rainfall is not a limiting factor. Other factors such other nutrient deficiencies are assumed not to affect maize development and yield adversely. QUEFTS was validated using data from the best rainfall season (SR 2008 data for Simbi and LR 2008 for Kageyo).

Economic analysis

Basic economic indicators were calculated for different treatments in different farms and field types. The analysis was based on the costs incurred during maize cropping (seed and fertilizer purchase, labour cost). The total cost for labour invested in pruning and chopping *Calliandra* was estimated at 12 US \$ Mg^{-1}. Maize seed price was fixed at 400 Frws (0.7 US \$ kg^{-1}), assuming 22 kg maize seed needed ha^{-1}. Labour for land preparation, planting, weeding (first and second) were estimated based on data collected during maize trials and estimated at 55, 27, 25 and 20 man-days ha^{-1} respectively for land preparation, planting, first weeding and second weeding, giving a total of 127 man-days ha^{-1}. Labour for harvesting and threshing was estimated based on the hired labour used during the trials and estimated at 8 man-days Mg^{-1} for harvesting and 14 man-days Mg^{-1} for threshing operations. Labour costs fluctuate over the seasons, ranging from 500 and 700 RwF. An average labour wage of 600 RwF man-day^{-1} (1 US \$ man-day^{-1}) was used. Maize price varied between 150 and 250 RwF kg^{-1} and an average of 200 RwF kg^{-1}(0.3 US \$ kg^{-1}) was used for the study. TSP fertiliser was sourced from Uganda at 50.000 UG Shillings per 50 kg bag (28 US \$ bag^{-1}, 0.56 US \$ kg^{-1}). The cost for pesticide application (Sumithion: 20 cc/20 L water for 0.1 ha of maize for the control of maize stalkborer (*Busseola fusca* Fuller) in Simbi was negligible and was not included. Net returns were calculated by subtracting the total costs from the total gross benefits for individual farm and fields, assuming the opportunity cost for labour and capital were nil in the area. B/C was estimated by dividing the gross margin by the total cost for different treatments in different fields and farms. All monetary values were converted to US\$ at the prevailing exchange rate of 1 US\$ = 600 RwF.

Data analysis

Data were analysed separately for the two locations since trials were run at different seasons. Data on maize yield were analysed in ANOVA using REPEATED measures procedures of GENSTAT where ‘Plot’ was considered as subject, ‘Season’ as time point, ‘RG’, ‘field type (RG)’, ‘N rate’ and ‘P rate’ and their interactions as fixed factors. N apparent recovery fractions and N agronomic efficiency indices averaged over seasons were analysed in ANOVA using GLM with ‘field type’, ‘N rate’ and ‘P rate’ and their interactions as fixed factors and ‘farm’ as a random factor. Only SEDs for main effects of field type, N rate and P rate are shown because interactions were not significant. Economic parameters (Net benefit and B/C ratio) aggregated over farms and fields were analysed in ANOVA using PROC MIXED procedures with ‘RG’ and ‘field type (RG),’ and their interactions as fixed factors and ‘farm’ as the random factor in GENSTAT and standard errors of the differences (SED) reported (GenStat® Discovery Edition 3 2009). Simple regression was used to relate site-specific response to initial soil total N and available P content.

Results

Soil fertility variability on selected experimental farms and fields

Soils in Kageyo were more fertile than in Simbi (Table 5.1). pH was slightly higher in infield than in the outfield in all farms and was highest in RG 3 of Kageyo with values of 6 to 6.1. In other farms, values varied between 4.7 and 5.6. Organic C was the highest in Kageyo. For instance, soil organic C was 33.7 g kg^{-1} and 21.0 g kg^{-1} infield and outfield in RG 2 farms of Kageyo and 18.7 and 13.0 g kg^{-1} on respective fields in RG 3 farms in Simbi. N contents were twice as high in Kageyo than in Simbi on similar fields. N was largest in infield of RG 3 farm of Kageyo (3.2 g N kg^{-1}) and the smallest in the outfield of RG 1 farm of Simbi (1.1 g N kg^{-1}). Available P also had greater values in Kageyo compared with Simbi. CEC followed the same trend as other soil indicators with the largest value in infield of RG 3 farms (17.8 cmol (+) kg^{-1}). The smallest value was recorded in outfield of RG 1 in Simbi farm with 7.6 cmol(+) kg^{-1}. Sandy loam was the predominant soil texture class on all fields and farms in both locations.

Table 5.1 Physical and chemical properties of soil for the fields used at Simbi and Kageyo

AEZ/Location	Sector	Farm type	Field type	pH (water)	C (g kg^{-1})	N (g kg^{-1})	Extractable P (mg kg^{-1})	CEC (cmol$_{(+)}$kg^{-1})	Sand (%)	Silt (%)	Clay (%)	Soil texture class
Central Plateau	Simbi											
		RG 1	HF	5.4 (5.0-5.8)	15.0 (17-18)	1.5 (1.0-2.1)	10.3 (3.8-17.0)	10.2 (8.8-11.8)	65.0 (64-66)	22.7 (22-24)	12.3 (12-14)	Sandy loam
			OF	4.9 (4.3-5.6)	11.3 (13-15)	1.1 (0.9-1.3)	2.1 (1.5-2.7)	7.6 (4.2-9.20)	62.0 (58-67)	22.7 (22-24)	15.3 (14-17)	Sandy loam
		RG 3	HF	5.4 (5.0-5.7)	18.7 (16-21)	1.8 (1.1-2.2)	12.4 (11.2-13.5)	17.2 (15.4-19.0)	63.0 (55-76)	19.3 (18-20)	17.7 (17-25)	Sandy loam
			OF	4.7 (4.6-5.3)	13.0 (10-16)	1.3 (0.9-1.7)	2.3 (1.7-3.1)	8.3 (7.0-8.2)	71.7 (65-78)	20.6 (14-30)	7.7 (5-11)	Sandy loam
Buberuka	Kageyo											
		RG 1	HF	5.6 (4.7-5.6)	27.3 (22-31)	2.7 (2.2-3.3)	14.0 (12.2-16.6)	13.5 (9.2-16.2)	63.7 (64-66)	19.3 (22-24)	17.0 (14-18)	Sandy loam
			OF	5.3 (4.8-5.5)	19.0 (17-21.2)	1.9 (1.5-2.3)	10.6 (8.7-12.0)	10.2 (5.5-15)	66.3 (58-67)	20.0 (22-24)	13.7 (12-14)	Sandy loam
		RG 3	HF	6.1 (5.8-6.5)	33.7 (30-36)	3.2 (3.0-3.4)	15.4 (12.7-17.4)	17.8 (16.4-20.0)	61.7 (55-76)	20.0 (18-21)	18.3 (17-25)	Sandy loam
			OF	6.0 (5.9-6.1)	21.0 (18-23)	2.0 (1.7-2.4)	12.9 (11.9-13.4)	11.6 (5-15.2)	61.0 (65-78)	19.3 (14-30)	19.7 (18-30)	Sandy loam

Maize yield response to N and P fertiliser over seasons on different farms and fields of Simbi and Kageyo

In Simbi, maize yield differed significantly among seasons (*P* < 0.001), RG (*P* < 0.001) and the interaction between season, RG and plot type (*P* < 0.001) (Figure 5.2a). Maize yield was larger in SR 2008 (1.45 Mg ha^{-1}) than in LR 2008 (0.95 Mg ha^{-1}) and SR 2009 (0.90 Mg ha^{-1}) but similar between the later two seasons. Maize yield was greater in RG 3 (1.52 Mg ha^{-1}) than in RG 1 farm (0.68 Mg ha^{-1}). The significant interaction between seasons and plot type (RG) was due to the fact that maize yield was significantly larger in infield than in outfield in SR 2008 and LR 2008 but was similar among fields in SR 2009. Maize yield was on average 1.69 Mg ha^{-1} and 1.21 Mg ha^{-1} in infield and outfield respectively during SR 2008 and 1.11 and 0.78 Mg ha^{-1} respectively during LR 2008. In SR 2009, maize yield was 0.97 and 0.84 Mg ha^{-1} respectively in infield and outfield.

Maize yield was significantly affected by N rate (*P* < 0.001) and the interaction between RG, field type and N rate (*P* < 0.001) (Figure 5.2b). Maize yield significantly increased with N rate up to 60 kg N ha^{-1} (0.7, 1.02, 1.27 Mg ha^{-1} at 0, 30 and 60 kg ha^{-1} respectively) but was similar at 60 and 90 kg ha^{-1} (1.39 Mg ha^{-1}). The interaction between plot type (RG) and N rate was due to the fact that maize yield was similar between infield and outfield without N (0 kg N ha^{-1}) while maize yield was significantly larger in infield than outfield when N was added. Without N, maize yield was 1.61 Mg ha^{-1} and 1.09 Mg ha^{-1}. With N applied at 30, 60 and 90 kg N ha^{-1}, maize yield was 1.93, 2.11 and 2.22 Mg ha^{-1} respectively in infield and 1.43, 1.55 and 1.70 Mg ha^{-1} respectively in outfield.

Maize yield was also significantly affected by P rate (*P* < 0.001) and the interaction between RG, N rate and P rate (*P* < 0.001) (Figure 5.2c). Maize yield was significantly larger with P (1.17 Mg ha^{-1}) than without P (1.00 Mg ha^{-1}). The interaction between RG, N rate and P rate was due to the fact that P alone or with 30 kg ha^{-1} had no significant effect in RG 1 farm while it had a significant effect on maize yield in RG 3. With 0 and 30 kg N ha^{-1}, maize yield was 0.21 and 0.51 Mg ha^{-1} without P respectively against 0.39 and 0.53 Mg ha^{-1} with P respectively on RG 1. On RG 3 farm, maize yield was 0.88 and 1.39 Mg ha^{-1} with 0 and 30 kg N ha^{-1} without P respectively against 1.37 and 1.58 Mg ha^{-1} with P respectively.

In Kageyo, maize yield was similar across seasons (P = 0.27) but was significantly affected by RG (P = 0.03) (Figure 5.2d). Averaged over RGs, maize yield was 1.5 t ha^{-1} in RG 1 and 1.9 t ha^{-1} in RG 3. Despite increased maize yield with increasing N rate (1.3, 1.68, 1.83, 2.06 Mg ha^{-1} respectively at 0, 30, 60 and 90 kg N ha^{-1}) and P rate (1.62 Mg ha^{-1}, 1.78 Mg ha^{-1} at 0 and 44 kg P ha^{-1} respectively), maize yield was similarly influenced by N rate (P = 0.12) (Figure 5.2e) and P rate (P = 0.19) (Figure 5.2f).

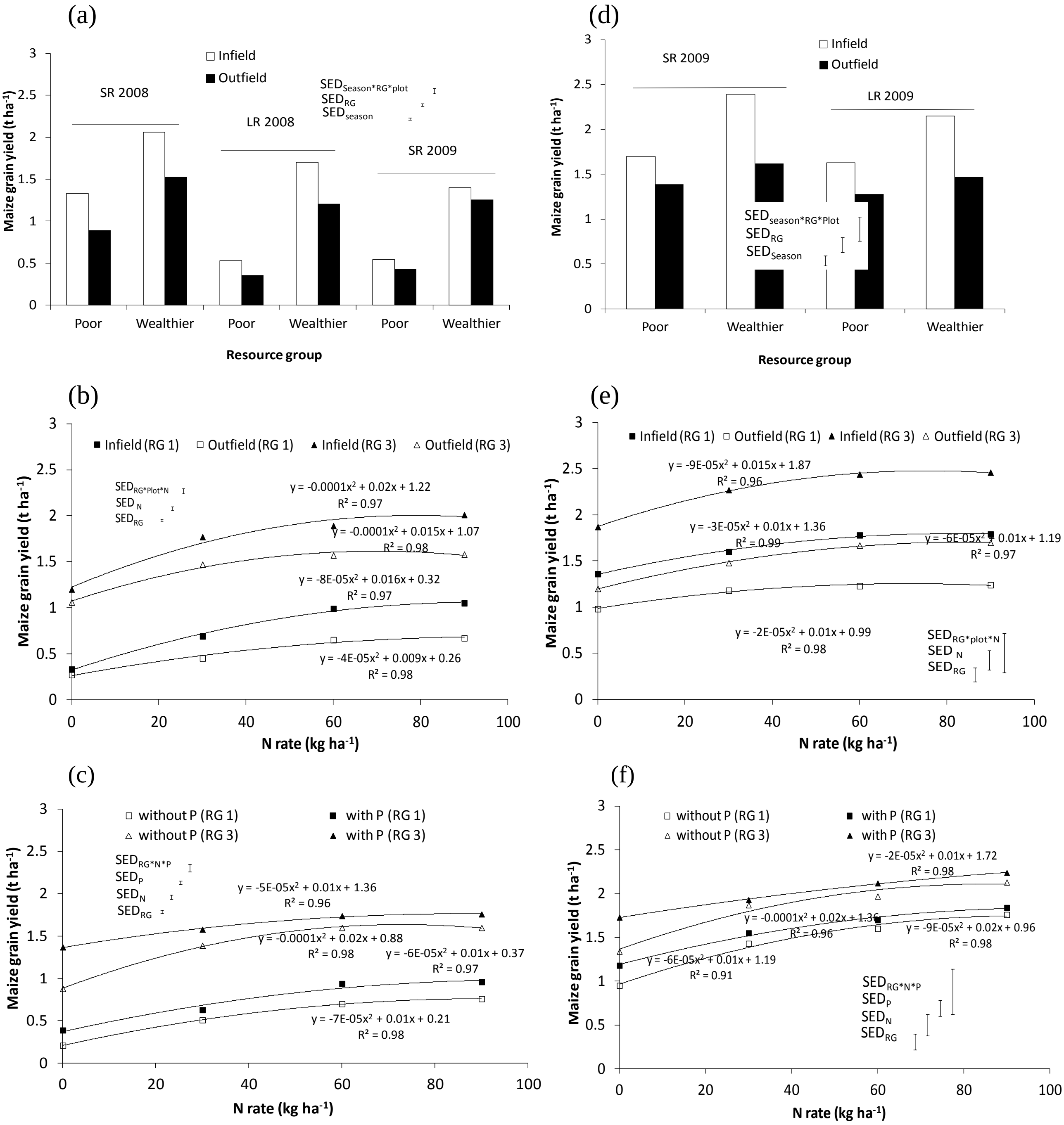


Figure 5.2 Maize yield as a function of season, RG, plot type, N rate and P rate during SR 2008, LR 2008 and SR 2009 seasons in Simbi (a, b and c) and Kageyo (d, e and f) respectively. Bars are SEDs.

QUEFTS overestimated yield on all fields and farms in both locations, especially in control plots (Figure 5.3). For instance, the simulated maize yield (2105 kg ha^{-1}) in control plot of RG 1 was five times greater than the measured yield (410 kg ha^{-1}) in Simbi. The calculated yield was two to three times the measured yields in other fields. Generally, Figure 5.3 shows good correlation between the calculated and measured yields in the two locations ($r^2 > 0.50$). Correlation was, however, weaker in infields due probably to QUEFTS overestimation of maize yield on the most fertile soils. In general, correlation was relatively stronger in Simbi (r^2 ranging from 0.52 to 0.88) than in Kageyo (r^2 ranging from 0.50 to 0.57).

Relationships between responses to N and P applied and initial soil N and extractable P content

Maize yield was related to the initial soil total N and extractable P content in Simbi and Kageyo (Figure 5.4). A stronger and significant linear relationship was found between maize yield and the initial total N of the topsoil in Simbi ($r^2 = 0.43$, $P = 0.02$). In Kageyo, the linear relationship was not significant ($r^2 = 0.02$, $P = 0.64$). Linear relation between maize yield and soil available P was weak in the two locations (r^2, not shown).

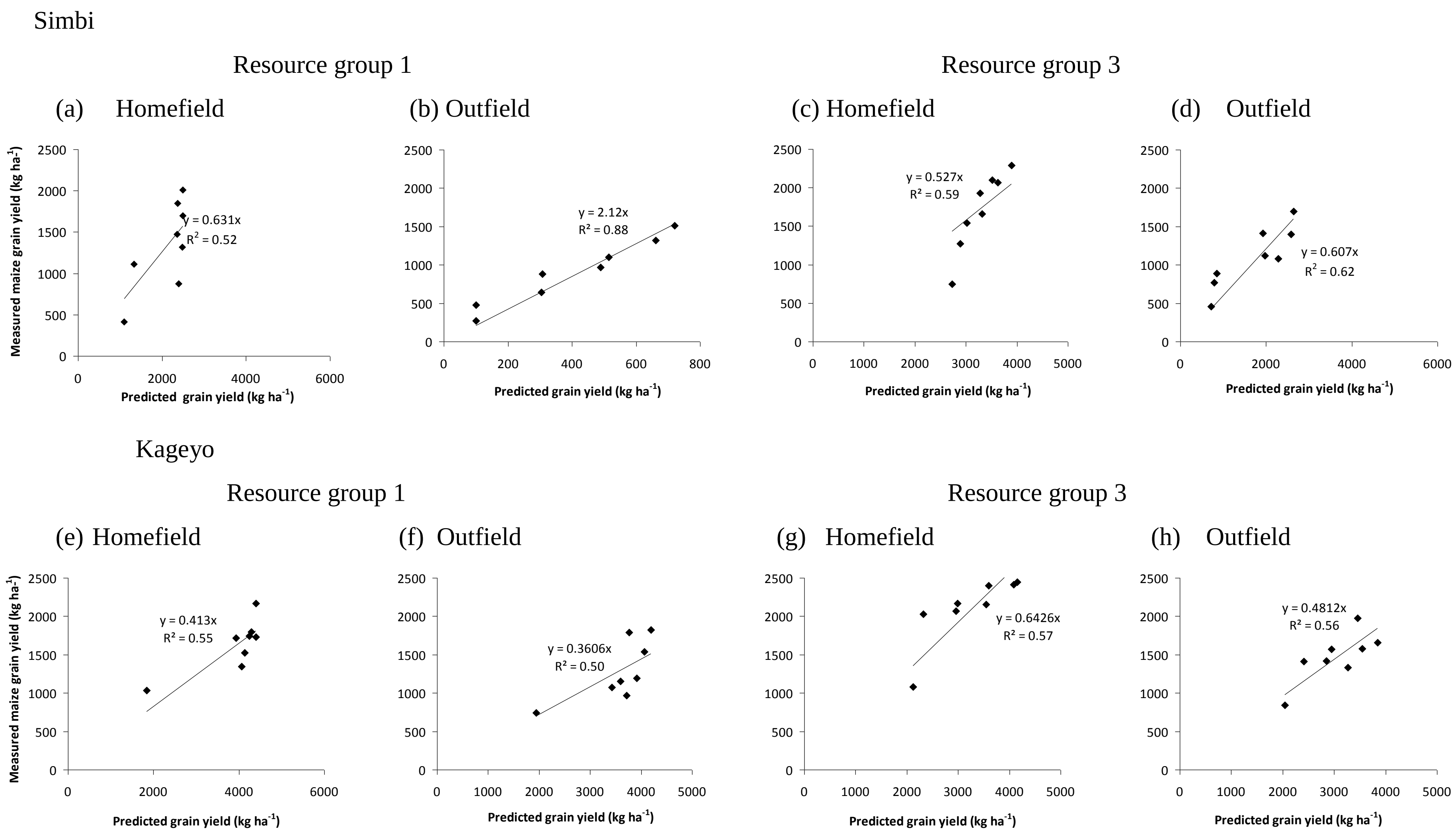
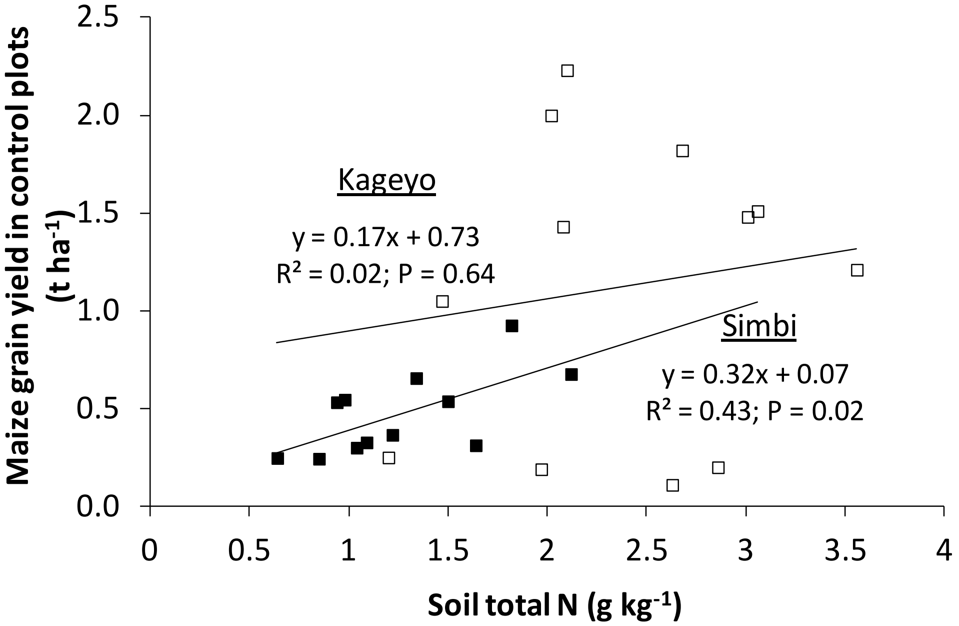


Figure 5.3 Relation between maize yield calculated from QUEFTS and measured from Homefield and Outfield (a and b) in RG1 and Homefield and Outfield (c and d) in Resource group 3 during Short Rains season 2008 season in Simbi and in Homefield and Outfield (e and f) in Resource group 1 and Homefield and Outfield (g and h) in Resource group 3 during Long Rains 2009 season in Kageyo.

(a)



(b)

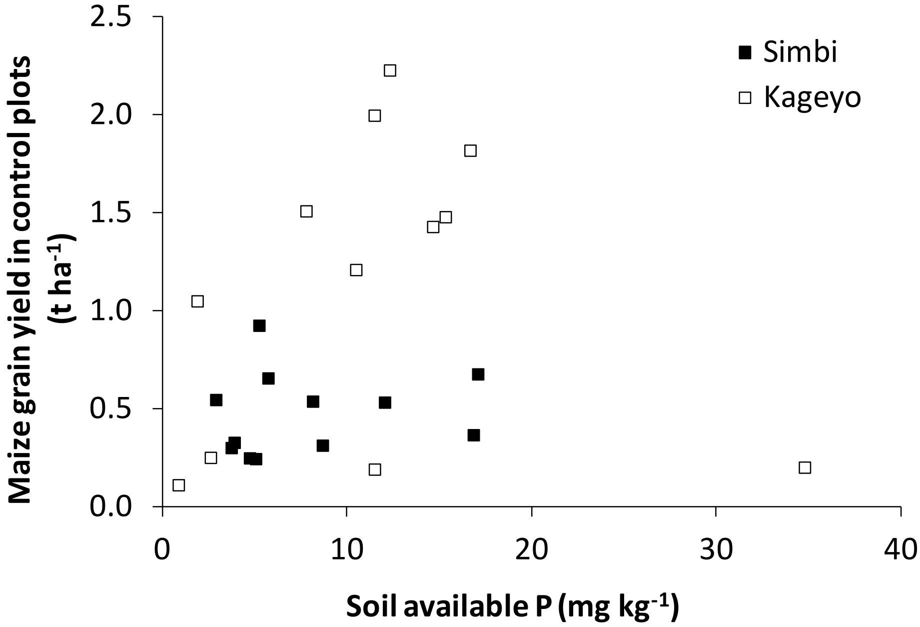


Figure 5.4 Relationship between maize grain yield in control plots and the initial soil total N content (a) and between maize grain yield in control plots and the soil available P (b). The number of observations is 12 (2 field types x 2 farm types x 3 farms per each type) in both Simbi and Kageyo.

N use efficiency as affected by P application and N rate on different farms and fields of Simbi and Kageyo

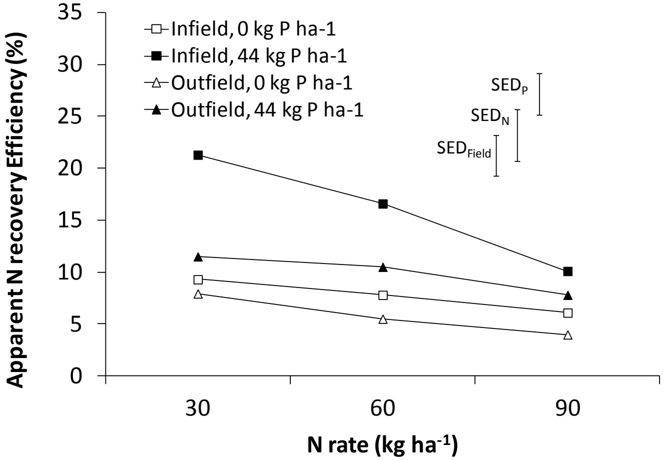
In both locations, N recovery (RE_N) was the highest in RG 3 (Figures 5.5a & 5.5b). In Simbi, RE_N was 20.3% in RG 1 (Figure 5.5a) and 30% in RG 3 (Figure 5.5b). In Kageyo, RE_N was 24.4% in RG 1 (Figure 5.5c) and 24.7% in RG 3 (Figure 5.4d). In Kageyo, field type (P = 0.03) and P rate (P = 0.04) significantly influenced RE_N. The average was 14.7% in infield, significantly larger than 10.03% in outfield. RE_N was significantly higher with P (15.9%) than without P (8.85%) in RG 1. In RG 3, N rate had a significant effect on RE_N. The average RE_N was the highest with 30 kg N ha^{-1} (20.85%) as compared with 90 kg N ha^{-1} but similar with 60 kg N ha^{-1}.

Agronomic N use efficiencies (AE_N) exhibited similar trends as RE_N. Values were greater in RG 3 than in RG 1(Figures 5.6). In Simbi, the highest AE_N was about 29 kg maize grain kg^{-1} N appl. in RG 3 (Figure 5.6b) compared with 17 kg maize grain kg^{-1} N appl. in RG 1 (Figure 5.6a). In Kageyo, the highest AE_N was 23 kg maize grain kg^{-1} N appl. in RG 3 (Figure 5.5c) and 20 kg maize grain kg^{-1} N appl. in RG 1(Figure 5.6d).

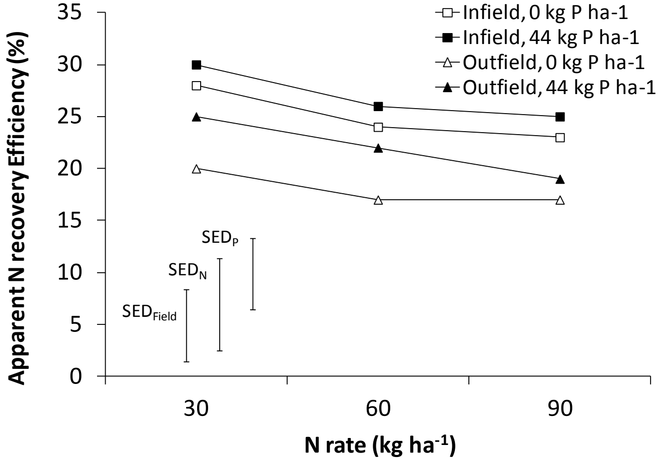
In Simbi, AE_N was significantly influenced by field type (P = 0.025) in RG 1. The highest value was obtained in infield (13 kg maize grain kg^{-1} N appl.). In RG 3, N use efficiency was significantly influenced by N rate (P = 0.02) and P rate (P < 0.001). The average was the highest with 30 kg N ha^{-1} (25 kg maize grain kg^{-1} N appl.) and with P (22 kg maize grain kg^{-1} N appl.). In Kageyo, agronomic N use efficiency was significantly affected by N rate (P = 0.001) in RG 1 and RG 3 (P < 0.001). It was the highest with 30 kg N ha^{-1} in RG 1 (17 kg maize grain kg^{-1} N appl.) and in RG 3 (20 kg maize grain kg^{-1} N appl.).

Simbi

Resource group 1 (a)

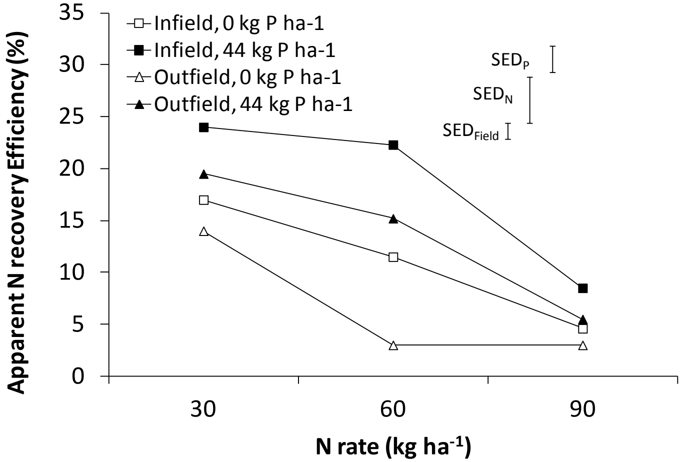


Resource group 3 (b)



Kageyo

Resource Group 1 (c)



Resource Group 3 (d)

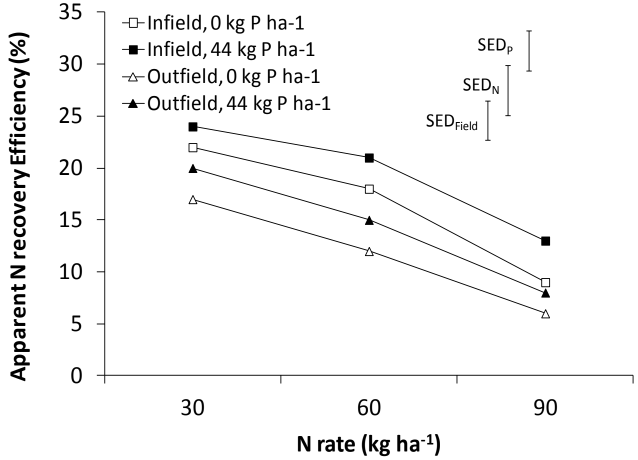
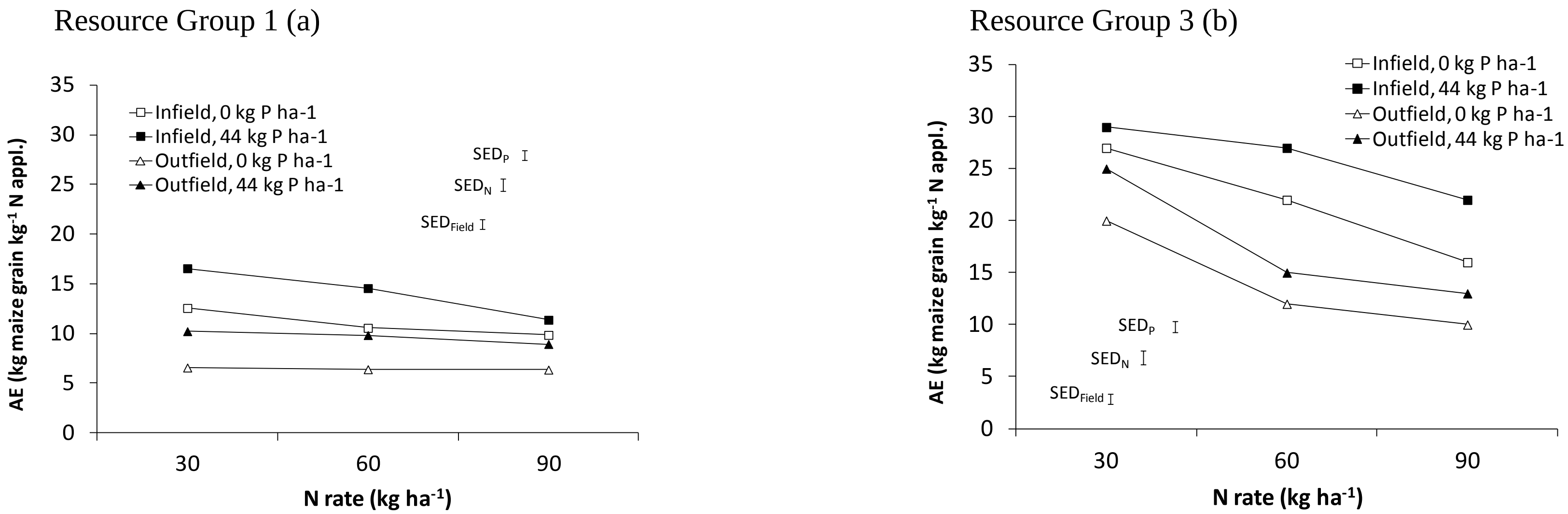


Figure 5.5 Apparent N recovery efficiencies in the homefield and outfield in Resource group 1 (a) and Resource Group 3 (b) in Simbi and in Resource Group 1 (c) and Resource Group 3 (d) farms in Kageyo for different N rates with or without P. Bars are SEDs, only SEDs for main effects are presented since interactions were not significant.

Simbi



Kageyo

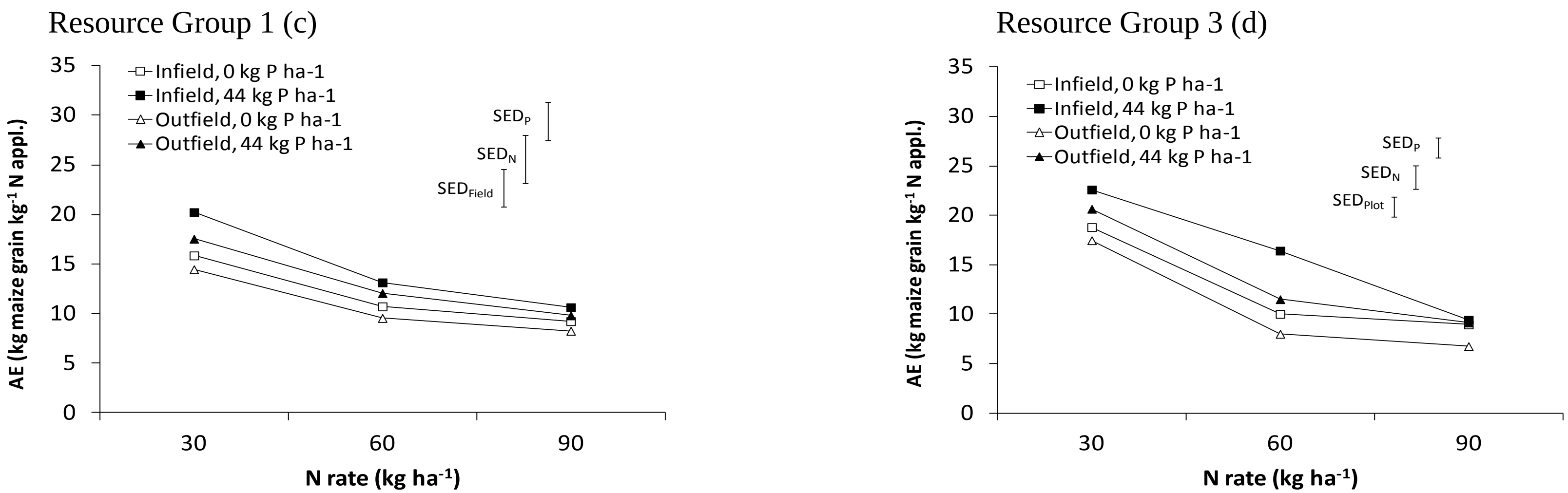


Figure 5.6 Agronomic N use efficiencies (AE_N) in the homefield and outfield in Resource Group 1 (a) and Resource Group 3 (b) in Simbi and in Resource Group 1 (c) and Resource Group 3 (d) farms in Kageyo for different N rates with or without P. Bars are SEDs, only SEDs for main effects are presented since interactions were not significant.

Assessing maize profitability under different N and P treatments in different fields and farms

Incorporating *Calliandra* residues with P into the soil resulted into additional income in the infields and outfields in Simbi and Kageyo as evidenced by economic indicators (Tables 5.2a & 5.2b). However, the benefits varied with location, RG, N rate, P rate and the interaction between RG and field type. Generally, Net benefit and B/C ratio were the greatest in Kageyo for all farms and field types. In Simbi, RG (P = 0.002), N rate (P < 0.001), P rate (P = 0.003) and field types (RG) (P < 0.001) had significant effects on the net benefit (Table 5.2a). Also B/C ratio was significantly affected by RG (P = 0.002), N rate (P < 0.001) and field types (RG) (P < 0.001). Net benefit and B/C ratio were significantly larger in RG 3 (225.7 US \$ ha^{-1} and B/C ratio of 2.7) than in RG 1 (55.9 US \$ ha^{-1}; B/C ratio of 1.4). Averaged over N rates, the net benefit significantly increased with increasing N rate with values of 76.4, 139.7, 201.5 and 232.9 US \$ ha^{-1} at 0, 30, 60 and 90 kg ha^{-1} respectively. B/C ratio had the similar trend as the net benefit with values significantly increasing with increasing N rate (1.46, 2.04, 2.46 and 2.64 at 0, 30, 60 and 90 kg N ha^{-1}). The net benefit was greater with P (184.42 US \$ ha^{-1}) than without P (140.85 US \$ ha^{-1}). Net benefit and B/C ratio were the highest in infield (85.8, 256.4 US \$ ha^{-1}and B/C ratios of 1.63 and 2.95 in RG 1 and RG 3 farms respectively) than in outfield (26, 195.1 US \$ ha^{-1} and B/C ratios of 1.19 and 2.47 in RG 1 and RG 3 farms respectively).

In Kageyo, the net benefit and B/C ratio were similar across RGs and P rates but significantly differed between N rates (P < 0.001 and P = 0.001 for both net benefit and B/C ratio respectively) and field types (RG) (P < 0.001 for net benefit and B/C ratios) (Table 5.2b). Net benefit and B/C ratios were smaller in control plots (Net income of 275 US \$ ha^{-1} and B/C ratio of 2.9) than in plots with 30, 60 and 90 kg N ha^{-1} (Net benefit of 366.9, 408.2 and 413.1 US \$ ha^{-1} and B/C of 3.4, 3.7 and 3.7 at 30, 60 and 90 kg N ha^{-1} respectively). Net benefit and B/C ratios were significantly greater in infields (458 US \$ ha^{-1}; B/C ratio of 4.09) than in outfields (271 US \$ ha^{-1}; B/C ratios of 2.91) in RG 1 but not in RG 3.

Table 5.2a Net benefit (US \$ ha^{-1}) and B/C ratio for maize in different farms and fields under different fertiliser treatments in Simbi (US \$ = 600 Frws)

	Resource Group 1/Poor farm				Resource Group 3/wealthier farm			
	Infield		Outfield		Infield		Outfield	
	Net Benefit	B/C ratio	Net Benefit	B/C ratio	Net Benefit	B/C ratio	Net benefit	B/C ratio
N rate (kg ha^{-1})								
- P (0 kg ha^{-1})								
0	- 46.0	0.60	-61.8	0.46	154.4	2.16	120.2	1.90
30	59.3	1.46	19.4	1.15	246.0	3.12	186.1	2.46
60	129.2	1.99	45.0	1.36	274.4	3.24	269.5	2.62
90	200.8	2.47	101.7	1.79	350.9	3.28	204.6	2.92
+ P (44 kg ha^{-1})								
0	3.2	1.02	-50.3	0.64	312.7	2.82	178.6	2.10
30	67.8	1.44	-1.7	0.98	332.7	3.26	208.1	2.51
60	172.2	2.07	76.7	1.50	432.0	3.77	213.5	3.15
90	213.7	2.30	136.3	1.86	384.7	3.54	270.6	3.00
P								
RG			0.002	0.002				
N rate			< 0.001	< 0.001				
P rate			0.003	0.55				
RG/Field			< 0.001	< 0.001				
SED								
RG			34.4	0.19				
N rate			12.6	0.06				
P rate			8.95	0.04				
RG/Field			27.9	0.15				

Table 5.2b Net benefit (US \$ ha^{-1}) and B/C ratio for maize in different farms and fields under different fertiliser treatments in Kageyo (US \$ = 600 Frws)

	Resource Group 1/Poor farm				Resource Group 3/wealthier farm			
	Infield		Outfield		Infield		Outfield	
	Net Benefit	B/C ratio	Net Benefit	B/C ratio	Net Benefit	B/C ratio	Net Benefit	B/C ratio
N rate (kg ha^{-1})								
- P (0 kg ha^{-1})								
0	310.9	3.52	140.8	2.17	288.0	3.29	182.4	2.42
30	415.4	4.17	261.3	3.09	420.9	3.58	371.0	3.56
60	511.9	4.68	300.0	3.41	455.4	3.75	295.1	3.31
90	531.2	4.74	372.3	3.66	271.6	3.22	382.7	3.81
+ P (44 kg ha^{-1})								
0	408.5	3.62	206.7	2.40	381.2	3.34	288.9	2.77
30	454.8	3.84	248.2	2.59	460.2	4.26	303.5	2.86
60	505.3	4.03	294.9	2.88	471.9	4.26	431.7	3.51
90	526.8	4.13	346.9	3.10	487.2	3.88	386.5	3.42
P								
RG			0.99	0.96				
N rate			< 0.001	0.001				
P rate			0.15	0.12				
RG/Field			< 0.001	< 0.001				
SED								
RG			184.2	1.02				
N rate			35.6	0.21				
P rate			25.2	0.15				
RG/Field			135.6	0.76				

Discussion

Soil fertility parameters indicated clear differences between the two locations (Table 5.1). For specific fields, the soil fertility was much higher in Kageyo (Buberuka) compared with Simbi (Central Plateau). The results are comparable with the findings reported 20 years ago on the two agro-ecological zones (Yamoah et al., 1989; 1990), except for pH levels (4.3 for Central Plateau and 4.8 for Buberuka) that are relatively low compared with our measurements (5.1 for Simbi and 5.7 for Kageyo).

Maize grain yields varied across the seasons, especially in Simbi in response to rainfall (Figure 5.2a). Averaged over seasons, maize grain was 61% higher in SR 2008 than in LR 2009 (low rainfall season) in Simbi. The better maize yield was accompanied by higher nutrient N uptake in maize grain in SR 2008 due to better moisture availability. The absence of a seasonal effect in Kageyo, Buberuka highlands (Figure 5.2d) could be due to higher moisture content prevailing in the highlands favoring crop development throughout the year.

Application of different N and P rates resulted in variable maize yield responses across locations (Figure 5.4a & 5.2b). The relationship between soil initial total N and maize grain yield in control plots indicated the potential for a stronger response in Simbi than in Kageyo. The stronger response in Simbi may be related to the poor soil fertility level (low soil organic C and P, Table 5.1). In earlier studies, strong maize response was found on fields with relatively little soil organic C and P compared with the fields with larger organic C and P (Vanlauwe et al. 2006). Similarly, Tittonell et al. (2007b), using a set of 600 samples from western Kenya showed evidence of a decrease of grain yield response to N-P-K fertiliser for soils with higher organic C and extractable P contents.

The results indicated that RE_{N} and AE_{N} were the highest in RG 3, infield plots and decreased with increasing N rate (Figures 5.5 & 5.6). The results are in agreement with the findings from studies in Zimbabwe in which RE_N and AE_N were shown to decrease from home-fields to the outfields, wealthier to poor farms and with increasing N application rates, particularly when no P was applied. N recoveries are in the range of those reported by other authors (Giller and Cadisch 1995; Mafongoya et al. 1997, Vanlauwe et al. 2000).

Low maize yield with 30 kg N ha^{-1} (Figure 5.2) was due to the imbalance caused by insufficient N levels relatively to other nutrients, suggesting that N was the most limiting factors in this case. According to Liebscher's law of the optimum, a production factor that is in minimum supply contributes more to the production the closer other production factors are to their optimum (de Wit 1992), and therefore N availability which was at minimum was the main driver of maize yield in this case.

Maize yield was the highest with N applied at 60 kg N ha^{-1} (Figure 5.2b) in Simbi. The current fertiliser recommendation in Rwanda is about 250 kg NPK (17-17-17) ha^{-1} and 50 kg Urea ha^{-1} (46% N) applied as top dressing for maize, meaning a total of 65.5 kg N ha^{-1}, 18.2 kg P ha^{-1} and 35.2 kg K ha^{-1}. Our results suggest that 60 kg N ha^{-1}, slightly less than the currently recommended rates (65.5 kg N ha^{-1}) would be sufficient for soils in both locations. There was a significant and strong positive relationship between maize yield and soil total N in Simbi (Figure 5.4a). In Kageyo, though different N rates had similar effects on maize yield (Figure 5.2e), the greatest benefit was realized with 60 kg N ha^{-1} and was comparable to the economic benefit with 90 kg N ha^{-1}. Our results indicate the need to revise the fertiliser rates for specific soils in different agro-ecological zones. The results demonstrate a clear link between soil fertility (soil nutrients supply), maize productivity and economic profitability. For instance, net benefit and B/C ratio were largest in Kageyo and in infield plots due to better crop productivity (Table 5.1 and Figures 5.2 a, b, d & e). The plots where the best response was found were richer soils as evidenced by soil fertility indicators. Application of increasing N rates resulted into a greater net benefit and B/C due to the stimulation of more maize productivity. A B/C ratio greater than 1 indicates that an enterprise will be attractive for smallholders (Mangisoni 2000). The value was the smallest (< 1) with no N added to soils of Simbi (poorest soils) and greater than 1 when N was applied at 60kg ha^{-1}. The study illustrates the importance of combining organic manure and mineral fertilizer on smallholder farms to ensure efficient use of applied nutrients and crop productivity as reported in earlier studies (Vanlauwe 2002; Vanlauwe and Giller 2006; Tittonell et al. 2008a).

QUEFTS simulated maize response to fertilizers quite well as indicated by stronger correlation between calculated and measured yields. The yields calculated with QUEFTS refer to soils with no other limitations than those related to N, P and K (Janssen et al. 1990). Use of tools such as QUEFTS may allow scaling-up the study to more locations and considering other soil improving options within different farming systems of Rwanda. Since the model requires relatively few data, it may assist as a management tool in agronomic and policy decision in fertiliser use at farm or regional levels.

Conclusions

Variability in soil fertility between fields and farms had a significant influence on the productivity of the maize grain. Though maize yield was greater in Kageyo than in Simbi, the crop was more responsive to fertilizers in Simbi than in Kageyo. In both locations, N recovery and agronomic efficiency were best in infield plots, suggesting that it would be beneficial for smallholder farmers to target the most responsive fields such as fields close to home compound for fertiliser application.

The results demonstrated that 60 kg N ha^{-1}, slightly less than the current recommended rate would be adequate to generate higher maize crop and subsequent income to smallholder farmers, suggesting that current fertilizer recommendations should be adjusted basing on soil responsiveness to fertilizer and resource use efficiency.

Combining organic fertilizer resource with mineral P could generate substantial benefit to smallholder farms with limited resources. *Calliandra* shrubs, largely regarded as an important source of stakes and animal feed in smallholder farms in Rwanda (Bucagu et al. 2013) may equally be used to improve soil fertility in smallholder farms where other resources are lacking. A total amount of 2.2 t *Calliandra* DM biomass ha^{-1} (60 kg N ha^{-1}) combined with P could potentially increase grain yield by 56% relatively to the control without fertilizer. Though a huge amount of *Calliandra* residues would be required for soil fertility improvement on farm, labour investment for transporting it would not be high since *Calliandra* shrubs are mostly established on edges of bench or progressive terraces close to or within the food crop fields.

Chapter 6

Assessing current and potential fodder availability within smallholder farming systems in southwest Rwanda

This chapter has been submitted as:

Charlotte. J. Klapwijk, Charles Bucagu, Mark T. van Wijk, Bernard Vanlauwe, Esron Munyanziza and Kenneth E. Giller. Assessing fodder availability under different scenarios within different farming systems in southwest of Rwanda. *Agricultural Systems*

Abstract

Livestock is an essential component of smallholder farming systems in the East African highlands. Recently, the 'One cow per poor family' programme was initiated in Rwanda as part of a poverty alleviation strategy, aiming to increase the livestock population. A four month-study was conducted in Umurera village (Simbi sector), southern Rwanda with the objectives to (1) quantify the on-farm fodder availability, (2) quantify the amount and quality of fodder on offer to livestock, (3) analyse the potential fodder availability under five future scenarios and (4) evaluate the implications and feasibility of the programme. Farmers' surveys, measurements of field sizes together with daily measurements of fodder on offer, milk production and fodder refusals were conducted. Feeds used were diverse, comprising grasses (56%), banana plant parts (21%), residues of several crops (15%) and other plants (8%). Herbs collected from valley-bottoms and crop residues were predominant fodder types on poorer (Resource group 1 - RG1) farms while *Pennisetum* and *Calliandra* were predominant fodder types for moderate (RG2) or better resource-endowed (RG3) farms. The amount of fodder on offer for cattle ranged from 20-179 kg fresh weight animal^{-1} day^{-1}. The milk yield ranged between 1.33 - 4.58 L day^{-1}. The amount of *Pennisetum* and *Calliandra* available decreased in the dry season with a concomitant increase in reliance on banana leaves and pseudostems. The poorer RG1 farmers were not able to feed a local cow under all scenarios. RG2 farmers can sustain a local cow during both seasons when using all possible fodder resources. RG3 farmers can feed an improved cow during the rainy season under two scenarios and the same accounts for only one scenario and doubled banana production during the dry season. None of the farmers were able to sustain a crossbred lactating cow year-round under any of the future scenarios. We conclude that the 'One cow per poor family' programme needs to be adjusted to increase its effectiveness. Our main recommendations are to shift to livestock that require less feed, for example local cattle or small ruminants such as goats.

Keywords: 'One cow per poor family' programme, Ubudehe, Resource groups, Fodder availability, Scenarios, Rwanda

Introduction

Mixed crop-livestock farming is practiced as landholdings as small as 0.5 ha in the highlands of East Africa in which crop production and livestock play complementary roles (Tittonell et al. 2005a; MINAGRI 2009). Livestock contributes to food security through provision of high value protein in the form of milk and meat, provision of additional income to the household and as mean to store capital and meet social obligations of the farmer (Powell and William 1993). Cattle is the major livestock species in Rwanda with a population estimated at one million head comprising 86% of local, 13% of cross and 1% of exotic breeds (MINAGRI 2006; 2009). Crops together with cultivated grasses provide the bulk of feed for cattle, small ruminants (goats and sheep), pigs and to some extent rabbits, which return soil nutrients to the cycle through the supply of soil nutrients through organic manure.

Cattle feeding is largely based on a zero-grazing system in which fodder is carried to the animal kept in confinement. Reasons for this practice are land-scarcity and limited forage resources, minimizing the risk of overgrazing and environmental degradation. The total available grazing area is estimated at 831,563 ha, translating into a carrying capacity of 614,000 tropical livestock units (MINAGRI 2006). Cattle grazing outside the farm is prohibited, though small ruminants (e.g. goats) may be tethered outside the farms to browse on roadside vegetation.

Animal feeds are diverse, including grasses and legumes (both indigenous and improved), crop residues and other organic household wastes (Mutimula and Everson 2011). Crop residues commonly fed to livestock include sweet potato vines, foliage and damaged tubers, banana pseudo-stems and leaves. Some agroforestry species such as *Calliandra calothyrsus* and *Sesbania sesban* are used to provide fodder and have shown good potential for biomass production (Niang et al. 1998; Roose and Ndayizigiye 1997).

Livestock production occurs in a diverse biophysical and socio-economic context. Variation in annual rainfall and its irregular distribution are key factors determining seasonal fluctuations in fodder availability. Feeds shortage is most acutely felt during the dry season when the fodder quantity is often insufficient for the number of cattle, leading to starvation of grazing animals, as well as poor productive and reproductive performance (Hall et al. 2008; Mapiye et al. 2006). Farmers shift from dependence on one type of fodder to another depending on its relative availability. In Kenya, for instance, in both of the rainy seasons, the bulk of the fodder consists of fodder crops and weeds, while in the dry season these are supplemented by crop residues and banana pseudo-stems (Abate et al. 1992; Paterson et al. 1999). Moreover, feed shortage is often compensated through the use of poor quality fodder, which is inadequate to sustain lactating and/or reproducing cattle (Lanyasunya et al. 2006; Shem 1996).

Besides climate variability, local conditions may determine fodder production such as the strong heterogeneity in soil fertility within smallholder farming systems caused by natural factors (type of parental material and topography) and farmer management practices (Giller et al. 2006; Tittonell et al. 2005b; Zingore et al. 2007b). For instance, Napier grass (*Pennisetum purpureum*) is mostly established on field-edges close to annually cultivated food crops and therefore receives nutrients through application of manure or mineral fertilizer. Other fodder types such as weeds or uncultivated grasses grow in fallowed plots or degraded fields.

Recently, the Government of Rwanda initiated the ‘One cow per poor family’ programme, which aims to make cattle available for the most vulnerable households. The programme seeks to reduce malnutrition through increasing milk consumption of the rural poor, to provide farmers with manure for soil fertility improvement, to promote social cohesion through a system where the first born calf is passed on to others in need, and to create opportunities for earning additional income. Currently, milk consumption is estimated to be only 13 L person^{-1} year^{-1} in Rwanda, far less than the 220 L person^{-1} year^{-1} recommended by FAO. Child malnutrition in Rwanda is estimated to average 43% (MINAGRI 2006).

The community selects beneficiaries of the programme based on strict criteria such as the families owning no cattle and less than 0.75 ha of land. Some 668,763 families are expected to benefit from the programme nationwide (MINAGRI 2006). The 'One cow per poor family' programme focuses on providing cross-bred cows, motivated by their higher milk production compared with local breeds. Lukuyu et al. (2009) estimated the milk production from a typical Friesian crossbred at 5 to 9 L day^{-1} while indigenous cows (*Bos indicus*) produced 1 to 4 L day^{-1}. The larger live weight of improved cattle automatically results in a higher feed demand. For example, the Jersey breed (*Bos taurus*) can easily reach double the live weight of a local African cow (Felius 1985). Dairy cattle requires as much as 14 to 17 kg DM day^{-1} per animal or 5,100 to 6,200 kg DM annually (Paterson et al. 1998).

Despite the envisaged benefits of the 'One cow per poor family' programme there is scanty information on the availability of fodder resources on smallholder farms of Rwanda. Existing information is based largely on estimates by farmers themselves, collected through surveys (Mutimula and Everson 2011). Knowledge of on-farm availability of fodder resources and their quality is key in exploring opportunities to increase fodder production. We conducted this study to: (1) quantify fodder availability on different farm types in south-west Rwanda, (2) quantify the amount and quality of fodder offered to livestock by farmers who currently own cattle, (3) analyse potential fodder availability across seasons under different future scenarios and (4) analyze the implications of our results for the 'One cow per poor family' programme.

Materials and Methods

Study site

The study was conducted in Umurera village (164 households, 1324 people) located 17 km from Butare, Southwestern Rwanda ($2^{o}30'28''$ and $028^{o}42'09''$) with a population density of 520 inhabitants km^{-2}. The area is located in Simbi sector and shares biophysical and socio-economic features with the Central Plateau agro-ecological zone (AEZ) (Table 6.1). The topography of the zone is dominated by hills and valleys lying at an altitude around 1634 m above sea level. The average temperature is $20^{o}C$ (Tmin: $10^{o}C$, Tmax: $30^{o}C$). Rainfall ranges from 1050 to 1200 mm annually and has a bimodal distribution pattern, allowing two major cropping seasons, the short rainy season from September until December and the long rainy season from mid-February until June (Hagedorn et al. 1997).

The majority of soils in the area are acidic (pH 4.3 to 5.7), sandy loam or sandy clay loams with high variation among fields. Soil organic carbon (SOC) ranges from 1.3 to 4.0% and total N from 0.12 to 0.39%. The socio-economic characteristics in Simbi (household size, farm size) are typical for the Central Plateau AEZ. The cropping system is dominated by basic food crops including beans (*Phaseolus vulgaris* L.) and sweet potato (*Ipomoea batatas* L.). Other important food crops are maize (*Zea mays* L.), sorghum (*Sorghum bicolor* (L) Moench), banana (*Musa* spp.) and White potatoes (*Solanum tuberosum* L.). Coffee (*Coffea arabica* L.) is the main cash crop. Cattle are the main livestock species alongside small ruminants (sheep and goats) as well as pigs and chickens. Livestock was quantified in tropical livestock units (TLU) of 250 kg; where 1 TLU = 0.7 cattle, 10 sheep/goats and 5 pigs (Janke 1992).

Agroforestry is widely practiced with a large diversity of tree species on individual farms. Trees and shrubs including timber, fruit and legume species, are planted in different niches. Fruit trees (avocado, *Persea americana* Mill, being the most visible on farm) are established near the homestead, legume species for stakes and fodder are established on field-edges (e.g. *Calliandra calothyrsus* Meissner, *Sesbania sesban* (L.) Merr., *Leucaena leucocephala* (Lam.) de Wit) and timber tree species (e.g *Eucalyptus* spp.) are established away from crop fields (Bucagu et al. 2013).

Farm selection

In Simbi, farm households were categorised in three resource groups (RG): poor resource group (RG 1; representing 86.6% of the households), moderate resource group (RG 2; 8.5%) and wealthier resource group (RG 3; 4.9%) based on key agricultural and socio-economic indicators including family-size, education level, available family labour, land size, food self-sufficiency and livestock ownership (Bucagu, this thesis). Initially twelve farms were selected; four farms per each of three resource groups (RG). During the data analysis, one household was found to have been categorized mistakenly in RG 1, and was reclassified as RG 2. Data collection was interrupted for one RG 3 farm when the farmer was unavailable. Therefore, data analysis was complete for on 11 farms, comprising 3 farms from RG 1 and RG 3 and five farms from RG 2. Interviews were conducted during the short rainy season (September to December 2010). The first interview was conducted to collect general data such as the number of household members, livestock and number and area of fields. A second interview was conducted during the last weeks of the study and focused specifically on sources of uncultivated fodder; locations and ways of as well as rules for collection.

Fodder availability

Measurements of the length of field edges were done for all fields (both uphill and valley-bottom) of each farmer using a 50 m measuring tape. The surface of each field was calculated using the measurements of the edge-lengths. Measurements of the total edge-length available per farmer were required to estimate possibilities for fodder production. The farmers measured the amount of fodder on offer for cattle on a daily basis.

Table 6.1 Major biophysical and socio-economic characteristics of Simbi compared with the Central Plateau Agro-ecological zone

Variables	**Units**	**Simbi**	**Central Plateau AEZ****
Altitude	m	1634*	1500-1700
Rainfall	mm	1050 to 1200**	1200
Population density	# inhab km^{-2}	520**	400 to 500
Dominant crops		Predominance of sweet potatoes, beans, maize, sorghum, Irish potatoes, cassava and bananas*	Sweet potatoes, cassava, beans, maize, bananas, colocasia and soybeans
Predominant tree and shrub species		Timber trees (*Eucalyptus* spp. and *Grevillea robusta*), fruit trees (*Persea americana*, *Citrus* spp.), legume shrubs (*Calliandra calothyrsus*, *Sesbania sesban*) *	*Eucalyptus spp*., *Grevillea robusta*, *Markhamia*, fruit trees (mostly *Persea americana*), indigenous (*Ficus thonningii*, *Dracaena afromontana* and *Euphorbia tirucalii*) around the rugo (home compound).
Dominant Livestock		Cows (both local and cross-bred) kept under zero-grazing system, pigs, goats under semi-stabled*	Cows, pigs, goats and sheep, mostly intensive, semi-stabled
Dominant soils		Sandy-loam, Sandy clay loam*	Clay sandy soils
Mean household size	# family members $household^{-1}$	4 - 6*	5.1
Soil chemical parameters			
pH		4.3–5.7*	4.3
OC	%	1.3–4.0*	1.2 - 1.4
Total N	%	0.12– 0.39*	0.15
Clay	%	11–27*	29

*Own observations or measurements,** obtained from several sources (den Biggelaar, 1986; Yamoah et al., 1989; Verdoodt, 2003; Mugabo, 2003)

A 50 kg mechanical hanging scale with units of 0.5 kg was used to weigh different types of fodder at each feeding time (morning, midday and/or evening). Fresh weights were recorded and converted to DM using the average DM content. The average amount of daily fodder on offer per week was derived using measurements from seven consecutive days. The daily milk production (L day^{-1}) was measured by five farmers who owned a lactating cow during at least one week of the research period using a 500 ml cup. Refusals were measured during the last five weeks of the research. Fodder refused by cattle was weighed at the end of a day. All farmers put the refusals inside the stable at the end of each day to act as bedding. In general, the stable was emptied into a compost-pit once or twice a month. The fodder types offered to cattle were classified into napier grass (*Pennisetum purpureum* Schumach.), uncultivated grass (mixed grass species with dominance of scutch grass, *Cynodon dactylon* (L.) Pers.), banana plant parts (*Musa* spp., pseudo-stems and leaves), crop residues (mainly sweet potatoes: *Ipomoea batatas* and beans: *Phaseolus vulgaris*), marshland herbs (*Cyperus* spp., *Commelina benghalensis* L.) and 'others' (comprising exceptions such as leaves of *Ficus thonningii* Blume. and avocado, *Amaranthus* spp. and *Tithonia diversifolia* (Hemsley) A. Gray).

Farmers were asked to rank their top three fodder types, according to use, for both the dry and the rainy season. The most important fodder type was given three points, while the third type received one point. This information was translated into an 'expected' diet composition for each of the seasons.

Future scenarios

Five scenarios were formulated in which the area under cultivation for three major fodder types (*Pennisetum purpureum*, *Calliandra calothyrsus* and banana plant parts) was either increased, kept equal, or decreased. For the production of *Pennisetum* and *Calliandra*, the total edge-length (0.5 m width) of all uphill fields was taken as potential production area and increased to a maximum in each scenario. The edges of fields in the valley-bottom were excluded from the calculations, because it is unlikely that farmers will cultivate fodder on their most fertile fields. For the production of banana pseudo-stems, the percentage of total available land intercropped with banana was increased from 10 to 20% in Scenarios 3 and 4. *Calliandra* needs to be offered in a mixture, therefore the scenarios in which both *Pennisetum* and *Calliandra* are increased (Scenarios 2, 3 and 5), a ratio of 0.8:0.2 is used, derived from farmers' interviews. In Scenario 5, banana production was set to zero to see if farmers could maintain cattle when banana pseudo-stems are excluded from the diet. The three fodder types were chosen, because of their importance in the livestock diet and because production figures are available in the literature, allowing us to calculate the potential fodder production. The five scenarios were formulated as follows:

Scenario*	**Pennisetum**	**Calliandra**	**Banana**
1	Increased to 100%	Kept equal	Kept equal (10%)
2	Increased to 80%	Increased to 20%	Kept equal (10%)
3	Increased to 80%	Increased to 20%	Increased to 20%
4	Increased to 100%	Kept equal	Increased to 20%
5	Increased to 80%	Increased to 20%	Decreased to 0%

* The second and third column relate to field-edges, the last column relates to total available land

The number of *Calliandra* shrubs and the edge-length currently cultivated with *Pennisetum* were estimated. Fodder production was calculated by multiplying the number of shrubs or the production area (m^2) by average yield figures obtained from several sources. Biomass yield of *Calliandra* cultivated on contours was estimated at 3.8 kg DM shrub^{-1} year^{-1} (Bucagu et al. 2013). The width of a *Pennisetum*-edge was assumed to be 0.5 m, a cultivated edge of 10 m therefore translated into an area of 5 m^2. We used an average *Pennisetum* yield of 2.13 kg per m^2 calculated from production measured in comparable environments in Rwanda and other East African countries (Niang et al. 1998; Mwangi et al. 2004; Tibanyurwa et al. 2010). The potential production of banana plants was calculated using both literature and measurements. The number of banana fields for farmers in Umurera was estimated to be 10% of all fields. Using total farm-size and an average planting density of 3,000 plants per ha (Hauser and Van Asten 2008), we estimated the total number of banana plants per farm. The average total DM content used to calculate the production of banana pseudo-stems was 3.84 kg pseudo-stem^{-1} (Van Asten 2011 pers. comm.).

The added amount of the three fodder types (*Pennisetum*, *Calliandra* and banana plant parts) was calculated and used to derive the daily total fodder production for each farm type. Potential fodder production during the dry season was calculated by either adding or subtracting the fraction of fodder types representing the change in fodder availability relatively to the rainy season. Daily fodder availability was then compared with the estimated daily feed requirements for one cow (local, improved and lactating). The predicted annual fodder production was plotted against annual feed requirements of a local, improved and a lactating cow, assuming the amounts of fodder collected from the valley-bottom to be constant over time since water is not a limiting factor. Annual demands were derived by multiplying the daily available fodder amounts during the rainy season by 240 days (8 months) and the daily available fodder amounts during the dry season by 120 days (4 months).

Statistical analysis

Socio-economic characteristics, estimated production area and levels for major shrubs and grass species were compared between farms using a one-way ANOVA with 'Resource group' as a fixed factor and farm as replicate (Genstat® Discovery Edition 3 2009). SEDs are reported.

Results and Discussion

Farming systems

Fodder collection and feeding strategies occur in an integrated system in which resources flow between fields, livestock, households and the market (external to the system) (Figure 6.1). In the diagrams illustrating the types of farming systems, the farm boundaries are limited to the fields located uphill while the valley-bottom is considered an external niche since most farmers rent fields on a contract basis. Most crop residues used as fodder are produced in mixed cropping systems with sometimes more than three crops within a single field. Beans (*Phaseolus vulgaris*, climbing and bush types) is the predominant crop during both the short and long rainy season, occupying about 20% of cultivated land. Sweet potato (*Ipomoea batatas*) is also an important staple crop of which vines and damaged roots are used as fodder. Napier grass (*Pennisetum purpureum*) is one of the most important sources of fodder, planted along the edges of most fields and is also a cash crop for RG 1farmers who sell the fodder to cattle owners during periods of shortage. Banana plants are established both around the household and in crop fields. Pseudo-stems used for fodder are collected mainly from suckers on banana plants scattered in the crop fields, while plants near the household are used to produce fresh banana bunches or beer. Nutrient flows from fields to the livestock occur through the collection of crop residues, *Pennisetum*, uncultivated grass, banana pseudo-stems and several herbs (*Commelina benghalensis* and *Cyperus* spp.). In return, livestock provides manure to be used in the fields. Urine is not collected and flows into the soil, often next to the home compound. Collected fresh manure is usually stored in a compost pit or piled within the home compound together with crop residues and other organic materials (e.g. fodder refusals). The interactions between livestock and crops occur in different farms with the following patterns:

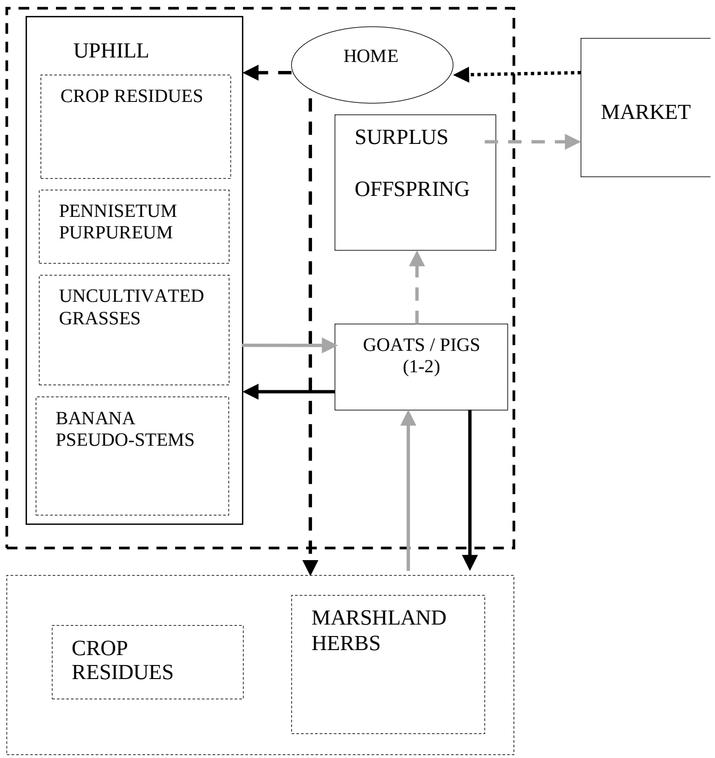
<u>Resource Group 1: Poor farmers without cattle, keeping small ruminants (1 or 2 goats/pigs).</u> Livestock is primarily fed with crop residues, uncultivated grasses, herbs from the valley-bottom and banana pseudo-stems, with *Pennisetum* mainly established to sell. The small amounts of manure collected from the animal stall together with crop residues and other materials are applied mainly to fields cropped with beans and sweet potato. No forage legumes are used as fodder, despite having *Calliandra* shrubs planted along field-edges. Major livestock products are

offspring of small ruminants sold to the market. Labour is used to transport fodder and manure between fields and stables.

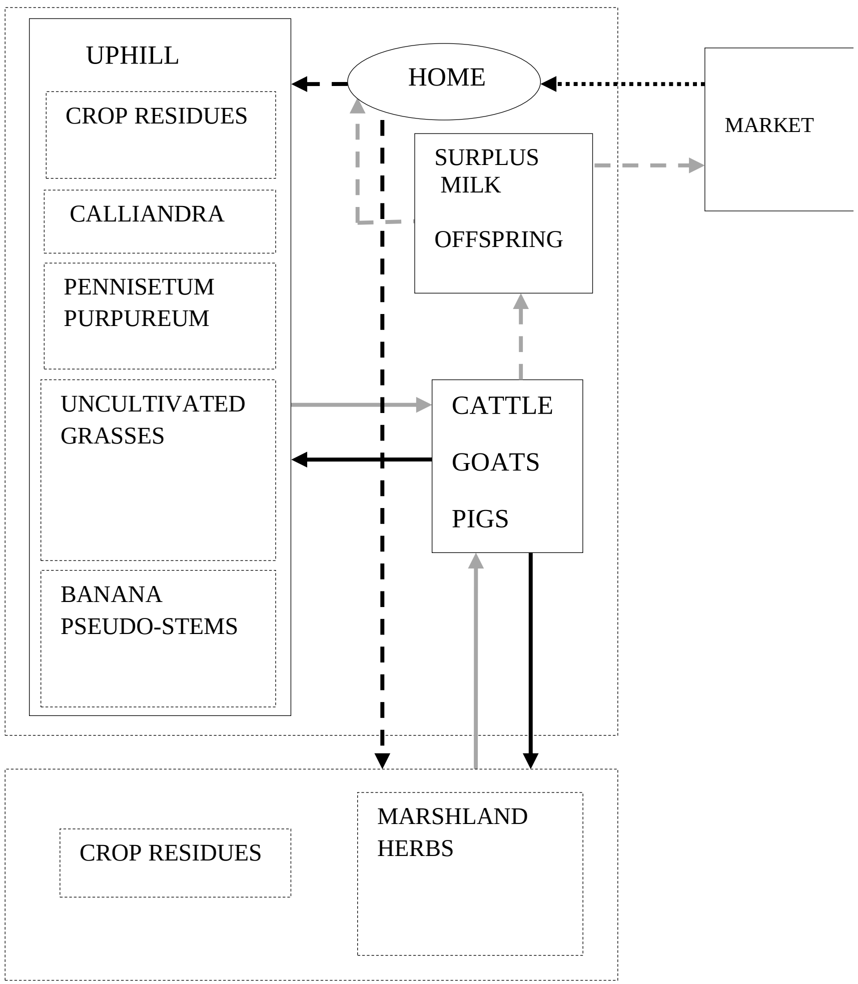
Resource Group 2: Moderate farmers keeping cattle (2 local or cross-bred), goats and pigs. Livestock have several functions; cattle are kept mainly to produce milk and manure while goats and pigs are kept to generate cash. Main source of fodder is *Pennisetum* produced on field-edges, supplemented with several other resources (uncultivated grasses, banana pseudo-stems and crop residues). The contribution of herbs from valley-bottoms is smaller than RG 1. Fodder legumes contribute to livestock feeding.

Resource Group 3: Wealthier farmers keeping cattle (3 head), goats and pigs. Generally, cattle are kept in a roofed stall. Similar to RG 2, cattle are kept for milk and manure production while small ruminants are kept to generate cash. *Pennisetum*, uncultivated grasses and banana pseudo-stems are the major fodder types. Farm-sizes are large, with many fields, allowing for a greater production area for *Pennisetum*. Labour demand is high due to the various cropping and livestock activities. In addition to family labour, a full-time labourer is often hired to take care of livestock fodder. Cash is generated from the sales of surplus milk and offspring of goats and pigs, either local or to traders.

RG I (Poor farm) (0.11 ha)



RG II (Moderate farm) (0.46 ha)



RG III (Wealthier farm) (1.71 ha)

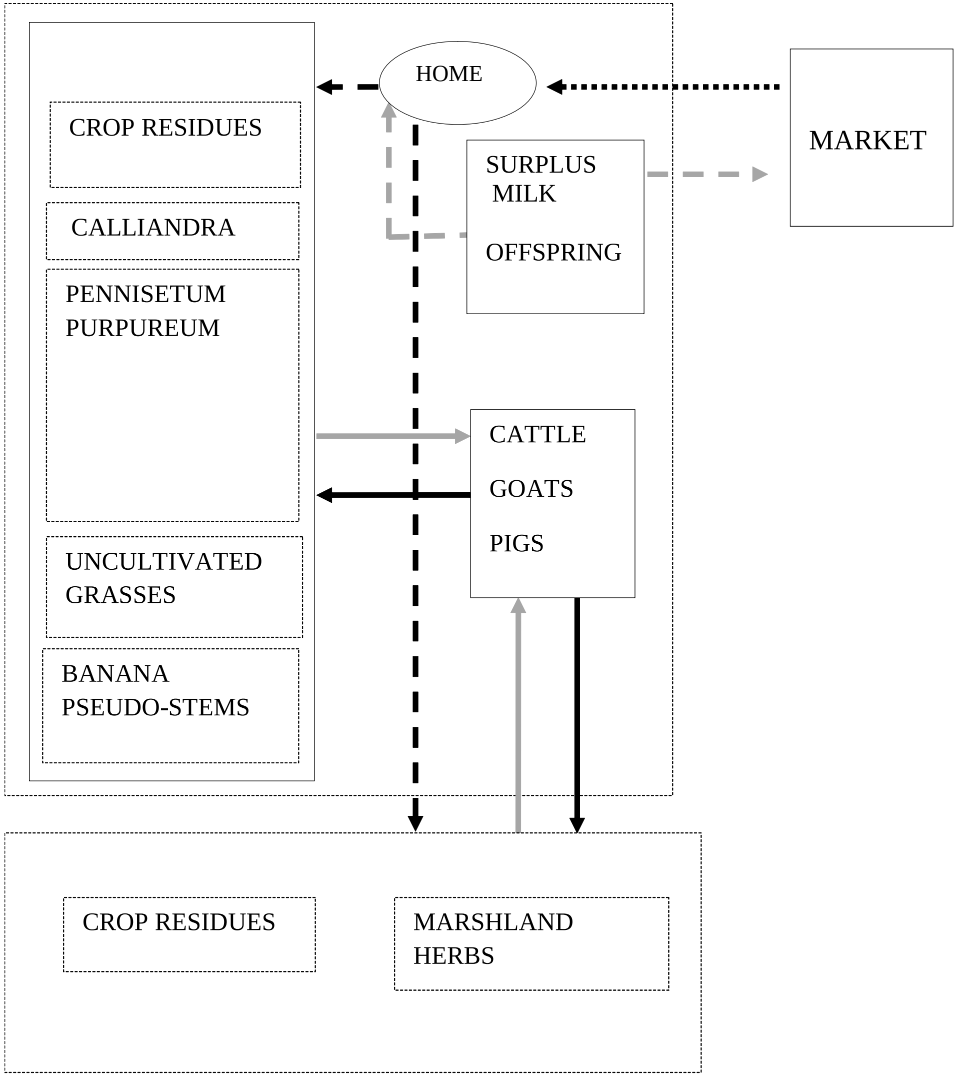


Figure 6.1 Schematic representation of fodder sources and allocation patterns for the resource groups (RG 1-3). The sizes of the components and the systems boundaries indicate the relative importance (not to scale). Arrows indicate the types of flows between components. HOME: Household.

Socio-economic characteristics

The average number of family members in RG 2 and RG 3 was significantly larger (P = 0.03) (6.3 and 5.6 people family^{-1}) compared with the RG 1 farmers (4.0 people family^{-1}) (Table 6.2). However, the average was similar for RG 2 and RG 3 farmers. Land available for fodder production was located both uphill and in the valley-bottom. In the uphill areas, available land was significantly larger (P = 0.02) in RG 3 (1.26 ha) than in RG 2 and RG 1 farms (0.32 and 0.08 ha respectively). Similarly, available land for RG 3 farmers in the valley-bottoms (0.45 ha) was also larger (P = 0.01) compared with RG 2 (0.13 ha) and RG 1 farmers (0.03 ha). Larger available land both uphill and in the valley-bottom resulted in RG 3 farmers having the most total land available for fodder production (1.71 ha), compared with 0.46 and 0.11 ha in RG 2 and RG 1 farms respectively. RG 3 owned more livestock (2.59 TLU) than RG 1 (0.36 TLU) but a similar number as RG 2 (2.06 TLU).

Table 6.2 Socioeconomic characteristics of different farm resource groups (RG1-3) selected for the study conducted from September to December 2010 in Simbi (means with ranges in parentheses).

Farm type	*N*	Family size	Land availability (ha)			[b]Livestock value (TLU)			
			Uphill	Marshland	Total	Cattle	Goats	Pigs	Total
RG 1[a] (Umukene)	3	4.00 (4-4)	0.08 (0.06-0.1)	0.03 (0-0.06)	0.11 (0.10-0.13)	0.2 0 (0-0.7)	0.16 (0.1- 0.2)	0.00 (0-0)	0.36 (0.2-1.2)
RG 2[a] (Umukene wifashije)	5	5.60 (5-6)	0.32 (0.21-0.32)	0.13 (0.02-0.23)	0.46 (0.44-0.48)	1.68 (0.7-2.1)	0.26 (0.1- 0.4)	0.12 (0-0.2)	2.06 (1.3-3.6)
RG 3[a](Umukungu)	3	6.30 (5-7)	1.26 (0.46-2.56)	0.45(0.16-0.90)	1.71(0.9-2.8)	2.10 (2.1-2.1)	0.36 (0.1-0.6)	0.13 (0-0.2)	2.59 (3.1-3.8)
P value		0.026**	0.03**	0.08[NS]	0.01**	0.03**	0.32 [NS]	0.21 [NS]	0.03**
SED		0.6	0.42	0.16	0.37	0.35	0.11	0.07	0.54

[a]Corresponding farm categories in Ubudehe classification,
[b]1 TLU = 0.7 cattle = 10 goats = 5 pigs
**significant at $P < 0.05$ and NS: not significant

Fodder availability on different farm types

The availability of the most important shrubs and grasses was assessed in terms of available production area and weekly yield per farm (Table 6.3). *Pennisetum purpureum* was generally planted on field-edges or contours of terraces. The available land area and biomass production for *Pennisetum* was significantly greater (P = 0.007) on RG 3 farm (831 m^2, 885 kg $farm^{-1}$ $week^{-1}$) than on RG 2 and RG 1 farms. Production was also significantly larger on RG 2 (418 m^2) than on RG 1 farms (90 m^2). The wide range in land cultivated with *Pennisetum* (ranging from 52 to 153 m^2 on RG 1 farms) was due to the variation in the number of fields and therefore the number of field-edges. The amounts of *Pennisetum* available were estimated at 885, 445 and 96.3 kg $farm^{-1}$ $week^{-1}$ on RG 3, RG 2 and RG 1 farms respectively. *Pennisetum* produced by RG 1 was mainly sold to cattle-owning farmers. The number of *Calliandra* shrubs was similar on RG 3 and RG 2 farms (125 and 58 shrubs $farm^{-1}$) but many more than on RG 1 farms (19 shrubs $farm^{-1}$). Estimated *Calliandra* biomass collected per week was comparable on RG 2 and RG 3 farms (532 and 249 kg $farm^{-1}$ $week^{-1}$ respectively) but significantly larger than on RG 1 farms (81 kg $farm^{-1}$ $week^{-1}$). The average number of banana pseudo-stems and their fresh biomass were also significantly larger on RG 3 (340 plants $farm^{-1}$; 1305 kg $farm^{-1}$ $week^{-1}$) than on RG 2 (138 plant $farm^{-1}$; 531 kg $farm^{-1}$ $week^{-1}$) and RG 1 farms (34 plants $farm^{-1}$; 131 kg $farm^{-1}$ $week^{-1}$). Thus, the total amount of the major three fodder types was largest on RG 3 farms (4954 kg $farm^{-1}$ $week^{-1}$). Similarly, the total amount of fodder per week was significantly larger on RG 2 (2344 kg $farm^{-1}$ $week^{-1}$) than on RG 1 farms (685 kg $farm^{-1}$ $week^{-1}$).

Fodder sources were diverse across the different resource groups. Based on daily measurements (Fig. 6.2), the percentage of *Pennisetum* fed to livestock was 16% of the diet on RG 1 farms. Other fodder sources were supplied in comparable proportions (20 to 23% of the total feeds). The small amounts of grasses used by RG 1 farmers were compensated by feeding larger quantities of marshland-herbs and crop residues, representing 21 and 23% of the total amount of fodder respectively. Clear differences in diet composition between RG 2 and RG 3 farms were reflected in the larger proportion of uncultivated grasses used on RG 2 (31%) compared with RG 3 farm (20%) and a greater amount of *Pennisetum* grass on RG 3 (35%) than on RG 2 farms (29%). Proportions of other fodder sources were comparable between the two RGs with banana plant parts representing 21% and 22% in RG 2 and RG 3 respectively and crop residues representing 14% in both RG 2 and RG 3. The most important part of the banana plant used as fodder was the pseudo-stem; only 3.1% and 2.5% of the banana plant parts used as fodder were banana leaves.

Table 6.3 Current availability and production of main fodder types (*Pennisetum purpureum*, *Calliandra calothyrsus* and banana pseudo-stems) for different farm types in Simbi.

Farm type	N	*Pennisetum purpureum*		*Calliandra calothyrsus*		Banana (*Musa* spp.)		Total fresh biomass	
		Land available (m^2)	Fresh biomass (kg $farm^{-1} week^{-1}$)	Number of shrubs $farm^{-1}$	Fresh biomass (kg $farm^{-1} week^{-1}$)	Plants $farm^{-1}$	Fresh biomass (kg $farm^{-1} week^{-1}$)	3 feed species (kg $farm^{-1} week^{-1}$)	All feed species (kg $farm^{-1} week^{-1}$)
RG 1	3	90 (52-153)	96.3 (55.5-163)	19.0 (5-34)	81 (21-145)	34 (30-39)	130.6 (115-150)	308 (241-435)	684.9 (435-941)
RG 2	5	418 (178-720)	445 (189-767)	58.0 (0-180)	249 (0-740)	138 (117-144)	530.8 (449-588)	1224 (723-1785)	2344.9 (1781-2781)
RG 3	2	831 (690-972)	885 (735-1035)	125.0 (100-150)	532 (426-639)	340 (270-411)	1305 (1037-1573)	2725 (2711-2739)	4954.4 (4925-4983)
P value		0.007**	0.007**	0.18^{NS}	0.18^{NS}	< 0.001***	< 0.001***	< 0.001***	< 0.001***
SED		144.5	153.9	57	200.1	32.8	124.8	274.6	317

* significant at $P < 0.1$** significant at $P < 0.05$, ***: significant at $P < 0.001$ and NS: not significant,

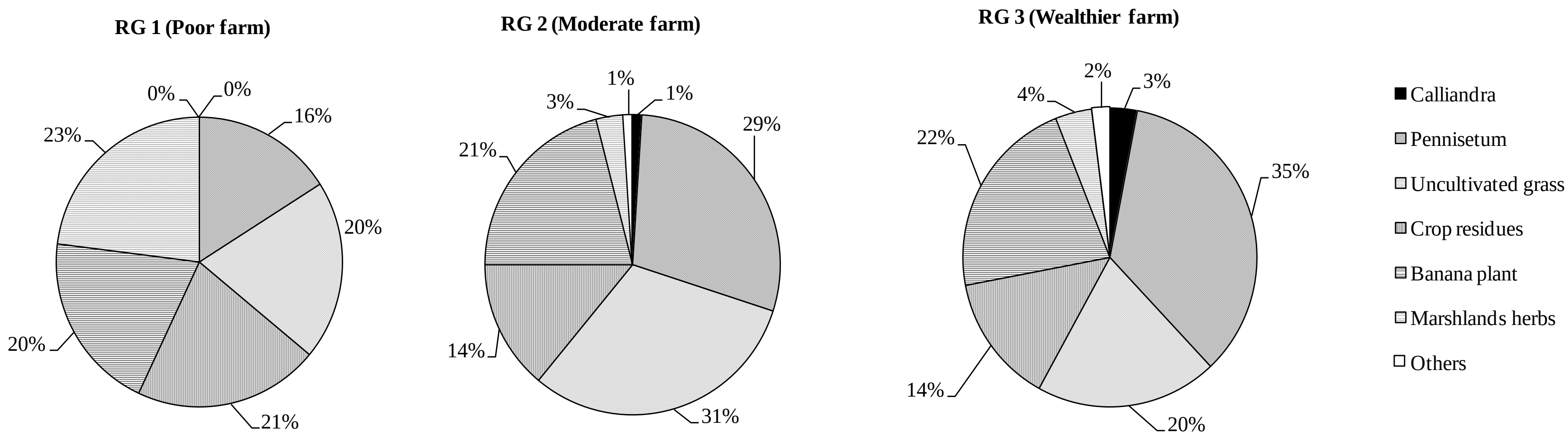


Figure 6.2 Composition of fodder on offer (% of the total fresh weight) for the three Resource Groups in Simbi (averages over seven weeks)

Fodder on offer and refusals

Due to practical reasons, measurements of fodder on offer were only made by RG 2 farmers, for two local cows (LC1: 6 yr and LC2: 7-8 yr, lactating) and one improved cow (IC: Mature, lactating) (Figure 6.3). The daily amount of fodder on offer for the two local cows ranged between 41 kg (LC2) to 70 kg (LC1), while for the improved cow, the average daily amount of fodder on offer was 144 kg. Large daily variation was observed with offered fodder ranging from 50-90 kg for LC1, 20-58 kg for LC2, and 120-178 kg for IC. The cows readily consumed almost all fodder on offer, so there were few refusals; ranging from 2.2-7.5 kg per day. The amount of refusals remaining from the improved cow was so small that it was impossible to quantify. On occasions when this animal refused feed (at 314 and 316th Julian days), an avocado tree had been cut down and leaves were offered as fodder. Surprisingly, refusals were recorded for cow LC 2 while the amount of fodder on offer for this animal was extremely small. This can probably be explained by the poor quality of fodder on offer. For example, 3-4% of the diet consisted of *Cyperus* spp., which was later explained by the farmer to be offered to livestock to increase the amount of compost**.**

Our results indicate a large diversity of animal feeds with a predominance of *Pennisetum purpureum*, consistent with other findings in the tropics (Mapiye et al. 2006; Lanyasunya et al. 2006). *Pennisetum* grown on field-edges and small plots serves both fodder source and as soil conservation measure. Surprisingly, maize stover was not an important source of fodder in Simbi, despite the large area cropped with maize in the valley-bottom and the proportion of farmers cultivating maize. In contrast to other countries in East Africa (Uganda, Kenya) where maize stover is a major source of livestock fodder (Paterson et al. 1999), farmers in Simbi prefer to use maize stover as stakes, firewood, or leave it in the fields for mulching. Although the amount of fodder on offer in Umurera was comparable to the amounts fed to cattle in Kenya: *Pennisetum* intake of about 80 kg animal^{-1} day^{-1}, or equivalent dry matter in terms of crop residues, weeds and parts of banana plants (Paterson et al. 1999), the diet in Kenya case was supplemented with 2 kg of commercial dairy meal, resulting in higher feed quality than in Umurera (Rwanda). Ongadi et al. (2010) reported that farmers in Kenya provided an average amount of fodder ranging 35-65 kg animal^{-1} day^{-1} to stall-fed cattle.

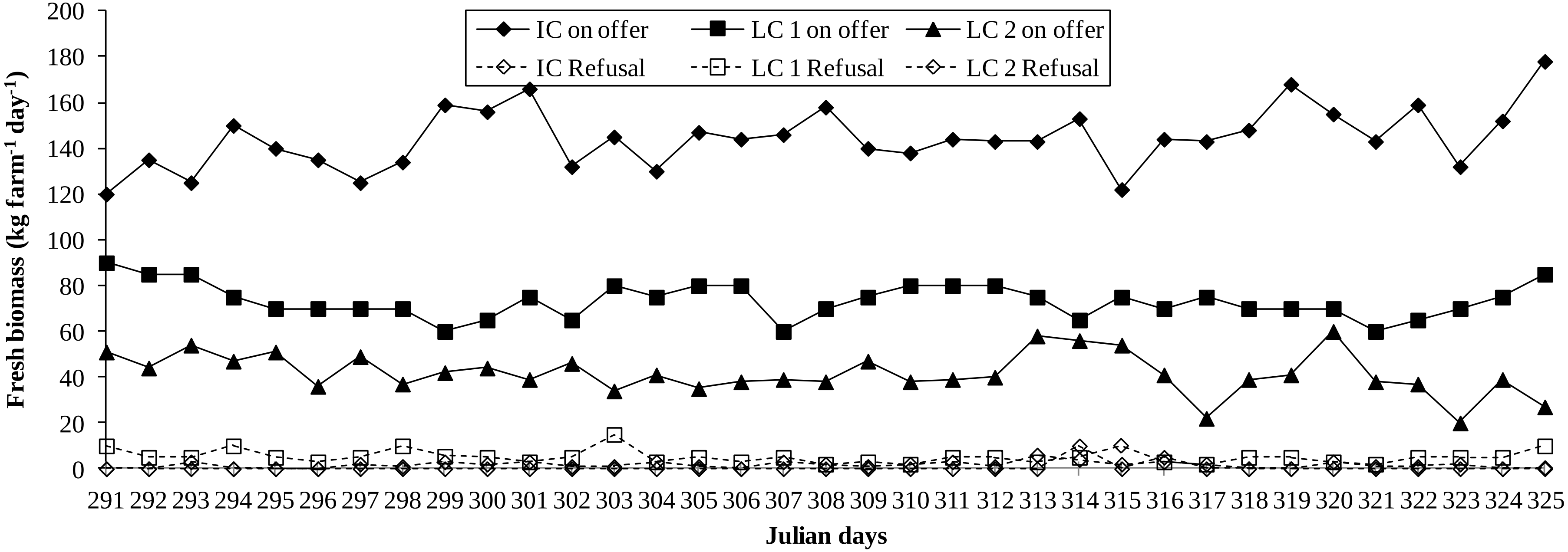


Figure 6.3. Total amount of fodder on offer (plain lines) and refusals (dotted lines) in kg fresh weight/animal/day for local and improved cattle of RG 2. IC: improved cow (mature cow lactating), LC 1: local cow 1 (6 yr), LC 2: local cow 2 (mature cow, lactating > 7-8 yr).

Milk production

Daily milk yields (DMY) were recorded for five individual cows; E (6 yr), F (>3 yr), H (>7 yr), J (8 yr) and K (15 yr) (Figure 6.4). Cow F was crossbred, the other animals were 100% local breeds. The highest daily milk yield (4.58 L day^{-1}) was recorded for cow F. The high production was probably due to the presence of a calf, as suckling is known to increase the milk production and ejection by (mixed) *Bos indicus* breeds (Hatungumukama et al. 2006). On the other hand, cow H was also suckled, but still produced only a small amount of milk (1.85 L day^{-1}). Therefore, a more plausible explanation could be the genetic background of cow F, as milk production is known to be enhanced by *Bos taurus* inheritance (Bee et al. 2006). The DMY of cows F, H and K (4.58, 1.85 and 3.23 L day^{-1} respectively) was fairly constant over time, while the production of cow J (2.2 L day^{-1}) decreased substantially. The owner stated that this cow was near the end of her lactation, which in Umurera is 2-5 months.

Most reports on dairy production in Africa focus on improved cattle, while there is little information on pure *B. indicus* breeds. The daily milk yield (DMY) of the only improved cow in Umurera (F: 4.58 L day^{-1}) is close to yields reported for Jersey cows in Kenya of 5.0 L day^{-1} (± 2.1) (Juma et al. 2006). Bee et al. (2006) however measured a DMY of 6.7 L day^{-1} for crossbred cows (Friesian and Ayrshire) in Tanzania. Paterson et al. (1999) recorded 10 L day^{-1} from improved cattle managed with a zero-grazing system, fed mainly *Pennisetum* and crop residues. In this case, a supplementation with 2 kg of concentrate, or its equivalent in the form of *Calliandra calothyrsus* (6 kg fresh material), was provided to each animal daily. The average DMY of pure Sahiwal (*B. indicus* spp.) cows in Burundi was 6.69 L day^{-1} for milked and suckled cows, and 2.88 L day^{-1} for cows when only milked (Hatungumukama et al. 2009).

There appears to be scope to improve daily milk yield in the Central Africa region. Inadequate nutrition is the main cause of low milk production by African cattle (Teferedegne 2000; Paterson et al., 1998). Therefore, improving both feed quantity and quality should be the focus of attempts to reach the genetic potential of cattle. A high protein content of fodder is essential to meet the requirements of lactating cattle, as protein is secreted in the milk (Juma et al. 2006). A common way to increase the protein content of a livestock diet is the supplementation with commercial concentrates (Ongadi et al. 2010), but the majority of subsistence farmers is unable to invest in such additions (Mwangi et al. 2004). A more viable option for farmers in Umurera is the supplementation with a protein-rich fodder such as *Calliandra calothyrsus*.

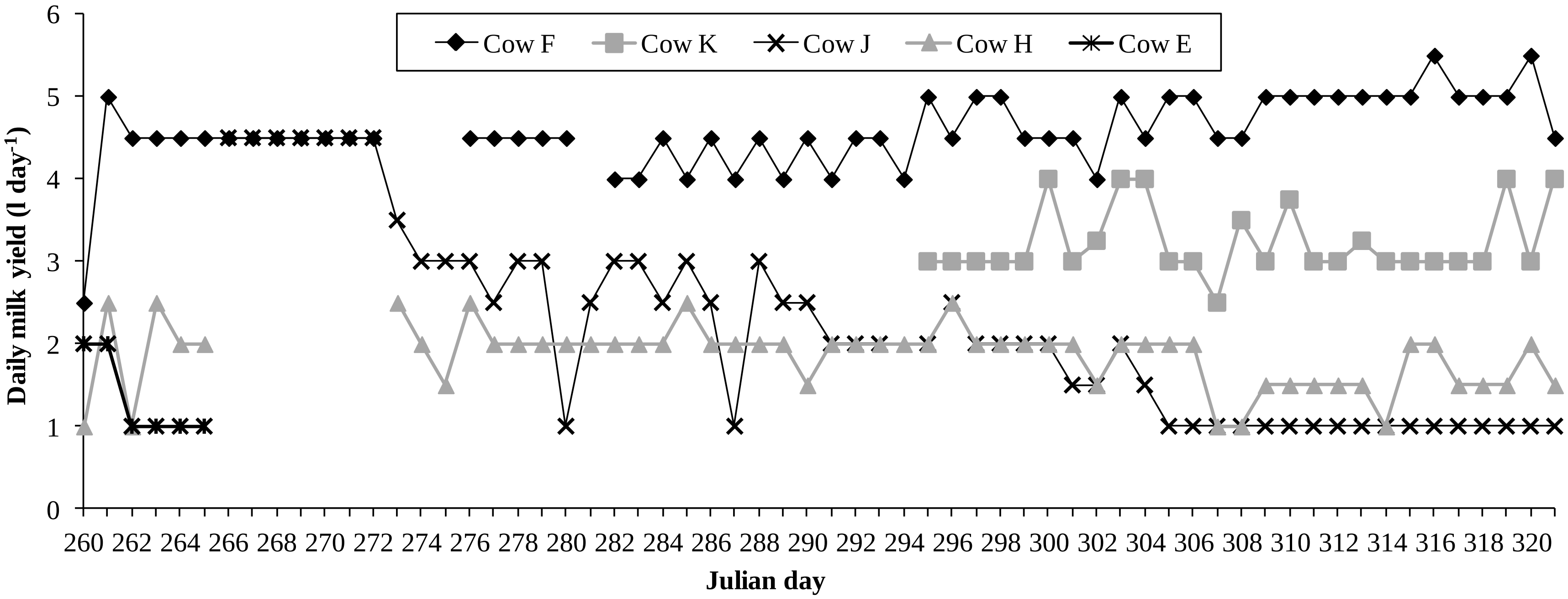


Figure 6.4. Milk production per day for five individual cows; E (6 yr), F (> 3 yr), H (> 7 yr), J (8 yr) and K (15 yr). Cow F is crossbred, the other animals are local. Unrecorded data denote days when cows were not milked.

Fodder availability under five future scenarios

Our calculations of potential fodder production in five scenarios suggest that the poorest farmers (RG 1) are unable to maintain either a local, improved or a lactating cow even during the rainy season (Figure 6.5a). The largest fodder production was 3.90 kg farm^{-1} day^{-1} considering only the three main feeds and 4.20 kg farm^{-1} day^{-1} (Scenario 3) when all feeds are considered. This fodder availability is less than the requirements of a local (6.2 kg farm^{-1} day^{-1}) or improved cow (12.2 kg farm^{-1} day^{-1}) (Khalili and Varvikko 1992). A RG 2 farmer (Figure 5b) can barely meet the requirements of a local cow using the three major feeds under Scenario 3 (5.84 kg farm^{-1} day^{-1}), but would be able to maintain a local cow when using all fodder sources (least fodder production of 8.62 kg^{-1}farm^{-1} day^{-1}) for all scenarios. To keep an improved cow, (s)he would need to use all fodder types in Scenario 3 (11.57 kg farm^{-1} day^{-1}). A RG 3 farmer (Figure 6.5c) can meet the requirements of a local cow under all scenarios, even when using only the three major fodder types (the least production being 6.50 kg farm^{-1} day^{-1} under Scenario 5). However, to be able to maintain an improved cow, (s)he would need to utilize other fodder sources. Under Scenario 5 (banana plant parts completely removed), the amount of feeds (11.86 kg farm^{-1} day^{-1}) was less than the requirements of an improved cow (12.2 kg farm^{-1} day^{-1}), highlighting the importance of banana pseudo-stems within the livestock diet. None of the three RG 3 farmers was able to produce the required amount of fodder for a crossbred lactating cow (16 kg farm^{-1} day^{-1}) under any of the scenarios, neither in the rain or dry seasons.

During the dry season, fodder production on RG 1 farms was reduced resulting in critical fodder shortage (Figure 6.5a). The largest expected fodder production of 3.67 kg farm^{-1} day^{-1} (all fodder types under Scenario 3) was only half the 6.2 kg farm^{-1} day^{-1} required by a local cow. The RG 2 farmers (Figure 6.5b) were able to meet the requirements of a local cow when using all fodder types under all scenarios in the rainy season. RG 2 farmers were unable to maintain an improved cow under all scenarios (the largest production was 9.35 kg farm^{-1} day^{-1} under any of

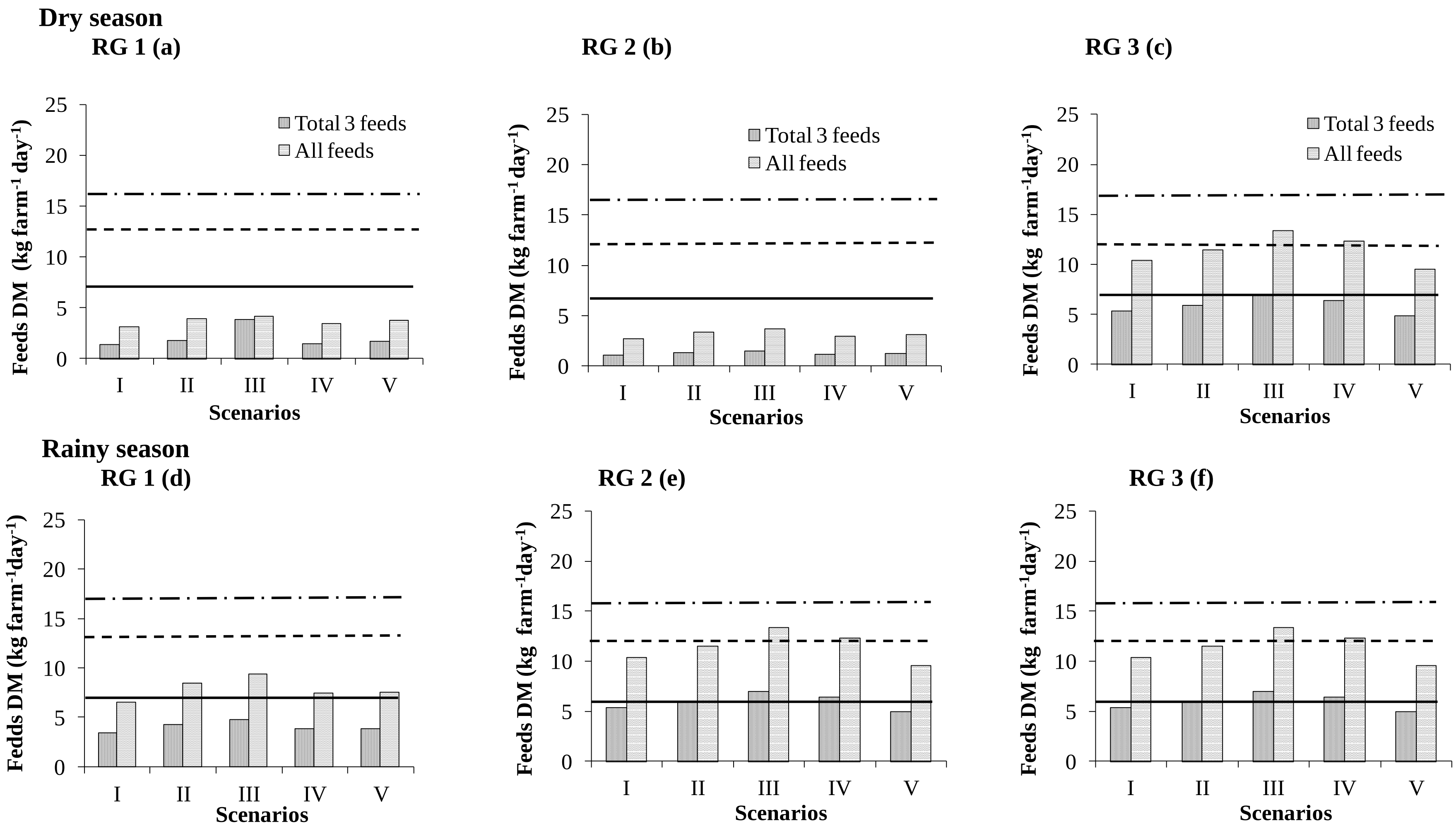


Figure 6.5. Estimated amount (kg DM day^{-1}) for three major fodder types (*Pennisetum purpureum*, *Calliandra calothyrsus* and banana pseudostems) and all fodder available on RG 1, RG 2 and RG 3 farms in Simbi during rain (a,b,c) and dry season (d,e,f) under different scenarios (1: 100% of upland edges with *Pennisetum*, *Calliandra* and banana production kept unchanged, 2: 80% with *Pennisetum* and 20% planted with *Calliandra*, banana production kept equal , 3: 80% of edges with *Pennisetum* and 20% planted with *Calliandra* and banana production doubled, 4: 100% of edge with *Pennisetum* and banana production doubled, *Calliandra* kept equal, 5: 80% of edges with *Pennisetum* and 20% of edges with *Calliandra* and banana production set at zero). Amounts were compared with feed requirements for a local cow (6.25 kg DM, solid line) and improved cow (12.2 DM day^{-1}, dashed lines) and a lactating improved cow (16 DM day^{-1}, semi-dashed line).

the scenarios, neither in the rain or dry seasons.

During the dry season, fodder production on RG 1 farms was reduced resulting in critical fodder shortage (Figure 6.5d). The largest expected fodder production of 3.67 kg $farm^{-1}$ day^{-1} (all fodder types under Scenario 3) was only half the 6.2 kg $farm^{-1}$ day^{-1} required by a local cow. The RG 2 farmers (Figure 6.5e) were able to meet the requirements of a local cow when using all fodder types under all scenarios in the rainy season. RG 2 farmers were unable to maintain an improved cow under all scenarios (the largest production was 9.35 kg $farm^{-1}$ day^{-1} under Scenario 3 < 12.2 kg $farm^{-1}$ day^{-1}). For RG 3 farms (Figure 6.5f), the farmers can potentially maintain a local cow using only the three main fodder types under Scenarios 3 and 4 (production of 6.93 and 6.37 kg $farm^{-1}$ day^{-1} respectively). Under the same scenarios a RG 3 farmer could keep an improved cow when all fodder sources are used (production of 13.38 and 12.32 kg $farm^{-1}$ day^{-1} respectively), while during the rainy season the same farmers could keep an improved cow under Scenarios 1, 2, 3 and 4. These results indicate that during the dry season the 31% reduction in the amount of *Pennisetum* and 9% in *Calliandra* substantially reduced the capacity of the RG 3 farmers to keep an improved cow. None of the three RG3 farmers could meet the requirements of a lactating cow (16 kg $farm^{-1}$ day^{-1}) under any of the five scenarios.

Our results confirm earlier findings on the importance of seasonality in fodder availability in Eastern Africa (Abate et al. 1992) and throughout sub-Saharan Africa (Renard 1997) where both the quantity and quality of fodder offered to cattle are reported to be far below optimum requirements. There is a strong need to increase both the volume and the quality of fodder during the dry season.

The estimated annual fodder production on farms of the different resource groups was plotted for the five scenarios to determine whether farmers would be able to keep animals year round (Figure 6.6). A farmer of RG 1 (Figure 6.6a) is unlikely able to produce sufficient fodder to maintain even a local cow. A RG 2 farmer (Figure 6.6b) would be able to keep a local cow if all possible fodder sources are used (the least production was 2,851 kg^{-1} farm^{-1} day^{-1} under Scenario 1 > 2,232 kg year^{-1} required). A RG 3 farmer (Figure 6.6c) could easily keep a local cow under all scenarios, using only the three major fodder types. However, to keep an improved cow, (s)he would need to use all possible fodder sources in Scenarios 1-4. None of the wealthiest farmers appear to be able to produce the amount of fodder required for an improved lactating cow (5,661 kg^{-1} farm^{-1} day^{-1}). For all farmers, collection of fodder (uncultivated grasses and weeds) from outside the farm is essential to feed their cattle. An increase in the number or quality of cattle in the village will result in an increased pressure on these off-farm resources.

The expected increased production under Scenario 3 is due to the importance of banana pseudo-stems in the diet of livestock in Rwanda. This is highlighted by a drastic reduction of the available fodder when banana pseudo-stems are excluded in Scenario 5. In Rwanda, bananas are found on every single farm, planted densely in fields close to the homestead and less densely in crop fields. Banana plant parts are reported to be of poor fodder quality due to their low protein content (< 1%), leading to a relatively low dry matter intake (Ffoulkes and Preston 1978). The importance of banana pseudo-stems in livestock diets is probably responsible in part for the poor milk production in Simbi (Figure 6.4).

Our results indicate that while RG 2 and RG 3 farmers would be able to maintain a local cow and even an improved cow under specific scenarios, this is not feasible for RG 1 farmers. With the extremely small land area available (0.11 ha, Table 6.1) and nationwide land scarcity in Rwanda, the RG 1 farmers face a critical constraint and high risks when investing in cattle. In the scenario of maximised fodder production (Scenario 3) and under favourable conditions during the rainy season, the total production of RG 1 farmers could reach a maximum of 4.20 kg DM day^{-1}, which is still lower than the 6.20 kg day^{-1} minimal requirements for maintenance and milk production of a local cow.

Estimated annual fodder production

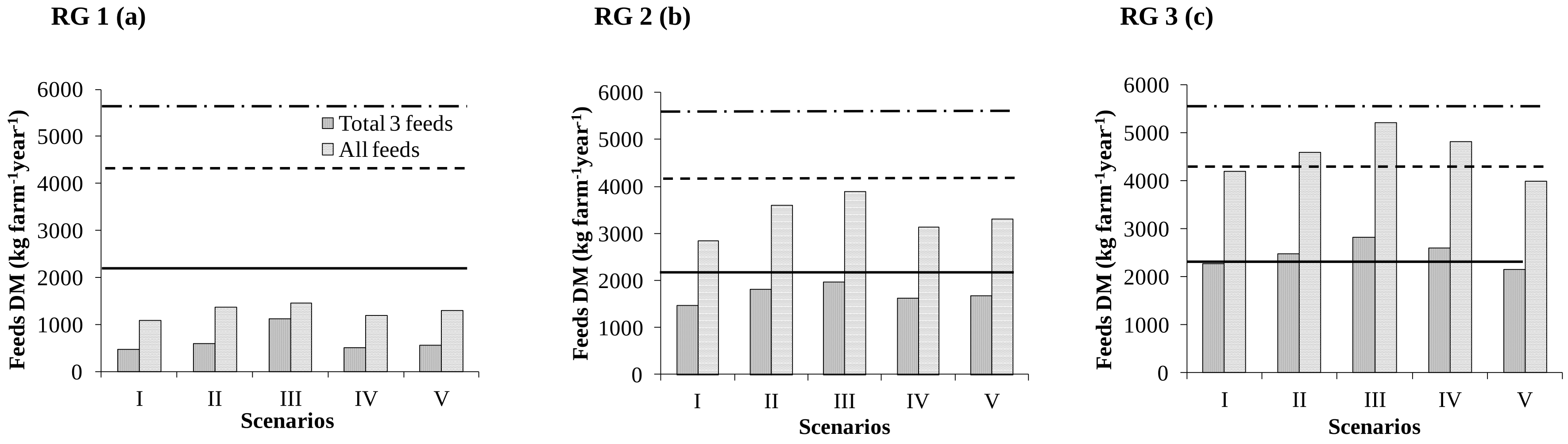


Figure 6.6. Estimated amount (kg DM farm^{-1} year^{-1}) of the three major feeds (*P. purpureum*, *C. calothyrsus* and banana pseudostems) and all feeds available on RG 1 (a), RG 2 (b) and RG 3 (c) farms in Simbi under different scenarios (1: 100% of upland edges with *Pennisetum*, *Calliandra* and banana production kept unchanged, 2: 80% with *Pennisetum* and 20% planted with *Calliandra*, banana production kept equal , 3: 80% of edges with *Pennisetum* and 20% planted with *Calliandra* and banana production doubled, 4: 100% of edge with *Pennisetum* and banana production doubled, *Calliandra* kept equal, 5: 80% of edges with *Pennisetum* and 20% of edges with *Calliandra* and banana production set at zero). Amounts were compared with feed requirements for a local cow (2232 kg DM year^{-1}, solid line) and improved cow (4453 DM year^{-1}, dashed lines) and a lactating improved cow (5661 DM year^{-1}, semi-dashed line).

The situation is likely to worsen during the dry season when fodder production and quality are further reduced. Fodder collected during the dry season has a low crude protein (CP) content (< 3%) and when CP is below 7 to 8%, animal growth is compromised (Evans 1968).

A realistic possibility for smallholder farmers to increase fodder quality is to supplement with a protein-rich fodder such as *Calliandra calothyrsus*. The majority of the farmers in Umurera already cultivate *Calliandra*, which has good potential for biomass production in Rwanda (Roose and Ndayizigiye 1997). According to Paterson et al. (1998), a farmer needs approximately 250 m of hedge annually to supplement one cow, which is a viable option for the RG 2 and RG 3 farmers. For the poorest farmers (RG 1), between 50 and 100% of their available field-edges would have to be planted with *Calliandra*, resulting in high investments. *Calliandra* can only be used for supplementation; the basal fodder of cattle still needs to come from other plants. A possible downside of cultivating all the edges with fodder plants could be negative edge-effects on crop production which could be exacerbated on small fields.

At village scale, the increased number of cattle should be accompanied by effective integrated soil fertility management, otherwise nutrient mining would lead to decline in production in feed producing areas. Implementation of such practices is not guaranteed, as farmers appear to prioritise manure for food production.

Many constraints are expected to appear when cattle would be given to smallholder farmers, especially for the poorest. For the programme to be successful, all recipients must be able to access sufficient fodder (Budisatria and Udo 2012), which will be a constraint in densely populated areas. Other necessary investments, such as the construction of a pen structure, might not be possible for the most resource-constrained farmers (Van den Berg 2009). The majority of poor farmers (71%) do not even possess sufficient land to qualify for participation in the programme (Uwimana 2010). Therefore, we suggest adjusting the programme and include the distribution of small animals, since these are more suitable for livestock programmes than large ruminants (Udo et al. 2011). Goats produce some income and can serve as capital saving (Budisatria and Udo 2012) and provide manure and meat. Even though of smaller livestock benefits might be less, requirements and investments are also less (Van den Berg 2009). Our research in Simbi showed that feed requirements of goats were far below those of cattle, with an average of 9-14 kg of fresh matter day^{-1}.

Conclusion

Whilst smallholder farmers use a wide variety of fodder types, the availability of fodder limits opportunities for livestock keeping and milk production in southwest Rwanda. Fodder availability differed strongly among farmers due to differences in available land-size and its productivity. The better-resourced farmers (RG 2 and RG 3) with larger farms grew more *Pennisetum*. The poorest farmers (RG 1) compensated the limited availability of *Pennisetum* by feeding more crop residues and uncultivated grasses and herbs. Our results indicate that RG 2 and RG 3 farmers are probably able to maintain a local or even an improved cow under specific scenarios, but for RG 1 farmers, who comprise 86% of the population, it seems impossible to keep either a local or improved cow.

Legume species, such as *Calliandra calothyrsus*, are still underutilised as fodder probably due to the limited farmer's knowledge of the high fodder quality of this shrub. Legume species such as *Calliandra* can supplement low quality fodder effectively and increase milk production (Paterson et al. 1999). The issue of fodder quantity and quality is also of importance in maintaining nutrient recycling through the livestock diet (Delve et al. 2001). In addition, *Calliandra* planted on field-edges was reported to be effective in maintaining soil fertility through biological nitrogen fixation (Nyaata et al. 2000). Further efforts are needed to develop strategies for effective integration of legume shrubs and trees into the livestock diet of dairy cattle. Intercropping of *Pennisetum* with leguminous fodder trees or shrubs could boost the quantity and quality of fodder production, especially during the dry season. The feasibility of on-farm fodder conservation strategies (hay-making of grasses and legumes) could also be explored to make use of possible surpluses produced during the rainy season.

The ‘One cow per poor family’ programme is a strategic spear point of the Government of Rwanda and an attempt to empower the most disadvantaged households. The programme is part of strategies to fulfil a long-term vision seeking to substantially reduce poverty rates in rural areas and to improve people’s nutrition (MINAGRI 2009). In 2000, the average land-surface available per Rwandan household was only 0.71 ha, even less compared with land availability during the eighties, when households possessed an average of 1.20 ha (Ansoms 2008). Combining this acute land-scarcity with the socio-economic conditions of the poorest smallholder farmers, our results suggest that the ‘One cow per poor family’ programme should be reviewed to increase its effectiveness. Under current conditions in Simbi, the poorest farmers, representing the majority of smallholders, are not expected to be able to produce a sufficient amount of fodder to maintain even local cattle. Land-scarcity makes the expansion of available land an unrealistic option and currently available land is much needed for food production. We recommend the livestock promoted as part of the programme should be changed to local cattle or goats that require less feed.

Chapter 7

General Discussion and Conclusions

Introduction

In this chapter, I synthesize my main findings and explore how the results can address major issues of farm productivity and food security within the smallholder farmer context of Rwanda. The results and the options for agroforestry explored in this thesis are then placed in the general context of smallholder farming across sub-Saharan Africa. A trade-off analysis is performed to understand opportunities for application of agroforestry techniques within mixed crop- livestock farming systems in the context of food self-sufficiency. Trade-offs for the use of agroforestry biomass production are analysed in a study case in which *Calliandra* biomass can be used either as green manure to improve soil fertility or as animal feed for improving milk production in smallholder farms. The future of agroforestry in farming system is discussed to highlight the direction that agroforestry development is likely to take in Rwanda, given the current pressing issues in the agricultural sector and in the light of the findings of this thesis.

Food security hurdles in sub-Saharan Africa

Food self-sufficiency is a major concern in most of sub-Saharan African countries and is being associated with several factors, including poverty and land degradation, as well as low crop productivity. In the case of Rwanda, the agricultural sector has been hampered by a number of factors including the scarcity of land, small farm size, overpopulation, poor productivity, and ineffective agricultural extension. Land continues to be a scarce resource and the per capita availability of arable land has gradually declined over time from 0.17 ha to 0.13 ha per household in the last 40 years (Fig. 7.1). High pressure on land and poor land management resulted in unsustainable production systems translating into low crop production and food shortage of households, particularly on farms with least resources (comparable to RG 1 farms of this thesis) as shown by the findings from this thesis (Chapter 2).

Alleviating constraints to the agricultural production is seen as a key strategy to boost food self-sufficiency in sub-Saharan Africa. The political will to tackle the issue of agricultural intensification was shown by the commitment of African heads of States to promote the use of mineral fertilizers in Abuja in 2006 (Vanlauwe et al. 2011). Rwanda has put into place ambitious plans for the transformation of agricultural sector in the country with the overall objective of boosting food self-sufficiency (MINAGRI 2009). Policies supporting agricultural intensification (intensive use of fertilizers inputs, promotion of agroforestry and crop-livestock integration, the 'One cow per each poor farm policy') are receiving much attention. These policies need to be supported by research that would advise on how best they can be implemented.

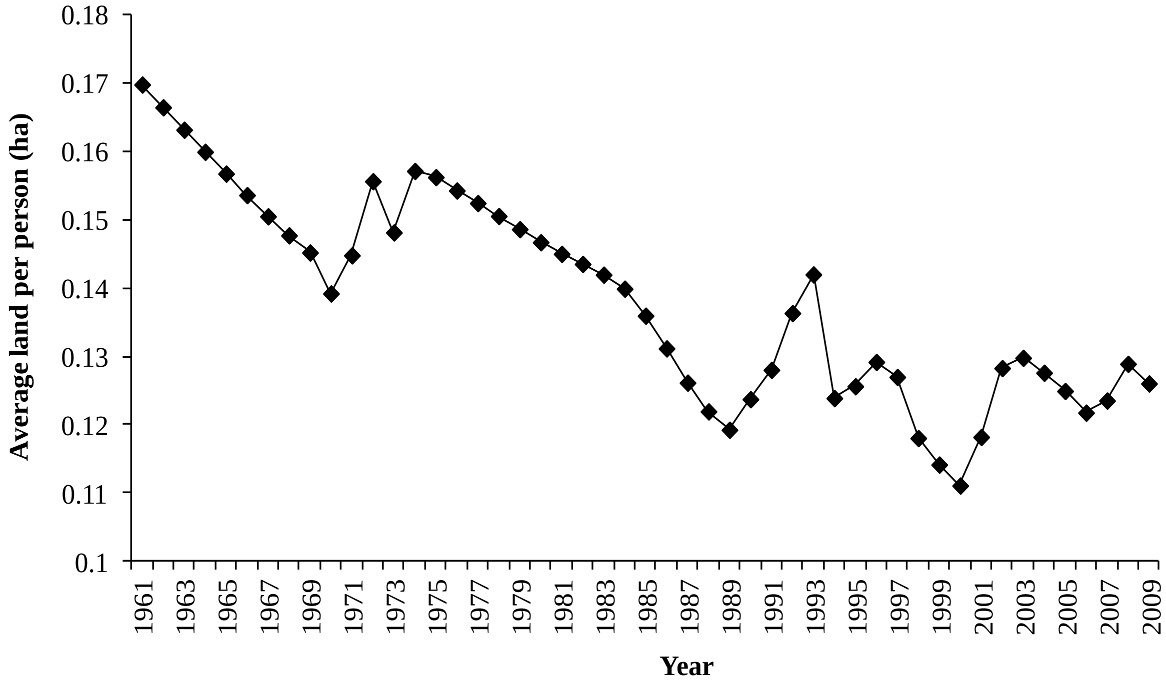


Figure 7.1 The average land area per household over time in Rwanda (World Bank, 2008)

Adapting research to the diversity in farming systems in sub-saharan Africa

Numerous studies in the last years have documented on the diversity of farming systems in sub-Saharan Africa (Giller et al. 2006; Ruthenberg 1980). In smallholder farms in East Africa, large differences in soil fertility status were found among fields even within farms as small as 1.5 ha

(Tittonell et al. 2005a). Biophysical factors (agro-ecological, season, soil fertility) and socioeconomic factors (farm size, household size, available labour, etc.) were shown to play a critical role in farmer's decision making.

The current study provides a hierarchical classification that zooms in to farm-level, based on a wealth grouping (Chapter 2). The approach contrasts with previous classifications of land use systems for Rwanda. These were in general based on biophysical factors (Delepierre 1974; Clay and Dejaegher 1987), generating a broad agro-ecological classification based on altitude, rainfall and temperature with little information on variability at farm scale. Our study contributed in developing and applying an approach that integrates biophysical and socioeconomic factors to help understanding the management aspects of households. Most households in the study areas are below the poverty line and are facing land and other resources scarcity, limiting significantly land productivity and compromising food self-sufficiency (Chapter 2). These households are priority beneficiaries of poverty reduction strategies (e.g. one cow for one poor family). Management decisions at farm scale are guided by both biophysical and socio-economic factors and may have an important impact on the resulting soil fertility and crop productivity (Giller et al. 2006).

Diversified agroforestry practices within farming systems

The results of the thesis indicated that choices and management of trees and shrubs vary widely in Rwanda and farmers have developed their own way of managing trees. This thesis applied a multidimensional approach (see Ojiem, 2006) to identify socio-ecological niches for integration of legumes in smallholder farming systems.

A thorough inventory of agroforestry trees/ shrub in the targeted study areas highlighted the wide diversity and varying density on farms from different farmer categories (Chapter 3) with greater tree diversity and density on large farms. The large number of trees on large farms may be related to more land being available (Chapters 2, 3) but also to other socio-economic traits that are particular to the RG 3 farmer. As farm size becomes smaller, farmers tend to select the most urgently needed species and to concentrate the few tree species they have on a small area, resulting in low diversity and high density systems. Similar to Rwanda, a wide diversity in agroforestry species/technologies has been recorded in other regions of the East African highlands (e.g. Fernandes et al. 1984 in Tanzania; Franzel et al. 2002 for Kenya).

In this thesis, a tree testing in Simbi and Kageyo locations indicated that farmers preferred the exotic fruit trees (*Persea americana* and *Citrus sinensis*) above other trees species in Simbi and Kageyo (Chapter 3). In broader context, people in tropical areas are familiar with indigenous fruit species (Sanchez et al. 1997), which are excellent sources of vitamin C that can reduce malnutrition (Akinnifesi et al. 2007). Beside nutritional aspects, agroforestry also plays a role in providing daily household needs such as firewood, stakes and other services such as soil conservation. The trees the farmers wanted most after the fruit trees, were trees for timber and firewood such as *Grevillea robusta* and *Eucalyptus* spp. Currently, firewood and charcoal supply energy for cooking to 92.2% of the population in rural areas and to 93.5% of the population in urban areas (Ndayambaje and Mohren 2011). Several surveys in Rwanda (e.g. AFRENA 1988; Den Biggelaar 1996) have reported that farmers may collect firewood on unsuitable tree species such as *Vernonia amygdalina*, *Euphorbia tirucalli* and *Ficus thonningii* and even from old fruit trees (Chapter 3, in this thesis), a clear indication of firewood shortage in the country and the need to promote and diversify firewood sources at the farm level. Stakes for climbing beans are important for smallholder farmers in Rwanda. Climbing beans are most prefered due to their better resistance to diseases (e.g. anthracnose and root rot) and pests (e.g. bean stem fly), high yielding ability (producing double to triple the yields of bush beans) and provision of green leaves that can beare consumed as vegetables. One of the constraints to the intensification of climbing beans is the lack of strong woody stakes that can last longer and be used several times contrary to other types of stakes. Given the current population growth rate of 3% on annual basis, it is anticipated there will be an increasing demand for woody products needed to support food production (*Eucalyptus* sp., and other species). Among the trees offered to farmers, the forage legume tree *Calliandra calothyrsus*, which also coppices well to produce stakes for beans, was preferred over *Tephrosia vogelii* which is used for catching fish or as an insecticide, and is promoted for improving soil fertility.

Despite major advantages of agroforestry shown in this thesis, a number of drawbacks are associated to agroforestry practices. Trees grown on farms compete with crops for water, nutrients and light if grown closely together. Farmers are generally aware of which trees might limit crop production therefore decide on specific locations to mitigate the competition effects. Other trees, although they can compete strongly with crops, can still be attractive to farmers because of their high market value. Furthermore, some agroforestry technologies may require substantial investment of labour. Farmers generally allocate their labour available to different tree species in accordance with their preferences. In Chapter 3, for example, fruit trees received more care (compost application, weeding and watering) than other species, demonstrating their importance for the farmers. Fruit trees were also planted close to the homestead where they could be better looked after. Trees for timber or firewood tended to be planted on field and farm margins or in woodlots, and the fodder trees on erosion control bunds. This showed that there are specific niches for different types of trees on farms. An agroforestry technology is most likely to be adopted if it is feasible, acceptable and profitable within the farmers' specific biophysical and socioeconomic context.

Potential of legume species for coffee production and economic profitability

Coffee has a great economic potential, both for individual smallholder farmers and for Rwanda as a nation. However, coffee growing areas and yields in Rwanda have steadily increased since its introduction in the 1905, before experiencing a dramatic decline due to war and the genocide of 1994. Major efforts by the government of Rwanda aimed at rehabilitating the coffee sector after 1994 emphasized the use of inputs and production of specialty coffee. These efforts are undermined by poor coffee production levels, partly due to poor soil fertility, low nutrient inputs and poor mulch quality. The lack of availability of mulch in some of the most important coffee producing areas has compromised coffee yield.

Although *Tephrosia vogelii* was among the trees least favoured by farmers in Chapter 3, I investigated whether the *Tephrosia* can be used to improve the availability of high quality mulch for coffee systems and thereby improve coffee production per unit area. *Tephrosia* was chosen for this purpose instead of *Calliandra* as it is easy to establish directly from seed in the field, and can readily be killed and removed. By contrast, *Calliandra* seedlings grow slowly and need to be propagated in a nursery, yet once established *Calliandia* coppices and may be hard to remove, thus potentially competing with coffee. The results showed that *Tephrosia* grew poorly on degraded outfield soils (Chapter 4). Fertiliser inputs may be necessary to stimulate N_2-fixation and accumulation of other nutrients into the plant. As a consequence, land where legumes would grow best and can make a significant contribution to soil fertility management is the land that farmers prefer to commit directly to the production of staple or cash crops. In the context of Rwanda where land is a scarce resource, mulch was best produced *in situ* between the coffee trees where the soils were relatively fertile due to the long-term mulching.

Tephrosia intercropped with coffee and *in situ* mulching was more profitable than *Tephrosia* mulch transfer. Other studies have reported advantages of intercrops in agroforestry over monocropping in terms of soil fertility improvement (Vandermeer 1988; 1990), enhancing agricultural productivity and financial and economic returns (Godoy and Bennett 1991). Better returns from intercrops are largely due to reduced labour costs and increased yield of the economic crops due to improvement of soil physical and chemical fertility. Our promising results on *Tephrosia* mulching in coffee systems can be generalised to highlands areas of Rwanda and more broadly to highland areas in East African countries where the agro-ecological conditions and soil fertility management are comparable. Beneficial effects of *Tephrosia* as green manure for maize have been reported from other East African countries (Gichuru, 1991;

Rutunga et al 1999; Baijukya et al. 2005), but do not know of previous studies that have used this species for mulching of coffee.

Other leguminous species can potentially be useful for production of mulch material. These include *Sesbania sesban*, *Leucaena diversifolia* and *Calliandra calothyrsus* that have been successfully tested in various farming systems in Rwanda (Yamoah et al. 1989). However, limitations related to low coppicing ability (e.g. *Sesbanian sesban*), and the need for pre-establishing seedlings in nurseries which requires extra labour, may discourage widespread use of these species by smallholder farmers. Species like *Calliandra* do have an advantage of being recognized as good fodder crops, which is the major reason they have become frequent species on smallholder farms in Rwanda. If grown for fodder, the biomass could also be used as mulch for food or cash crops.

Calliandra residues for maize crop improvement

Farming systems in sub-Saharan Africa are diverse, dynamic and highly heterogeneous. Soil fertility gradients are seen as a consequence of the allocation of nutrients to some fields at the expense of others (Chapter 2), thus making current fertiliser recommendations of limited use at the farm scale because of the large field to field variability. This suggests the need to make recommendations at small scale (field) level. This approach would help to increase the efficiency in resource use, which is the important objective of land use intensification

The results of Chapter 5 indicated that maize response to *Calliandra* residues was influenced by the agro-ecological zone where it is growing but also by the soil fertility at field level. Fields closer to the homestead responded better to fertilizer inputs than those located further away from the homestead. These results are in agreement with earlier findings which demonstrated that biophysical, socio-economic and farmer management are determining factors for production in smallholder farming systems of sub-Saharan Africa (Tittonell et al. 2008a).

The results also indicate that the level of resource use reflects the potential to increase crop productivity in smallholder farms. This is illustrated in the findings in Chapter 5, where N agronomic use efficiency (AE_N) and apparent N recovery (RE_N) were higher in infields than in outfields and the difference was enhanced by P fertiliser addition. Subsequently, maize productivity was much better on infields. Identifying the different responses of different fields or farms to fertiliser inputs would allow us to make a typology of fields or farms in accordance to response to nutrients supply that can subsequently facilitate fertiliser use recommendations.

Multiple roles of legume technologies in farming systems and their limitation in addressing soil fertility

Legumes species are well known for their multiple products and their N_2-fixation ability, the main reasons why they are recommended for low input systems (Giller 2001). In addition to N_2-fixation, extra nutrient capture by agroforestry species may also occur through other mechanisms (Nair, 1993; Sanchez et al. 1997). The contribution of legume shrubs in improving productivity may also be due to soil and water conservation. Additional benefits of legumes occur through increase and maintenance of organic matter. In Chapter 4, some beneficial effects of *Tephrosia* mulch as improving soil fertility technologies could partly be attributed to the physical effect of the mulch.

Legumes alone cannot address the entire soil fertility problem in sub-Saharan Africa, due to their limitation in provide sufficient nutrients other than nitrogen (for instance phosphorus, P) to the soils. Leafy biomass of trees has a low P content (Palm 1985). This is supported by the findings from this study (Chapter 4) that showed that low amounts of P are returned to the soil in *Tephrosia* mulch without NPK fertiliser inputs. As a consequence, the integration of organic materials with inorganic P fertilizers is essential to improve the availability of P in sub-Saharan soils where N and P have been recognized as the most common limiting nutrients (Giller et al. 1998).

Integrating legumes within crop-livestock subsistence smallholder farms, scenario analysis and impact on food self-sufficiency

Mixed crop–livestock systems constitute the backbone of agriculture sector in the tropics. As population density increases and less land becomes available, there is a general trend for crop and livestock activities to integrate. However, smallholder farms in SSA are faced with limited production resources which they need to allocate in a strategic way to generate the highest returns. Trade-offs in the allocation of the available resources to competing production activities are common within most of farms (Tittonell et al. 2007c). In order to increase farmer returns and advise on the best way resources should be used within the complex farming systems, trade-offs and scenario analyses of farmer objectives can be performed in simplified case studies (Tittonell et al. 2007c). Such analyses may allow us to formulate recommendations for extension officers and policy makers.

In this thesis, Chapters 5 and 6 dealt with *Calliandra calothyrsus* biomass as soil amendment and animal feeding separately. In each case the utility of the *Calliandra calothyrsus* biomass was clear – it is useful as green manure to stimulate maize production on poor soils (Chapter 5), and it is an important source of fodder for livestock (Chapter 6). Given the limited *Calliandra calothyrsus* resources that are available on smallholder farms, it is desirable to know what the best options of allocating the available *Calliandra* biomass are to reach farmers' objectives. We therefore conducted a simple trade-off analysis considering RG 1 and RG 2 farms selected from Umurera village (Simbi sector) where integrated crop and livestock farming activities take place with limited access to organic resources. These farmers therefore need to decide how they allocate these resources, as soil amendments or as livestock feed.

In this analysis, we analysed an RG 1 farm with a cow donated via the 'One cow one family scheme'. For the RG 1 farmer to keep a cow, he may need to plant 50 to 100% of the available field-edges with *Calliandra calothyrsus*. We assume that 50% of the field-edges is planted with *Calliandra calothyrsus* due to the limited available land (123 m of the 246 m of the total edge length available). The *Calliandra* biomass production will then be 419 kg DM year^{-1}. For an RG 2 farm, we consider the observed average edge length planted with *Calliandra* (Chapter 6). The available edge length was 762 m with an estimated 20% of the total edge length under *Calliandra* (152 m), translating into a biomass production of 516 kg DM year^{-1}. The maize crop is fertilised with *Calliandra* combined with a little P in the analysis. The maize yield response to *Calliandra* biomass addition in RG 2 farms was quantified (Figure 7.1a) using the QUEFTS model (Jansen et al. 1990, see Chapter 5). The relationship between milk production and the rates of additional *Calliandra* biomass in the diet (Figure 6.1b) was based on data from Chapter 6. The total lactation period was estimated at 5 months in Simbi. The objectives analysed in the trade-off analysis were farm profitability and household food security; gross profitability and the amount of protein produced were used as indicators. Total protein from milk was estimated by multiplying the total volume of milk by 3.3% (Cerbulis and Farrell 1975), assuming a milk density of 1.03 kg L^{-1}. Total protein from maize grains was obtained using the same procedure as in Chapter 2 (Table 2.8). Gross profit was calculated by multiplying the total milk and maize yield by the price on the local market (0.3 US$ kg for maize and 0.25 US$ L^{-1} for milk).

Trade-offs and scenario analysis

Trade-off and scenarios analysis were conducted by progressively decreasing the amount of *Calliandra* fed to livestock (100 to 0%) while increasing *Calliandra* biomass applied to soils (0 to 100%). The scenarios analysed were as follows:

1) 100% of *Calliandra* biomass allocated to livestock feeding and nothing to soils
2) 75% of *Calliandra* biomass allocated to livestock feeding and 25% to soils
3) 50% of *Calliandra* biomass allocated to livestock feeding and 50% to soils
4) 25% of *Calliandra* biomass allocated to livestock feeding and 75% to soils
5) No *Calliandra* biomass allocated to livestock feeding and 100% to soils

Under the scenarios of decreasing amounts of *Calliandra* allocated to animal feed, there was a substantial reduction in milk production from 310 to 45 litres farm^{-1} in the RG 2 farm and from 260 to 45 litres farm^{-1} in the RG 1 farm over the five month lactation period (Fig. 7.2a). On the other hand, increasing the rate of *Calliandra* application to the soil from 0 to 516 kg, resulted in increases in maize yields, from 582 to 658 kg farm^{-1}yr^{-1} with P application and from 409 to 472kg farm^{-1}yr^{-1} without P application in the RG 2 farm. Similarly, an increasing amount of *Calliandra* biomass allocated to the soil (0 to 419 kg farm^{-1}) resulted in increased maize yield from 197 to 344 kg farm^{-1}yr^{-1} when P was added and from 128 to 259 kg farm^{-1}yr^{-1} without P in RG 1 farms (Fig. 7.2b). With *Calliandra* feeds decreasing from 516 to 0 kg, the contribution of protein was reduced from 9.30 kg farm^{-1}yr^{-1} to 1.37 kg farm^{-1}yr^{-1} in RG 2 and from 7.80 to 1.37 kg farm^{-1}yr^{-1} in RG 1 farms. By contrast, increasing the *Calliandra* residues rate allocated to soils resulted in an increase in the contribution of protein by maize from 52.3 to 59.2 kg farm^{-1}yr^{-1} with P and from 36.7 to 42.5 kg farm^{-1}yr^{-1} without P in RG 2 farm (Fig. 7.3a). In RG 1, increasing *Calliandra* residues allocated to soils gave an increase of protein by maize from 17.7 to 31.0 kg farm^{-1}yr^{-1} with P and from 11.4 to 23.2 kg farm^{-1}yr^{-1}. In RG 1 farm, the contribution of protein by maize crop was the highest with 100% of *Calliandra* allocated to the soil (31.0 kg farm^{-1} with P and 23.2 kg farm^{-1} without P) (Fig. 7.3a). Under all scenarios, *Calliandra* allocated to soils gave a higher financial return than the same amount of *Calliandra* allocated to livestock feeding.

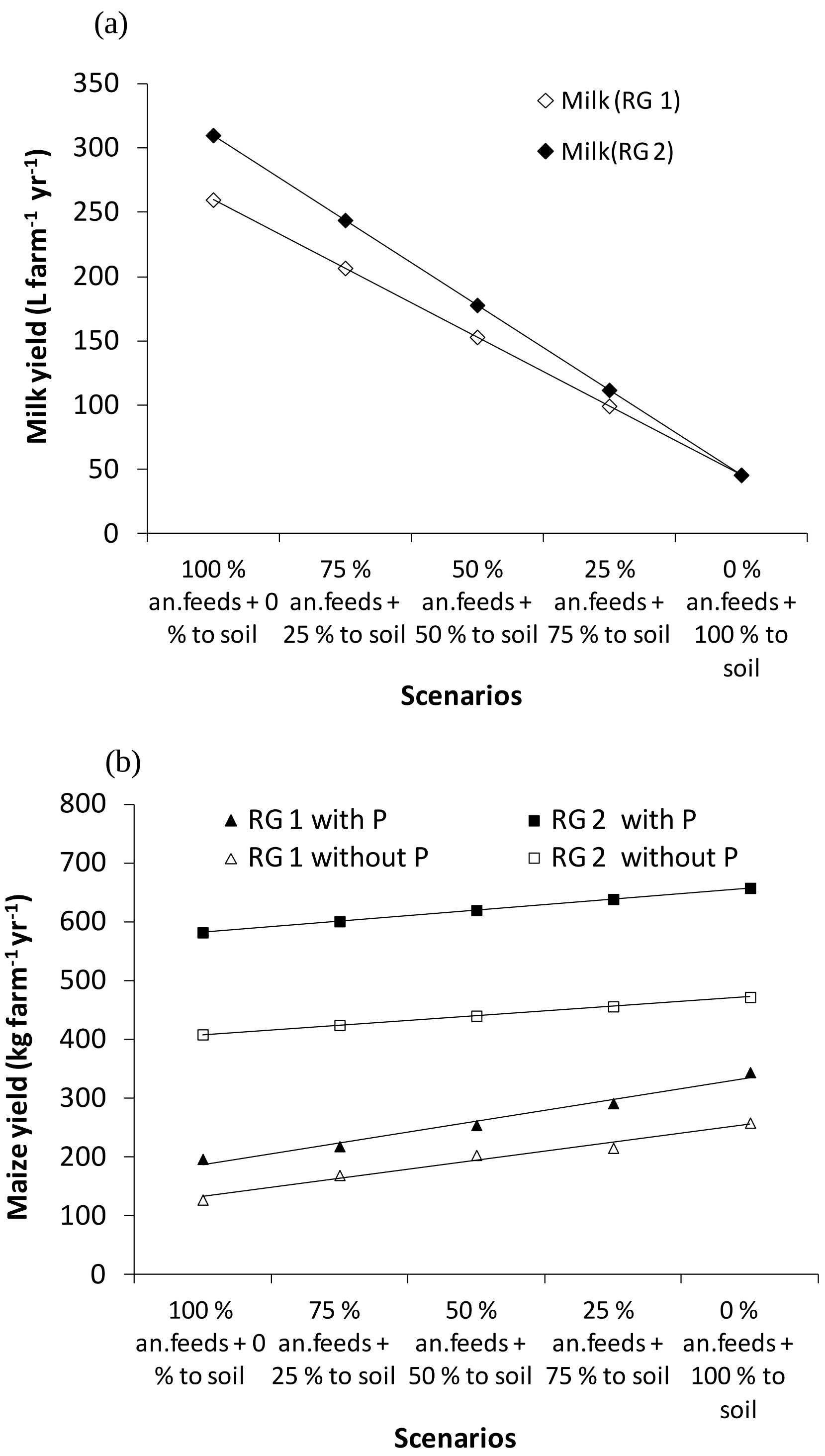
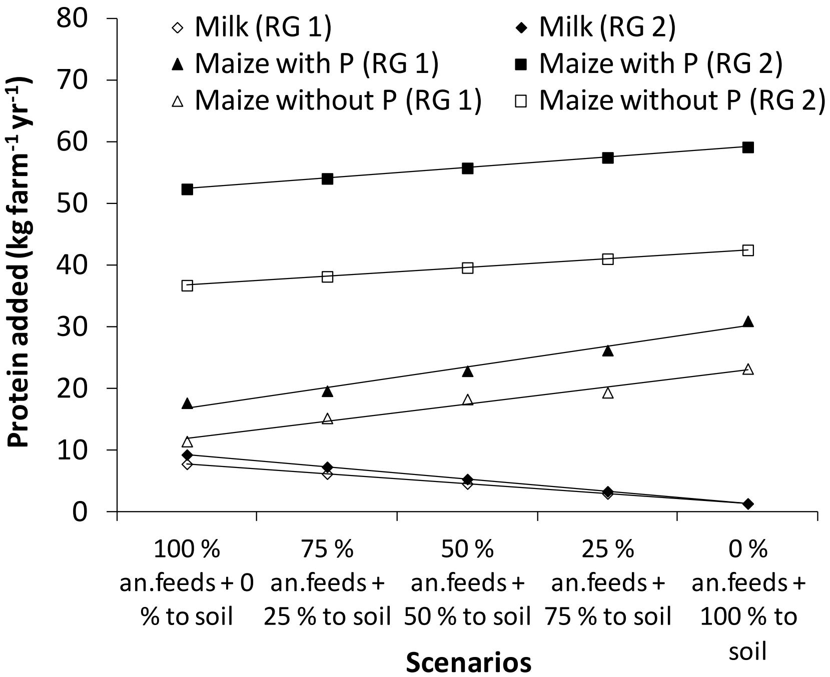


Figure 7.2 Milk yield (a) and maize yield (b) as function of *Calliandra* biomass added under different scenarios in RG 1 and RG 2 farms. The amount of available *Calliandra* was estimated at 638 kg ha^{-1} year^{-1} in RG 2 and 418 kg ha^{-1} year^{-1} in RG 1 farm. 1: 100% of *Calliandra* allocated to animal feeding and nothing to soil, 2: 75% of *Calliandra* allocated to animal feeding and 25% to soils, 3: 50 % of *Calliandra* allocated to animal feeding and 50% to soils, 4: 25% of *Calliandra* biomass allocated to animal feeding and 75% to soils and 5: 100% of *Calliandra* allocated to soils and nothing to animal feeding.

(a)



(b)

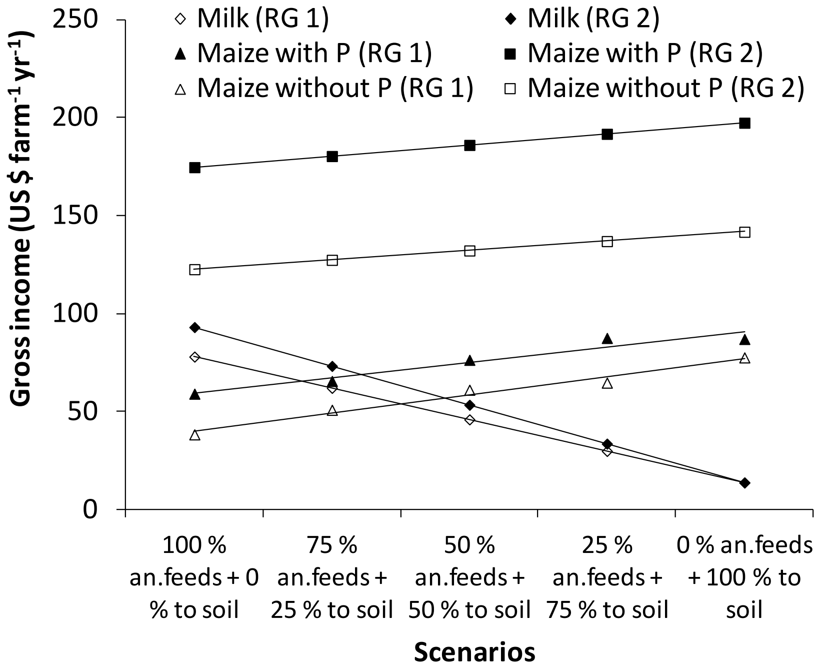


Figure 7.3 Protein added (a) and gross income (b) as function of *Calliandra* biomass added under different scenarios in RG 1 and RG 2 farms. The amount of available *Calliandra* was estimated at 638 kg ha^{-1} year^{-1} in RG 2 and 418 kg ha^{-1} year^{-1} in RG 1. 1: 100% of *Calliandra* allocated to animal feeding and nothing to soil, 2: 75% of *Calliandra* allocated to animal feeding and 25% to soils, 3: 50 % of *Calliandra* allocated to animal feeding and 50% to soils, 4: 25% of *Calliandra* biomass allocated to animal feeding and 75% to soils and 5: 100% of *Calliandra* allocated to soils and nothing to animal feeding.

For the RG 1 farm level returns were highest when 50 % of *Calliandra* was allocated to soils (60 to 76 US \$ farm^{-1} for maize). In the RG 2 farm, farm level returns were highest when 100% of *Calliandra* was applied to crop production together with application of with P (197 US \$ farm^{-1}) (Fig. 7.3b). These returns were larger than those when all of *Calliandra* was allocated to livestock feeding (197 US \$ farm^{-1}). Allocating *Calliandra* to the soil appears to be the most profitable in both RG 1 and RG 2 farms (Fig. 7.3b). Allocating *Calliandra* to livestock feeding is not as profitable due to poor milk production and the currently low market prices of milk. The trade-off analysis showed that the best use of the available *Calliandra* biomass will depend on the type of farm and fertilizer used in maize production. Limited maize production and the subsequent smaller contribution in terms of protein and income are due to small farm size and limited amount of *Calliandra* biomass production.

Future of agroforestry in farmer practice and agricultural research

The government commitment to agroforestry and the establishment of enabling policies should result in future implementations of agroforestry development and expansion programs in Rwanda. The approach to execute these policies will certainly have to be scaled down to local or community level. Two major reasons may justify this approach. Firstly, the limited land does not make provision of sufficient land for large scale reforestation. Secondly, a recent study indicated that forests as smaller than 0.01 ha constitute the source of wood products for the majority of the population in Rwanda (Nduwamungu et al. 2007), showing a tendency to increase the integration of the tree component into the cropping lands and to increase the relative importance of agroforestry.

Given the multiple and diversified agroforestry needs, research on agroforestry should focus on different suitable species and make several options available to farmers. Limiting research on few or little number of tree species or technologies will limit the farmer's need to choose in accordance to his/her preferences and the constraints he/she is facing. Both exotic and endogenous species should equally receive attention. To achieve this, a closer collaboration between farmers/beneficiaries and researchers is needed in which together problems and opportunities are identified and solutions are developed.

Implications for policies

The results of the thesis highlight the importance of agroforestry technologies in addressing food production and economic profitability in cases where access to organic and mineral fertilisers is problematic. Agroforestry/forestry is an important component in the current efforts to alleviate poverty and enhance food self-sufficiency in Rwanda (Ministry of Forestry and Mines 2010). The findings from this PhD study calls for more critical re-thinking towards matching the conceptual policies and the feasibility of implementation. We identify a number of issues that have implications for policy formulation.

1. Participatory approaches offer opportunities for local people and communities to identify, assess and implement their priorities for growing trees. The implementation of these approaches may generate a more reliable and certainly a more relevant research agenda. It is our view that agricultural policies should adopt a more farmer or community centered-approach and should engage more the potential beneficiaries.
2. Findings from this study demonstrated the influence of biophysical, socio-economic and farm management related factors on the choices the farmer makes with regard to agroforestry options. Furthermore, these factors play a critical role in the performance of technologies on different farms. The findings imply that researchers and extension workers should consider multiple goals and needs of farmers, and differences in resource availability when identifying the pool of options. Clear policies supporting integrating approaches in agroforestry and a link up with other policies should allow extension services to have diversified technologies options for dissemination.

3. Fruit trees were the most preferred by all farmers, an indication that these tree species should be given more research attention since they may contribute directly to increasing food self-sufficiency and reducing poverty. There is a need to revisit the agroforestry policy and make adequate adjustments as far as priority tree species are concerned.
4. The national forestry policy advised expanded use of multipurpose nitrogen-fixing species, but which species should be used and whether these legume species are appropriate for a systematic dissemination to the entire rural community remain unanswered questions. *Calliandra calothyrsus* was found to be popular with farmers with dairy cattle (Chapter 5), indicating that farmers are aware of the importance of *Calliandra* in enhancing milk productivity. However, the average number of *Calliandra* shrubs per farm was in the range of 19 to 125 while 250 shrubs are required to feed a single cow every day throughout the year (Chapter 6). This indicates the need for the extension services to promote more *Calliandra* and other legume species to boost on-farm milk production, in the anticipation of the growing dairy farming following the possible future implementation of the "One cow one poor family". Given the constraints on land for fodder provision, perhaps more attention should be given to promoting small ruminants such as goats and sheep, which also have the advantage that they reproduce more prolifically than cows (Udo et al. 2011).
5. Our results indicate that farmers with large farms (RG 3) that include woodlots and forest (especially in Kageyo) have a preference for timber tree species. Despite their benefits, *Eucalyptus* plantations in Rwanda have come under increased criticism from politicians and environmentalists in relation to potential negative environmental impacts. Some of the decision-makers are even suggesting uprooting and prohibiting the species in the country (Nduwamungu et al. 2007). We suggest that more extensive research should be undertaken on different *Eucalyptus* species to establish to what extent these species compete with crops in different agro-ecological zones and under different hydrological conditions, in order to

come up with valid recommendations before making drastic decisions regarding these species that are popular among farmers.

Concluding remarks

The hypothesis underlying this study was that: “on-farm agroforestry practices differ among farms and farming systems because of differing biophysical, socio-economic conditions and specific farmer preferences”. A corollary hypothesis stated that “farmers testing the same agroforestry technology (i.e. the same tree species) within similar or different agro-ecological zones would achieve different results”. Our analysis provided evidence of diversity of farms, fields within farms in different agro-ecological zones of Rwanda in terms of biophysical and socio-economic conditions that significantly influence resource management and crop production at the farm level (Chapter 2). Both biophysical and socioeconomic conditions determined farmer’s decision to invest in agroforestry (Chapter 3), influenced crop response to fertiliser inputs (Chapter 5) and the capacity of farmers to maintain livestock in a mixed crop-livestock farming system (Chapter 6). Therefore the research hypothesis was supported.

A multifaceted approach including combinations of techniques (surveys, focus group discussion, on-farm testing and trade-off analysis) was used for this study. Participatory approaches as the basis of the multidimensional approach aim at engaging both researchers and farmers with the intention of blending views from both partners in research towards the betterment of productivity of farming systems productivity.

Agroforestry is not a panacea, but part of a set of options that, in combination with other technologies may contribute to addressing the poor soil fertility and lack of livestock feed on smallholder farms. However the limited agroforestry resources may not be sufficient to satisfy each and every farmer’s needs. The trade-off analysis provided options that may potentially support feedback and discussion with farmers on their best options to generate more income and to ensure food self-sufficiency on different farms, and also support policy makers in deciding how best to support investments in agricultural development. Further scenario analysis is required for a more comprehensive study of the options available and to better fit agroforestry to the socio-ecological settings within different agro-ecological zones.

References

Abate, A., Dzowela, B.H., Kategile, J.A. 1992. Intensive animal feeding practices for optimum feed utilization. In: Kategile, J.A. and Mubi, S. (Eds.), Future of Livestock Industries in East and Southern Africa. International Livestock Centre for Africa, Addis Ababa, pp.9–19.

Abdulai, A., Barret, C.B., Hazell, P. 2004. Food aid for market development in su-saharan Africa. DSGD Discussion paper N°5. Development strategy and Governance Division International Food Policy Research Institute (IFPRI). Washington, D.C. 20006 U.S.A. 56 p.

Akinifessi, F.K., Chirwa, P.W., Ajayi, O.C., Sileshi, G., Matakala, P., Kwesiga, F.R., Harawa, H., Makumba, W. 2008. Contributions of agroforestry to livelihood of smallholder farmers in Southern Africa: Taking Stock of the Adaptation, adoption and Impact of Fertiliser Tree options. Agricultural Journal 3: 58–75.

Anderson J.M., Ingram J.S.I. 1993. Tropical Soil Biology and Fertiliser: A Handbook of Methods. CAB International, Wallingford, UK.

Ansoms, A. 2008. Striving for growth, bypassing the poor? A critical review of Rwanda's rural sector policies. Journal of Modern African Studies 46: 1–32.

Armstrong, E. L., Heenan, D. P., Pate, J. S., Unkovich, M. J. 1997. Nitrogen benefits of lupines, field pea and chickpea to wheat production in south-eastern Australia. Australian Journal of Agricultural Research 48:39–47.

Azam-Ali, S. N., Squire, G. R. 2002. Principles of Tropical Agronomy. Wallington: CAB International.

Balasubramanian, V., Egli, A. 1986. The role of agroforestry in the farming systems in Rwanda with special reference to the Bugesera-Gisaka-Migongo (BGM) region. Agroforestry Systems 4:271–289.

Balasubramanian, V., Sekayange, L. 1992. Five years of research on improved fallow in the semi-arid highlands of Rwanda. In: Mulongoy K, Gueye M, Spencer DSC (eds) Biological Nitrogen Fixation and Sustainability of Tropical Agriculture, Wiley & Sons, Chichester, pp 405–422.

Baligar, V. C., Fageria N. K., He, Z. L. 2001 Nutrient use efficiency in plants. Communication in Soil Science and Plant Analysis 32:921–950.

Baijukya, F. P., de Ridder, N., Giller, K. E. 2005. Managing legume cover crops and their residues to enhance productivity of degraded soils in the humid tropics: a case study in Bukoba District, Tanzania. Nutrient Cycling Agroecosystems 73:75–87

Barnes, D. K., Freyre, R. H. 1965 Recovery of natural insecticide from *Tephrosia vogelii*. II Toxicology properties of rotenoids extracted from fresh and oven-dried leaves. Economic Botany 21: 93–98.

Bee, J. K., Msanga, Y.N., Kavana, P.Y. 2006. Lactation yield of crossbred dairy cattle under farmer management in Eastern coast of Tanzania. Livestock Research and Rural Development. Retrieved on March 27, 2012, from http://www.lrrd.org/lrrd18/2/bee18023.htm

Bene, J.G., Beall, W.H., Cote, A. 1977 Tree Food and People – Land Management in the Tropics. International Development and Research Centre, Ottawa.

Bourke, M.R. 1985. Food, coffee and Casuarina: An agroforestry system from the Papua New Guinea Highlands. Agroforestry Systems 2: 273–792.

Brady, N.C., Weil, R.R. 2002. The nature and Properties of Soils. Thirteenth Edition. Prentice Hall, New Jersey, 653pp.

Bucagu, C., Vanlauwe, B., van Wijk, M.T., Giller, K.E. 2013. Assessing farmers' interest in agroforestry in two contrasting agro-ecological zones of Rwanda. Agroforestry Systems 87: 141-158.

Budisatria, I.G.S and Udo, H.M.J., 2012. Goat-based aid programme in Central Java: An effective intervention for the poor and vulnerable? Small Ruminent Research (*in press*)

Cerbulis, J., Farrell, H.M. Jr. 1975. Composition of milk of Dairy Cattle. I. Protein, Lactose, and fat contents and distribution of proteins fraction. Journal of Dairy Science, 58: 817–827

Clay, D.C., Dejaegher, Y. 1987. Agro-Ecological Zones: The Development of a Regional Classification Scheme for Rwanda. Tropicultura, December.

Crowley, E. L. 1997. Rapid data collection using wealth ranking and other techniques. International Centre for Research in Agroforestry/Tropical Soils Biology and Fertility Program. Nairobi.

Crowley, E. L., Carter, S. 2000. Agrarian Change and the Changing Relationships Between Toil and Soil in Maragoli, Western Kenya (1900–1994). Human Ecology 28: 383–414.

Cleaver K. M., Schreiber, G. A. 1994. Reversing the spiral; the population, agriculture and environment nexus in sub-Saharan Africa World Bank. Washington. 293 pp.

de Graaff, J., 1986. The economics of coffee. In: Centre for Agricultural Publishing and documentation (Pudoc) (Eds.), Economics of Crops in Developing Countries N°1, Wageningen, pp. 180–223.

de Graaff, J., Kessler, A., Nibbering, J.W. 2011. Agriculture and food security in selected countries in Sub-Saharan Africa: diversity in trends and opportunities. Food security 3: 195-213.

De Groote, H., Rutto, E., Odhiambo, G., Kanampiu, F., Khan, Z., Coe, R.,Vanlauwe, B. 2010 Participatory evaluation of integrated pest and soil fertility management options using ordered categorical data analysis. Agricultural Systems 103: 233-244.

De Jager, A. 2005. Participatory technology, policy and institutional development to address soil fertility degradation in Africa. Land Use Policy 22: 57–66.

De Wit, C.T. 1992. Resource use efficiency in Agriculture. Agricultural Systems 40: 125–151

den Biggelaar, C., 1994. Farmer Experimentation and Innovation. A case study of knowledge generation processes in agroforestry systems in Rwanda. PhD thesis. Department of Forestry. Michigan State University, East Lansing, Michigan, pp 1–20.

den Biggelaar C., Gold, M. A. 1995. The use and value of multiple methods to capture the diversity of endogenous agroforestry knowledge: an example from Rwanda. Agroforestry Systems 30: 263–275.

den Biggelaar, C., Gold, M. A. 1996. Development of utility and location indices for classifying agroforestry species: the case of Rwanda. Agroforestry Systems 34: 229–246.

Delepierre, P. 1974. Notes techniques. Institut des Sciences Agronomiques du Rwanda. N°13. Rubona, Rwanda.

Delve, R. J., Cadisch, G., Tanner, J. C., Thorpe, W., Thorne, P. J., Giller, K. E. 2001. Implications of livestock feeding management on soil fertility in the smallholder farming systems of sub-Saharan Africa. Agriculture Ecosystems and Environment 84 : 227–243.

Djimde, M. 1988. Potentiel agroforestier dans les systèmes d'utilisation des sols des hautes terres d'Afrique de l'Est à régime pluviométrique biomodal. Rapport AFRENA, 1. ICRAF, Nairobi

Drechsel, P., Steiner K., Hagedorn, F. 1996. A review on the potential of improved fallows and green manure in Rwanda. Agroforestry Systems 33:109–136.

Ebanyat, P., de Ridder, N., de Jager, A., Delve, R. J., Bekunda, M. A., Giller, K.E. 2010. Drivers of change in land use and household determinants of sustainability in smallholder farming systems in eastern Uganda. Population and Environment 31: 474-506

Evans, T. R., 1968. Source of nitrogen for beef production in the Wallum. Tropical Grasslands 2, 192–115.

Fagerström, M. H. H., van Noordwijk, M., Phien, T., Cong Vinh, N. 2001. Innovations within upland rice-based systems in northern Vietnam with *Tephrosia candida* as fallow species, hedgerow, or mulch: net returns and farmers' response. Agriculture Ecosystems and Environment 86, 23–37.

Fageria, N. K. 1992. Maximizing Crop Yields. New York: Marcel Dekker.

Felius, M., 1985. Genus *Bos*: Cattle breeds of the world MSD-AGVET (Merck & Co.), Rahway, New Jersey, 234 pp.

Fernandes, E., Oktingati, A., Maghembe, V. 1984. The Chagga homegardens: a multistoried agroforestry cropping system on Mount Kilimanjaro (northern Tanzania). Agroforestry Systems 2, 73-86.

Ffoulkes, D., Preston, T.R., 1978. The banana plant as cattle feed: digestibility and voluntary intake of different proportions of leaf and pseudo-stem. Tropical Animal Health and Production 3, 114–117.

Franzel, S. 2001. Use of an Indigenous Board Game, ‘bao’ for Assessing Farmers’ Preferences Among Alternative Agricultural Technologies. In Franzel S, Scherr SJ (Ed) Trees on the farm. Methods for Assessing Agroforestry Adoption Potential. CAB Publishing in association with ICRAF. Nairobi, Kenya, pp 11–35

Franzel, S., Ndufa, J. K., Obony, O. C., Bekele, T. E., Coe, R. 2002. Farmer-designed Agroforestry Trials: Farmers’ Experiences in Western Kenya. In Franzel S, Scherr SJ (Ed) Trees on the farm. Assessing the adoption potential of Agroforestry Practices in Africa. CAB Publishing in association with ICRAF. Nairobi, Kenya, pp 89–110

Fungameza, D. B. 1991. Agroforestry and eco-farming practices for soil conservation in Kigoma, Tanzania. PhD dissertation. Georg-August-University of Göttingen, Göttingen, 264 pp

GenStat® Discovery Edition 3. 2009.VSN International Ltd. Lawes Agricultural Trust. Rothamsted Experimental Station, Hertfordshire

Gicumbi DDP. 2007. Gicumbi District Development Plan 2008-2012. Gicumbi. Kigali, Republic of Rwanda.

Gichuru M.P. 1991. Residual effect of natural bush, *Cajanus cajan* and *Tephrosia candida* on the productivity of an acid soil in Southeastern Nigeria. Plant and Soil 134, 31–36.

Giller K.E. 2001. Nitrogen fixation in tropical cropping systems. 2nd edition. CAB International, Wallingford.

Giller, K. E., Cadish, G. 1995. Future benefits from biological nitrogen fixation: An ecological approach to agriculture. Plant and Soil 174:255–277.

Giller, K. E., Cadisch, G., Ehaliotis, C., Adams, A., Sakala, D., Mafongoya, P. L. 1997. Building soil nitrogen capital in Africa. In: Buresh, R.J., Sanchez, P.A., Calhoun, F. (Eds.), Replenishing Soil Fertility in Africa. SSSA Special Publication, N^{o}51, Madison, Wisc., USA.

Giller, K.E., Amijee, F., Brodrick, S.J. and Edje, O.T. 1998. Environmental constraints to nodulation and nitrogen fixation of Phaseolus vulgaris L. in Tanzania. II. Response to N and P fertilizers and inoculation with Rhizobium. African Crop Science Journal 6: 171-178

Giller, K. E., Rowe, E. C., de Ridder, N., van Keulen, H. 2006. Resource use dynamics and interactions in the tropics: Scaling up in space and time. Agricultural Systems 88: 8–27.

Cleaver, K. M., Schreiber, G. A. 1994. Reversing the spiral; the population, agriculture and environment nexus in sub-Saharan Africa. World Bank, Washington

Godoy, R., Bennett, C. P. A. 1991. The Economics of Monocropping and Intercropping by Smallholders: The Case of Coconuts in Indonesia. Human Ecology 19: 83-98

Godfray, H. C. J., Beddington, J. R., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., Pretty, J., Robinson, S., Thomas, S. M., Toulmin, C. 2010. Food Security: The Challenge of Feeding 9 Billion People. Science 327: 812–818.

Grandin, B. 1988. Wealth Ranking in Smallholder Communities: A Field Manual. Intermediate Technology Publications. Nottingham, UK.

Grote, U., Craswell, E., Vlek, P. 2005. Nutrient flows in international trade: Ecology and policy issues. Environmental Science & Policy 8: 439–451.

Hagedorn, F., Steiner, K. G., Sekayange, L., Zech, W. 1997. Effect of rainfall pattern on nitrogen mineralization and leaching in a green manure experiment in South Rwanda. Plant and Soil 195: 365-375.

Hall, A., Sulaiman, R. V., Bezkorowajnyj, P. 2008. Reframing technical change: Livestock fodder scarcity revisited as innovation capacity scarcity - A conceptual Framework. Systemwide Livestock Programme, in: In Lukuyu, B. A., Kitalyi, A., Franzel, S., Duncan, A. and Baltenweck, I. (Eds), Constraints and options to enhancing production of high feeds in dairy production in Kenya, Uganda and Rwanda, ILRI, Nairobi, 31 pp.

Hatungumukama, G., Sidikou, D. I., Leroy, P., Detilleux, J. 2006. Effects of non-genetic and crossbreeding factors on daily milk yield of Ayrshire x (Sahiwal x Ankole) cows in Mahwa station (Burundi). Livestock Science 110: 111–117.

Hauser, S., Van Asten, P. 2008. Methodological considerations on banana (*Musa* spp.) yield determinations, in: Dubois, T., Hauser, S., Staver, C., Coyne, D (Eds). Harnessing International partnerships to increase research impact. Proceeding of an International Conference on Banana and Plantain in Africa. Kampala, Acta Horticulturae 433–444.

Heisey, P. W., Mwangi, W. 1996. Fertiliser use and maize production in sub-Saharan Africa. CIMMYT Economic Working Paper 96-01. CIMMYT, Mexico, D.F., 35 pp.

Houngnandan, P., Sanginga, N., Okogun, A., Vanlauwe, B., van Cleemput, O. 2001. Assessment of soil factors limiting growth and establishment of mucuna in farmer's fields in the derived savanna of Benin Republic. Biology and Fertility of Soil 33:416–422

Huye DDP. 2007. Huye District Development Plan 2008-2012. Butare. Kigali, Republic of Rwanda.

ICRAF/ISAR/ECA. 2001. National Workshop on Agroforestry Research and Development strategic Plan. Building and Strengthening Partnerships for Scaling up the Impact of Agroforestry Research and Development. Kigali, Rwanda. 25-45 pp.

Ikpe, F. N., Owoeye, L. G., Gichuru, M. P. 2003. Nutrient recycling potential of *Tephrosia candida* in cropping systems of southeastern Nigeria. Nutrients Cycling in Agroecosystems 67: 129–136

ISAR 2011. Official website of Rwanda Agricultural Research Institute. Crop Production Unit. Maize research program. Rubona. Butare. Consulted on March, 6th, 2012.

Janke, H. K. 1992. Livestock production systems and livestock development in tropical Africa. ILCA, Addis Ababa, 253 pp.

Janssen, B. H. 1998. Efficient use of nutrients: an art of balancing. Field Crop Research 56: 197–201

Janssen, B. H. 2007. Report on a follow-up advisory mission on soil and plant analysis and integrated soil fertility management to Tanzanian Coffee Research Institute (TaCRI), Lyamungu (Moshi), Tanzania, 74pp

Janssen, B. H. 2011. Simple models and concepts as tools for the study of sustained soil productivity in long-term experiments. II. Crop nutrient equivalents, balanced supplies of available nutrients, and NPK triangle. Plant and Soil 339: 17–33

Janssen, B. H., Guiking, F. C. T. 1990. Modeling the response to crop to fertilizer**s.** In van Beusichem, M.L. (Ed), Plant nutrition-physiology and applications. Kluwe Academic Press, Dordrecht, pp. 699-703

Janssen, B. H., Guiking, F. C. T., van der Eijk, D., Smaling, E. M. A., Wolf, J., van Reuler, H. (1990). A system for quantitative evaluation of the fertility of tropical soils (QUEFTS). Geoderma 46: 299-318

Jones, P.G., Thornton, P.K. 2003. The potential impacts of climate change in tropical agriculture: the case of maize and Latin America in 2055. Global Enviornment Change 13: 51-59

Juma, H. K., Abdulrazak, S. A., Muinga, R.W., Ambula, M. K., 2006. Evaluation of *Clitoria*, *Gliricidia* and *Mucuna* as nitrogen supplements to Napier grass basal diet in relation to the performance of lactating Jerseys cows. Livestock Science 103, 23–29.

Kalinganire, A. 1996. Performance of *Grevillea robusta* in plantations and on farms under varying environmental conditions in Rwanda. Forest Ecology and Management 80: 279–285.

Kalinganire, A., Zuercher, E. 1996. Provenance Trials of *Grevillea robusta*: interim results. In Harwood, CE (Ed) *Grevillea robusta* in Agroforestry and Forestry. Proceedings of an international Workshop. ICRAF, Nairobi, Kenya, 190 pp.

Karanja, D., Endire, S.G., Ruraduma, C., Kimani, P.M., Kweka, S.O. and Butare, L. 2011. Value Added Bean Technologies for Enhancing Food Security, Nutrition, Income and Resilience to cope with Climate Change and Variability Challenges in Eastern Africa. Nairobi, Kenya, ILRI.

Kang, B.T., Wilson, G.F., Sipkens L. 1981. Alley cropping maize and *Leucaena leucocephala* Lam. in Southern Nigeria. Plant and Soil 63: 165–179.

Kelly, V., Murekezi, A. 2000. Fertiliser response and profitability in Rwanda. A synthesis of findings from MINAGRI studies conducted by The food Security Research Project (FSRP) and The FAO Soil Fertility Initiative. Ministry of Agriculture, Animal Resources and Forestry. Republic of Rwanda.

Khalili, H., Varvikko, T. 1992. Effect of replacing concentrate mixture by wilted *Sesbania* forage on diet digestibility, rumen fermentation and milk production in Frieshian × Zebu crossbred cows fed low quality native hay. Animal Feed Science and Technology 36: 275-85.

King, K. F. S. 1989. The history of agroforestry. In Nair PKR (Ed) Agroforestry Systems in the tropics, Kluwer Academic Publishers in collaboration with ICRAF, Volume 31, The Netherlands, pp 3–11.

Klaer, W., Konig, D., Mutwewingabo, B. 1993. Agroforestry au Rwanda, Actes du seminaire-atelier sur l'agroforesterie au Rwanda du 24 au 27 Novembre 1992. NUR/Université Johannes Gutenberg de Mayence/Rhenanie Palatinat

König, D. 1992. The potential of agroforestry methods for erosion control in Rwanda. Soil Technology 5: 167–176.

Lal, R. 2010. Beyond Copenhagen: mitigating climate change and achieving food security through soil carbon sequestration. Food security 2: 169–177

Lanyasunya, T. P., Wang, H. R., Mukisira, E. A., Abdulrazak, S. A., Ayako, W.O. 2006. Effect of seasonality on feed availability, quality and herd performance on smallholder farms in Ol-joro-orok location/Nyandarua District, Kenya. Tropical and Subtropical Agroecosystems 6: 87–93.

Loveridge, S., Mpyisi, E., Weber, M. T. 2002. Farm levels perspective in Rwanda's coffee supply chain coordination challenge. Agricultural Policy Synthesis. Rwanda Food Security Research Project, Ministry of Agriculture and Livestock resources, Kigali, pp 1–6.

Lukuyu, B. A., Kitalyi, A., Franzel, S., Duncan, A., Baltenweck, I. 2009. Constraints and options to enhancing production of high quality feeds in dairy production. ICRAF, Nairobi, 31 pp.

Mafongoya, P. L. and Nair, P. K. R. 1997. Multipurpose tree prunings as a source of nitrogen to maize under semiarid conditions in Zimbabwe. Nitrogen recovery rates in relation to pruning quality and method of application. Agroforestry Systems 35: 47–56.

Mafongoya, P. L., Chintu, R., Chirwa, T. S., Matibini, J., Chikale, S. 2003. *Tephrosia* species and provenances for improved fallows in southern Africa. Agroforestry Systems 59**:**279–288

Mangisoni, J. H. 2000. Economic efficiency and investment potential in the smallholder crop sector in Malawi. International Journal of Social Economics 27: 968-979.

Mango, N.A.R. 1999. Integrated soil fertility management in Siaya district, Kenya. Managing African soils n° 7, 28 pp.

Mapiye, C., Mwale, M., Chikumba, N., Poshiwa, X., Mupangwa, J. F., Mugabe, P. H., 2006. A review of improved forage grasses in Zimbabwe. Tropical and Subtropical Agroecosystems 6, 125–131.

Mercer, D. E., Miller, R. P. 1998. Socio-economic research in agroforestry: progress, prospects, priorities. Agroforestry Systems 38: 177–193.

MINAGRI. 2006. Ministry of Agriculture Proposal for 'A Cow to Each Poor Family' in Rwanda. Kigali, Rwanda. Kigali, 26 pp.

MINAGRI. 2009. Strategic Plan for the Transformation of Agriculture in Rwanda – Phase II (PSTA II). Final report. Ministry of Agriculture and Animal Resources. Kigali. 114 pp.

Ministère du Plan, 1988. Enquête Nationale sur le budget et la consommation des ménages. Volume 4: consommation alimentaire en milieu rural. Kigali.

Ministry of Forestry and Mines. 2010. National Forestry Policy. Republic of Rwanda, Kigali. Rwanda, 23 pp.

Mokwunye, A. U., de Jager, A., Smaling, E. M. A. 1996. Restoring and maintaining the productivity of West African soils: Key to sustainable development. International Fertilizer Development. Miscellaneous Fertilizer Studies N°14. Lome, Togo.

Mowo, J. G., Janssen, B. H., Oenema, O., German, L. A., Mrema, J. P., Shemdoe, R. S. 2006. Soil fertility Evaluation and Management by smallholder farmer Communities in Northern Tanzania. Agriculture, Ecosystems and Environment, 116: 47–59.

Mugabo, R. J. 2003. Farm-level incentives for fertilizer use in Rwanda's Kigali rural province: A financial analysis. M Sc dissertation. Michigan State University. East Lansing, 100 pp.

Mugendi, D.N., Nair, P.K.R., Mugwe, J.N., O'Neill, M.K and Woomer, P.L. (1999). *Calliandra* and *leucaeana* alley cropped with maize. Part 1: Soil fertility change and maize production in the subhumid highlands of Kenya. Agroforestry Systems 46: 39-50.

Musabyimana, J. D. 2008. Assessment of farmers' managed agroforestry technologies under different biophysical and economic conditions in Rwanda. M Sc Dissertation. National University of Rwanda. Butare, Rwanda.

Mutimula, M., Everson, T. M. 2011. Assessment of livestock feed resource-use patterns in low rainfall and aluminium toxicity prone areas of Rwanda. African Journal of Agricultural Research 15 : 3461–3469.

Mutwewingabo, B., Rutunga, V. 1987. Etude des sols des stations d'essai du projet PIA situés dans la Mwogo, à Gitarama, à Kaduha et dans la Vallée de l'Akanyaru, MINAGRI-PIA, 114 pp.

Mwangi, D. M. 2003. Adoption of forage legumes: The case of *Desmodium intortum* and *Calliandra calothyrsus* in central Kenya. Tropical Grasslands 37: 227–238.

Nair, P. K. R. 1996. Agroforestry directions and literature trends. In: Mc Donald P and Lassoie J (eds) The literature of forestry and Agroforestry, pp 74-95. Cornell University Press, Ithaca, NY, USA.

Nair, P. K. R. 1998. Directions in tropical agroforestry research: past, present, and future. Agroforestry Systems 38: 223–245, 1998.

Ndayambaje, J.D., Mohren, G.M. J. 2011. Fuelwood demand and supply in Rwanda and the role of agroforestry. Agroforest Syst. DOI 10.1007/s10457-011-9391-6

Ndiaye, S. M., Fofranko, A. J. 1994. Farmers' perception of resources problems and adoption of conservation practices in a densely populated area. Agriculture, Ecosystems and Environment 48: 35-47.

Nduwamungu, J., Munyanziza, E., Nduwamungu, J. D., Ntirugulirwa B., Gapusi, R. J., Bambe, J. C., tabana, D., Ndizeye G**.** 2007. *Eucalyptus* in Rwanda: are the blames true or false? Institut Des Sciences Agronomiques Du Rwanda (ISAR)

Niang, A. I., Styger, E. 1990. Les Systèmes d'utilisation des Terres et Leur Potentiel Agroforestier au Rwanda. In Niang AI, Gahamanyi A, Styger E (Ed) Actes de la Première Réunion Agroforstière par le Projet ICRAF/ISAR du 13 au 15/9/1990 à Kigali. AFRENA Report 36. ICRAF. Butare, Rwanda.

Niang, A. I., Styger, E., Gahamanyi, A., Hoekstra, D., Coe, R. 1998. Fodder-quality improvement through contour planting of legume-shrub/grass mixtures in croplands of Rwanda highlands. Agroforestry Systems 39: 263–274.

Nkeshimana, G. 2008. The relation between land management practices, soil physical properties and erosion in coffee systems in south Rwanda. M Sc Dissertation. Wageningen University and Research Centre, Wageningen, 66 pp.

Nyaata, O. Z., Dorward, P. T., Keatinge, J. D. H., O'Neill, M. K., 2000. Availability and use of dry season feed resources on smallholder dairy farms in central Kenya. Agroforestry Systems 50: 315–331.

Nziguheba, G. and Mutuo, P.K. 2000. Integration of *Tithonia diversifolia* and inorganic fertiliser for maize production. In The Biology and Fertility of Tropical Soils: TSBF report, pp 23.

Ojiem, J. O. 2006. Exploring Socio-ecological Niches for Legumes in Smallholder Farming Systems of Western Kenya . PhD dissertation. Wageningen University. The Netherlands.

Ojiem J. O., de Ridder, N., Vanlauwe, B., Giller K. E. 2007. Socio-ecological niche: a conceptual framework for integration of legumes in smallholder farming systems. International Journal of Agricultural Sustainability 4: 79–93.

Okalebo, J. R., Gathua, K. W., Woomer, P. L. 2002. Laboratory Methods of Soil and Plant Analysis: A working Manual. TSBF-CIAT. Nairobi, Kenya.

Okigbo, B. N. 1980. Nutritional implications of projects giving high priority to the production of staples of low nutritive quality. In the case for cassava (*Manihot esculenta*, Crantz) in the humid tropics of West Africa. Food Nutrition Bulletin 2: 1–10.

Ongadi, P. M., Wahome, R. G., Wakhung, J. W., Okitoi, L. O. 2010. Modelling the influence of existing feeding strategies on performance of grade dairy cattle in Vihiga, Kenya. Livestock Research for Rural Development 22. Retrieved March 27, 2012, from http://www.lrrd.org/lrrd22/3/onga22056.htm.

Palm, C.A. 1985. Contribution of agroforestry trees to nutrient requirements of intercropped plants. Agroforestry Systems 30: 105-124

Palm, C. A., Myers, R. J. K., Nandwa, S. M. 1997. Combined Use of Organic and Inorganic Nutrient Sources for Soil Fertility Maintenance and Replenishment. In R. J. Buresh, P. A. Sanchez, Calhoun, F. (Eds.). Replenishing Soil Fertility in Africa, 251 pp. Madison: ASSA, CSSA, SSSA.

Paterson, R. T., Karanja, G. M., Nyaata, O. Z., Kariuki, I. W., Roothaert, R. L. 1998. A review of tree fodder production and utilisation within smallholder agroforestry systems in Kenya. Agroforestry Systems 41: 181–199.

Paterson, R. T., Kiruiro, E, Arimi, H. K. 1999. *Calliandra calothyrsus* as a supplement for milk production in the Kenya highlands. Tropical Animal Health and Production 31: 115–126

Pinchón, F. J. 1997. Settler households and land use patterns in the Amazon frontier: farm levl evidence from Ecaduor. World Development 25: 67–91.

Pinners, E., Balasubramanian, V. 1991. Use of iterative diagnosis and design approach in the development of suitable agroforestry systems for a target area. Agroforestry Systems 15: 183–201.

Powell, J. M., William, T. O. 1993. An overview of mixed farming systems in sub-Saharan Africa. Volume II. Technical papers. In: Powell, J.M., Fernandez-Rivera, S., William, T.O., Renard, C. (Eds), Livestock and Sustainable Nutrient Cycling in Mixed Farming Systems of sub Saharan- Africa. Proceeding of an International Conference International Livestock Centre for Africa (ILCA), Addis Ababa, pp 21–36.

Prudencio, C. Y. 1983. Ring management of soils and crops in the West African semiarid tropics: The case of the mossi farming system in Burkina Faso. Agriculture, Ecosystems & Environment 47: 237–264.

Raintree, J. B. 1983. Strategies for enhancing the adoptability of agroforestry innovations. Agroforestry Systems 1: 173–187.

Renard, C. 1997. Crop Residues in Sustainable Mixed Crop/livestock Farming Systems. CAB International, Wallingford, pp 41–77.

Roose, E., Ndayizigiye, F. 1997. Agroforestry, water and soil fertility management to fight erosion in tropical mountains of Rwanda. Soil Technology 11: 109-119.

Roothaert, R. L., Franzel, S. 2001 Farmers's preferences and use of local fodder trees and shrubs in Kenya. Agroforestry Systems 52: 239–252.

Ruben, R., Pender, J. 2004. Rural diversity and heterogeneity in less-favoured areas: the quest for policy targeting. Food policy 29:303–320.

Rutunga, V, Karanja, NK, Gachene, C. K. K, Palm, C. A. 1999. Biomass production and nutrient accumulation by *Tephrosia vogelii* Hook F. and *Tithonia diversifolia* (Hemsley) A.Gray six-month fallows at Maseno, Western Kenya. Biotechn Agron Soc Environ 3: 237 – 246.

Rutunga, V., Gachenge, C. K. K, Karanja, N. K., Palm, C. A. 2003. Grain maize yield improvement using *Tephrosia vogelii* and *Tithonia diversifiolia* biomass at Maseno, Kenya. Tropical and Subtropical Agroecosystems 2:1–11.

Ruthenberg, H. 1980. Farming systems in the tropics. Third edition. Oxford.

Sanchez, P.A. 1995. Science in agroforestry. Agroforestry Systems 30: 5–55.

Sanchez, P. A., Leakey, R. R. B. 1997. Land use transformation in Africa: three determinants for balancing food security with natural resource utilization. European Journal of Agronomy 7: 15–23.

Sanchez, P. A., Shepherd, K. D., Soule, M. J., Place, F. M., Mokwunye, A. U., Buresh, R. J., Kwesiga,F. R., Izac, A. N., Ndiritu, C. G., Woomer, P. L. 1997. Soil fertility replenishment in Africa: An investment in natural resource capital, In: Buresh, R. J., nd Sanchez, P. A., (Eds), Replenishing soil fertility in Africa. Soil Science Society of America and American Society of Agronomy, Madison, Wisconsin, U.S.A, pp. 1–46.

Sanchez, P.A. 2002. Soil fertility and Hunger in Africa. Science 295: 2019-2020.Scoones, I., Toulmin, C. 1999. Soil nutrient budgets and balances: What use for policy? Agriculture, Ecosystems & Environment 71: 257–269.

Shem, M. N., Otsyia, R. 1997. Dairy production in urban and peri-urban areas of Tanzania. An analysis of Shinyanga urban. Proceedings of the 24th Scientific conference LITI-Tengeru, Arusha, pp 298–306.

Shepherd, K. D., Ohlsson, E., Okalebo, J. R., Ndufa, J. K. 1996. Potential impact of agroforestry on soil nutrient balances at the farn scale in the Eastern African Highlands. Fertiliser Research 44: 87–99.

Shepherd, K. D., Soule, M. J. 1998a. Soil fertility management in west Kenya: dynamic simulation of productivity, profitability and sustainability at different resource endowment levels. Agriculture Ecosystems & Environment 71:131–145.

Shepherd, K.D., Soule, M. J. 1998b. Assessment of the economic and ecological impacts of agroforestry and other soils management options on western Kenyan farms using a dynamic simulation model. Agriculture Ecosystems & Environment 83: 27–42.

Smaling, E.M.A., Braun, A.R., 1996. Soil fertility research in sub-Saharan Africa: new dimensions, new challenges.Communications in Soil Science and Plant Analysis 27: 365–386.

Smaling, E. M. A., Nandwa, S. M., Janssen, B. H.1997. Soil fertility in Africa is at stake. In:

Buresh, R. J., Sanchez, P. A. and Calhoun, F. (eds.). Replenishing Soil Fertility in Africa. Soil Science Society of America Special Publication N°51, Madison, Wisconsin, USA, pp 47-61

Smaling, E. M. A., Janssen, B. H. 1993. Calibration of QUEFTS, a model predicting nutrient uptake and yields from chemical soil fertility indices. Geoderma 59: 21–44.

Smaling, E. M. A., Louise, O. F., de Jager, A. 1996. Classifying, monitoring and improving soil nutrient stocks and flows in African agriculture. Ambio 5: 492–496.

Smaling, E. M. A., Stoorvogel, J. J., Windmeijer, P. N. 1993. Calculating soil nutrient balances in Africa at different scales. II. District scale. Nutrient Cycling in Agroecosystems 35: 237–250.

Soil Survey Staff. 1998. Keys to Soil Taxonomy, 6thed. SMSS Technical Monograph N^{o} 19. Pocahontas, Blacksburg, 541pp.

Stoorvogel, J. J., Smaling, E. M. A. 1990. Assessment of soil nutrient depletion in Sub-Saharan Africa. 1983-2000. Volume III: Literature review and description of Land Use Systems. Wageningen University, Wageningen.

Stoorvogel, J. J., Smaling, E.M.A., Jansen, B. H. 1993. Calculating soil nutrient balances in Africa at different scale. I: supranational scale. Fertiliser Research 35: 227–235.

Teferedegne, B. 2000. New perspectives on the use of tropical plants to improve ruminant nutrition. Proceedings of the Nutrition Society, pp 209–214.

Tibayungwa, F., Mugisha, J.Y.T. and Nabasirye, M., 2010. Modelling nitrogen excretion, elephant grass growth and animal production in a stall-feeding dairy system. African Journal of Agricultural Research 5, 2039-2044.

Tittonell, P., Vanlauwe, B., Leffelaar, P. A., Rowe, E. C., Giller, K. E. 2005a. Exploring diversity in soil fertility management of smallholder farms in western Kenya: I. Heterogeneity at region and farm scale. Agriculture, Ecosystems & Environment 110: 149–165.

Tittonell, P., Vanlauwe, B., Leffelaar, P. A., Shepherd, K. D., Giller, K. E. 2005b. Exploring diversity in soil fertility management of smallholder farms in western Kenya - II. Within-farm variability in resource allocation, nutrient flows and soil fertility status. Agriculture Ecosystems & Environment 110: 166–184.

Tittonell, P., Vanlauwe, B., de Ridder, N., Giller, K. E. 2007a. Heterogeneity of crop productivity and resource use efficiency within smallholder Kenyan farms: Soil fertility gradients or management intensity gradients? Agricultural Systems 94: 376–390.

Tittonell, P., Zingore, S., van Wijk, M. T., Corbeels, M., Giller, K. E. 2007b. Nutrient use efficiencies and crop response to N and P and manure applications in Zimbabwean soils: Exploring management strategies across soil fertility gradients. Field Crops Research 100: 348–368.

Tittonell, P., van Wijk, M.T., Rufino, M. C., Vrugt, J. A., Giller, K. E. 2007c. Analysing trade-offs in resource and labour allocation by smallholder farmers using inverse modelling techniques: A case-study from Kakamega district, western Kenya. Agricultural Systems 95: 76–95.

Tittonell, P. A., Corbeels, M., van Wijk, M. T., Vanlauwe, B., Giller, K. E. 2008a. Combining Organic and Mineral Fertilizers for Integrated Soil Fertility Management in Smallholder Farming Systems of Kenya: Explorations Using the Crop-Soil Model FIELD. Agronomy Journal 100: 1511–1526.

Tittonell, P. A., Shepherd, K., Vanlauwe, B., Giller, K. E. 2008b. Unravelling the effects of soil and crop management on maize productivity in smallholder agricultural systems of western Kenya - An application of classification and regression tree analysis. Agriculture Ecosystems and Environment 123: 137–150.

Thonnisen, C., Midmore, D. J., Ladha, J. K., Olk, D. C, Schmidhalter, U. 2000. Legume decomposition and nitrogen release when applied as green manures to tropical vegetable production systems. Agronomy Journal 92:253–260.

Thornton, P. K., Herrero, M. 2001. Integrated crop–livestock simulation models for scenario analysis and impact assessment. Agricultural Systems 70: 581–602.

Trumbho, P., Schlicker, S., Yates, A. A., Poos, M. 2002. Dietary reference intakes for energy, carbohydrate, fiber, fat, fatty acids, cholesterol, protein and amino acids. Journal of the American Dietetic Association, 1621–1630.

Tuwei, P. K., Kang'ara, J. N. N., Mueller-Harvey, I., Poole, J., Ngugi, F. K., Stewart, J. L. 2003 Factors affecting biomass production and nutritive value of *Calliandra calothyrsus* leaf as fodder for ruminants. Journal of Agricultural Sciences 141: 113–127.

Udo, H.M.J., Aklilu, H.A., Phong, L.T., Bosma, R.H., Budisatria, I.G.S., Patil, B.R., Samdup, T. and Bebe, B.O., 2011. Impact of intensification of different types of livestock production in smallholder crop-livestock systems. Livestock Science 139, 22-29

United Nations. 1994. World Population to 2300. Department of Economic and Social Affairs/Population Division, New York/ United Nations Secreetariat, 254 pp.

USAID. 2006. Assessing USAID'S investments in Rwanda's coffee sector- Best practices and learned to consolidate results and expand impact. Chemonics International, Kigali, 42pp.

Uwimana, G., 2010. Cattle and livelihoods of poor households in Rwanda: Impact assessment. MSc Thesis, Animal Production Systems Group, Wageningen University, 64 pp.

Van Asten, P.J.A., Wairegi, L.W.I., Mukasa, D., Uringi, U.O., 2011. Agronomic and economic benefits of coffee–banana intercropping in Uganda's smallholder farming systems. Agricultural Systems 104: 326–334.

Vandermeer, J.H., 1990. Intercropping. In: Carroll, C.R., Vandermeer, J.H., Rosset, P.M. (eds.), Agroecology. McGraw-Hill, New York, pp. 481–515.

Van den Berg, M., 2009. Dairy Cows – A creamy tool in rural development. A study on the role of a dairy cattle project in rural livelihood development in the districts of Suhum/Kraboa/Coaltar and Akuapem-South in the Eastern Region, Ghana. MSc Thesis, International Development Studies, Utrecht University, 118pp.

Van der Zaag , P. 1982. La fertilité des sols du Rwanda. Bulletin Agricole du Rwanda 15 : 3–24.

Vanlauwe, B., Sanginga, N., Merckx, R., 1997. Decomposition of four Leucaena and Senna prunings in alley cropping systems under sub-humid tropical conditions: the process and its modifiers. Soil Biology and Biochemistry 29: 131–137.

Vanlauwe, B., Nwoke, O. C., Diels, J., Sanginga, N., Carsky, R. J., Deckers, J., Merckx, R. 2000. Utilization of rock phosphate by crops on a representative toposequence in the Northern Guinea savanna zone of Nigeria: response by Mucuna pruriens, Lablab purpureus and maize. Soil Biology and Biochemistry 32: 2063–2077.

Vanlauwe, B., J. Diels, K. Aihou, E.N.O. Iwuafor, O. Lyasse, N. Sanginga, and R. Merckx. 2002. Direct interactions between N fertilizer and organic matter: Evidence from trials with 15N-labelled fertilizer. p. 173–184. In Vanlauwe, B., Diels, J., Sanginga, N. and Merckx, R. (eds) *Integrated Plant Nutrient Management in sub-Saharan Africa: From Concept to Practice.* CABI, Wallingford, UK, 352 pp.

Vanlauwe, B., Giller, K. E. 2006. Popular myths around soil fertility management in sub-Saharan Africa. Agriculture, Ecosystems & Environment 116:34–46.

Vanlauwe, B., Tittonell, P., Mukalama, J. 2006. Within-farm soil fertility gradients affect response of maize to fertiliser application in western Kenya. Nutrient Cycling in Agroecosystems 76:171–182.

Vanlauwe, B., Bationo, A., Chianu, J., Giller, K. E., Merckx, R., Mokwunye, U., Ohiokpehai, O., Pypers, P., Tabo, R., Shepherd, K. D., Smaling, E. M. A., Woomer, P. L., Sanginga, N. 2011. Integrated soil fertility management. Operational definition and consequences for implementation and dissemination. Outlook on Agriculture 39: 17–24.

Wambugu, C., Place, F., Franzel, S. 2011. Research, development and scaling-up the adoption of fodder shrub innovations in East Africa. International Journal of Agricultural Sustainainability 9:100–109.

Wanda, K. 2002. CIAT-ATDT/ISAR/IITA-FOODNET and PEARL Project Report– Rwanda. Maize Sub-sector market survey. Kigali. Rwanda. November, 2002. 50 pp.

Wilson, G. F., Kang, B. T. 1981. Developing stable and productive biological cropping system for the humid tropics. In Stonehouse, B. (eds). Biological Husbandry. A Scientific Approach to Organic Farming, Butterworth, London, pp 193–203.

Wopereis, M. C. S., Tamélokpo, A., Ezui, K., Gnakpénou, D., Fofana, B., Breman, H. 2006. Mineral fertilizer management of maize on farmer fields differing in organic inputs in the West African savanna. Field Crops Research 96: 355–362.

Yamoah, C. F., Grosz, R., Nizeyimana, E. 1989. Early growth of alley shrubs in the Highland region of Rwanda. Agroforestry Systems 9: 171–184.

Yamoah, C. F., Burleigh, J. R. 1990. Alley cropping *Sesbania sesban* (L) Merill with food crops in the highland region of Rwanda. Agroforestry Systems 10: 169–181.

Yamoah, C. F., Burleigh J. R., Malcolm M. R. 1990. Application of expert systems to study of acid soils in Rwanda. Agriculture, Ecosystems & Environment 30: 203–218.

Young, A. 1997. Agroforestry for Soil Management. 2nd Edition. CAB International in Association with the International Centre for Research in Agroforestry. Wallingford, UK.

Zingore, S., Murwira, H. K., Delve, R. J., Giller, K. E. 2007a. Influence of nutrient management strategies on variability of soil fertility, crop yields and nutrient balances on smallholder farms in Zimbabwe. Agriculture Ecosystems and Environment 119: 112–126.

Zingore, S., Murwira, H. K., Delve, R. J., Giller, K. E. 2007b. Soil type, historical management and current resources allocation: three dimesnions regulating variability of maize yields and nutrient use efficiencies on African smallholder farms. Field Crop Research 101: 296–305.

Summary

Food self-sufficiency is a major issue on the agenda of many development projects and government leadership in sub-Saharan Africa. Heavy soil losses and soil depletion due to continuous cropping and soil erosion, and shortage of fuelwood, timber and staking materials are additional agricultural constraints. Agroforestry has been proposed as an approach to contribute to alleviation of food shortage and solving problems of ecological degradation. The goal of this thesis therefore, was to understand the diversity of farming systems in Rwanda, to assess the current status and potential of different agroforestry practices and to evaluate the best options for its integration within selected smallholder farming systems in Rwanda.

Farm resource use and food self-sufficiency status were assessed in different agro-ecological zones of Rwanda (Central Plateau and Buberuka zones, all located at 1000 m above sea level and with over 1000 mm of rainfall). This was done as part of a characterisation of the farming systems to identify critical constraints for designing appropriate interventions. Simbi and Kageyo sectors were selected to represent predominant land uses in the respective zones. Wealth ranking and survey techniques allowed the identification and characteristics of three farm resource groups (RGs): RG 1 (76 to 86% of all sampled households in Simbi and 67.5 to 75.3% in Kageyo), RG 2 (RG 2, 8.5 to 18.2% in Simbi and 17 to 30.6% in Kageyo) and RG 3 (4.9 to 5.2% in Simbi and 2.0 to 7.5% in Kageyo). RGs differed in land ownership, number of cattle owned and food self-sufficiency status. RG 1 was the most vulnerable in terms of food self-sufficiency. Fields were categorised into homefield (HF), close field (CF) and outfield (OF) and these were different in soil fertility level. Soils in Kageyo were more fertile than those in Simbi as evidenced by all soil fertility indicators considered. Total annual DM yield was the largest in Kageyo (1.70 ton ha^{-1} yr^{-1}) and was significantly higher in homefields (1.64 ton $ha^{-1}yr^{-1}$) than in outfields (0.68 ton $ha^{-1}yr^{-1}$) due to higher soil fertility but also to higher inputs applied in those fields. N and P inputs were the largest in Kageyo (20.28 kg N $ha^{-1}yr^{-1}$; 6.50 kg P $ha^{-1}yr^{-1}$) but N partial balance was more negative in the same location (-35.87 kg N $ha^{-1}yr^{-1}$). In close fields and outfields, P balance recorded negative values as opposed to positive values in the homefield

(0.43 kg P $ha^{-1}yr^{-1}$). Calories and proteins intake by the local people were below accepted international standards in RG 1 in both locations and in RG 2 in Simbi.

A multidimensional approach, combining a formal survey, farmer's tree testing and farmer's evaluation was used to assess the current agroforestry situation, evaluate the preferred species by farmers and identify the best-fit agroforestry technologies for different farms. Tree species were more diversified in Simbi (4.5 tree species $farm^{-1}$) than in Kageyo (2.9 tree species $farm^{-1}$) due to biophysical (altitude, temperature) and social factors (population density). Poor farms had the largest number of trees ha^{-1} compared with wealthier and moderate farms, illustrating the inverse relationship between land holding size and tree density. More *Eucalyptus urophyla* trees were planted by wealthier farmers in Kageyo due to more available land. Strong preference for *Grevillea* in Simbi was largely attributed to the fact that the tree species grow faster, are more adapted to the area and produce large amount of biomass and stakes. *Calliandra calothyrsus* shrubs were established on contours or niches close to the croplands (contours or farm boundaries) and were major sources of firewood, stakes/poles and animal feeds and offered the possibility of soil conservation in a hilly landscape. Fruit tree species were either established in homefield or close fields and were highly valued due to their economic benefits. *Calliandra calothyrsus* was scored very high for palatability and less for its ability to supply poles in Kageyo, demonstrating the relative importance of livestock activity in the location. *Tephrosia* was the least preferred species.

Coffee is the most important cash crop in Rwanda, especially in the southern part of the country. Despite major efforts in promoting the coffee sector, coffee productivity has remained relatively low due to poor mulch and soil fertility level. We, therefore, investigated the growth and biomass production of *Tephrosia* species and their use as mulch in smallholder coffee plantations. A two seasons trial was conducted in Central Plateau zone (Maraba sector) to evaluate the impacts of two accessions of *Tephrosia* (*Tephrosia* ex. Gisagara and *Tephrosia* ex. Kisumu) planted within coffee or outside coffee on plant growth, biomass yield, and nutrient uptake, the impact of their use as mulch coffee fields and economic profitability over two successive seasons (2007/2008 & 2008/2009). In the second season, the assessment was on *Tephrosia* and coffee production when intercropped, with or without NPK fertilizer. Furthermore, an omission greenhouse trial was conducted to identify nutrients limiting growth of *Tephrosia* in Maraba. In 2007/2008 season, plant height (0.7-1.0 m) and biomass production (1.4-1.9 Mg ha^{-1}) of *Tephrosia* grown within coffee were greater than in the fields outside coffee (0.4-0.6 m; 0.6-0.7 Mg ha^{-1}). The soil within coffee fields was more fertile due to past farmer mulch management. Coffee yield was significantly greater (1.80-1.92 ton ha^{-1}) with *Tephrosia* mulch grown *in situ* within the coffee fields. Intercropped *Tephrosia* responded strongly when NPK fertilizer was applied to the coffee, resulting in greater production of *Tephrosia* mulch, more coffee yield, larger gross margin, returns to labour and benefit-cost ratio. *Tephrosia* productivity was limited particularly by P and K deficiencies, and to some extent Ca and Mg.

Given the large heterogeneity in soil fertility within smallholder farming systems, blanket recommendations are not appropriate. A study was conducted to evaluate the effect of *Calliandra calothyrsus* residues rates (0, 30, 60 and 90 kg N ha^{-1}) combined with different rates of P (0 and 44 kg P ha^{-1}) supplied as TSP on grain yield, nutrient use efficiency and economic profitability of maize. The results can then be used to develop site-specific nutrient management recommendations. The trial was conducted in three farms of the RG 1 and RG 3 farm categories in two contrasting fields (in-field and out-field) over three seasons in Simbi and two seasons in Kageyo. Maize yield was larger in SR (Short Rains) 2008 (1.45 Mg ha^{-1}) than in LR (Long Rains) 2008 (0.95 Mg ha^{-1}) and SR 2009 (0.90 Mg ha^{-1}). These differences were caused by differences in seasonal rainfall, resulting in higher nutrient N uptake in maize grain in SR 2008. The results indicated that N recovery (RE_N) and agronomic use efficiency (AE_N) were the highest in RG 3 and in-field plots and decreased with an increasing N (nitrogen) application rate. Our results indicated a slightly smaller optimal N-application rate (60 kg N ha^{-1}) compared with the current recommended rates (65 kg N ha^{-1}). Net returns and the ratio between gross margin and costs of inputs were greater in Kageyo than in Simbi and were improved by P application. A close relationship between soil fertility, maize productivity and economic profitability was evidenced by higher net benefit and B/C ratio in Kageyo and in the in-fields. In addition, increasing N rates resulted into a greater net benefit and B/C due to the stimulation of more maize productivity. QUEFTS simulated maize yields correlated with measured yields using the best seasons, indicating the potential of using the tool in more complex experiments and at large scale level. Livestock forms an important part of smallholder farming systems in sub-Saharan Africa and it can contribute strongly to food self-sufficiency. In order to understand the current and potential role of agroforestry species for smallholder livestock production in Rwanda, a study was conducted to quantify the animal feeds currently available and on offer to livestock in different farms (3 RG1, 5 RG 2 and 3 RG 3 farms) in the south-west of Rwanda. Also the potential fodder availability on seasonal basis was quantified under different scenarios for the different farmer's resource groups to quantify their ability to produce enough fodder to keep livestock. The results indicated that land available for forage production was largest in RG 3 farms (1.71 ha) and lowest in RG 1 farms. Animal feeds were more diversified with predominance of *Pennisetum* on wealthier farms. RG 1 farmers compensate for the shortage of grass by feeding larger quantities of marshland-herbs and crop residues. Napier and *Calliandra* were more available during the wet season than during the dry season, while this other way banana pseudo-stems. Compared with the standard feeds requirements, a poor (RG 1) farmer was found to be unable to meet feeds requirements of a local, improved or a lactating cow under all scenarios. RG 2 and RG 3 could maintain a local or improved cow only under specific scenarios of feeds availability. During the dry seasons, predictions indicated extreme shortage of animal feeds.

In conclusion, agroforestry can be seen as an approach that provides technologies that are readily accessible to smallholders and provides a wide variety of benefits. Agroforestry is not expected to be a unique remedy to all agricultural constraints but rather an option which, in combination with other technologies could substantially contribute in improving livelihood and food self-sufficiency within specific socioeconomic and biophysical settings. The multidimensional approach used in this study may assist in targeting agroforestry technologies that fit within the biophysical and socio-economic conditions of smallholder farming systems in different agro-ecological zones of Rwanda, to contribute to their food self-sufficiency and economic profitability. The existence of farming systems diversity within different agro-ecological zones and multiple farmers' needs and uses of agroforestry resources calls for rethinking and adapting research approaches. Agroforestry research should not only consider key determining factors of farm production in isolation, but should take a more integrated approach. The approach would help develop more attractive options, and integrated strategies for farmers. To achieve this, researchers need to engage more actively with the intended-beneficiaries of their research output, the smallholder farmers of sub-Saharan Africa.

Samenvatting

Zelfvoorziening in voedsel is een belangrijk punt op de agenda van veel ontwikkelingsprojecten en beleidsbepalers in Afrika ten zuiden van de Sahara. Bodem verlies en uitputting als gevolg van continue gewasproductie en bodemerosie, en een tekort aan brandhout, constructiehout en palen voor gewasondersteuning zijn bepalende limiterende factoren voor agrarische productie. *Agroforestry*, ook wel genaamd 'boslandbouw', is voorgesteld als een aanpak om voedseltekorten en problemen met ecologische degradatie te verminderen. Het doel van deze thesis was om: i) de diversiteit aan boerenbedrijven in Rwanda te begrijpen ii) de huidige status en potentie van verschillende *agroforestry* methodes te beoordelen en iii) de beste opties voor de integratie van deze opties in geselecteerde kleine boerenbedrijven in Rwanda te evalueren.

Het niveau van zelfvoorziening in voedsel op bedrijsniveau is beoordeeld in verschillende agro-ecologische zones in Rwanda (het centrale plateau en de Buberuka zone, allebei op een hoogte van 1000 m boven zeeniveau en met een jaarlijkse regenval van meer dan 1000 mm). Dit is gedaan als onderdeel van een karakterisering van agrarische bedrijfssystemen om de kritieke beperkingen te identificeren zodat de juiste inteventies ontworpen kunnen worden. De Simbi en Kageyo regios waren geselecteerd vanwege de aanwezigheid van de dominante landgebruikstypen van de 2 eerdergenoemde zones. Ordeningen van rijkdom en overzichtsinterviews maakten het mogelijk om 3 bedrijfstypen (BT) te indentificeren en te karakteriseren: BT1 (76 tot 86% van alle onderzochte huishoudens in Simbi en 67.5 tot 75.3% in Kageyo), BT2 (8.5 tot 18.2% in Simbi en 17 tot 30% in Kageyo) en BT3 (4.9 tot 5.2% in Simbi en 2 tot 7.5% in Kageyo) De BTs verschilden in landeigendom, hoeveelheid vee in eigendom en het niveau van voedselzelfvoorziening. BT1 was het meest kwetsbaar in termen van voedselzelfvoorziening. Velden werden geclassificeerd in thuisvelden (TV), binnenvelden (DV) en buitenvelden (UV) en deze waren verschillend in bodemvruchtbaarheid. De bodems in Kageyo waren vruchtbaarder dan die in Simbi. De totale jaarlijkse opbrengsten waren het het hoogst in Kageyo (1.7 ton drogestof per bedrijf per jaar). De opbrengsten waren hier siginicant hoger in de thuisvelden (1.64 ton drogestof per ha per jaar) dan in de buitenvelden (0.68 ton drogestof per ha per jaar) als gevolg van de hogere inputs die aan deze velden werden toegediend. N en P inputs waren het hoogst in Kageyo (20.28 kg N per hectare per jaar; 6.50 kg P per hectare per jaar), maar de partiele N balans was hier ook negatiever (-35.9 kg N per hectare per jaar). In de binnenvelden en de buitenvelden was de P-balans negatief, terwijl deze positief was in de thuisvelden (0.43 kg P per hectare per jaar). Inname van calorieen en proteinen door de lokale bevolking was onder de internationaal geaccepteerde standaarden in BT1 in beide locaties, en alleen in BT2 in Simbi.

Om de huidige *agroforestry* situatie te beoordelen, te identificeren welk boomsoorten boeren prefereren en wat de best-passende *agroforestry* technologieën zijn voor de verschillende bedrijven is gebruik gemaakt van een multidimensionele aanpak. Deze bestond uit een combinatie van: i) formele overzichtsinterviews; ii) het testen van bomen door boeren iii) hun evaluatie daarvan. De diversiteit in boomsoorten op de bedrijven was hoger in Simbi (gemiddelde 4.5 boomsoort per bedrijf) dan in Kageyo (2.9 boomsoort per bedrijf) als gevolg van biofysische (hoogte, temperatuur) en sociale (bevolkingsdichtheid) factoren. Arme boerenbedrijven hadden de hoogste dichtheden bomen per hectare, daarmee de inverse relatie illustrerend tussen hoeveelheid land in eigendom en boomdichtheid. Meer *Eucalyptus urophyla* bomen waren geplant door de rijkere boeren in Kageyo als gevolg van de hogere beschikbaarheid van land. Een sterke voorkeur voor *Grevillea* in Simbi werd waarschijnlik veroorzaakt doordat de soort snel groeit, beter geadapteerd is aan de groeilokatie en veel biomassa en takken produceert. *Calliandra calothyrsus* struiken stonden op de veld contouren of op plekken dicht bij de gewasvelden. Ze vormden een belangrijke bron voor brandhout, palen en voer voor dieren en waren bovendien nuttig als hulpmiddel voor bodembehoud in een heuvelachtig landschap. Fruitboomsoorten stonden of in de thuisvelden of in de binnenvelden, en ze werden erg gewaardeerd vanwege hun economische voordelen. *Calliandra calothyrsus* scoorde hoog als bron voor veevoer, en minder als gebruik voor palen in Kageyo, daarmee het grote belang van vee in de regio illustrerend. *Tephrosia* was de soort waar de boeren het minste voorkeur voor hadden.

Koffie is het belangrijkste geldgenererende gewas in Rwanda, zeker in het zuidelijke gedeelte van het land. Ondanks pogingen om de koffiesector te promoten, is de koffieproductie relatief laag gebleven door de lage hoeveelheid organische stof die beschikbaar is voor toevoeging en de lage bodemkwaliteit. Daarom onderzochten we de groei en biomassa productie van *Tephrosia* soorten, om de potentie van deze soort als bron van organisch materiaal voor koffieproductie te beoordelen. Een experiment van 2 seizoenen (2007/2008 & 2008/2009) werd uitgevoerd in het Centrale Plateau (Marba sector). Het doel van het experiment was om de invloed van 2 typen *Tephrosia* (*Tephrosia* ex. Gisagara en *Tephrosia* ex. Kisumu) die binnen of buiten het koffieveld geplant waren, op plantgroei, gewasopbrengst, nutrient opname en economische opbrengst van koffie te kwantificeren. In het 2^{e} seizoen werd de evaluatie alleen uitgevoerd als *Tephrosia* en koffie gemengd produceerd werden, met of zonder kunstmest. Verder werd een kasexperiment uitgevoerd om de meest groeibeperkende nutrienten van *Tephrosia* in Maraba te identificeren. In het eerste seizoen waren planthoogte (0.7 ton per hectare) en biomassa productie (1.4 tot 1.9 ton per hectare) van Tephrosia die binnen de koffievelden groeiden groter dan die in velden buiten de koffie (0.4 tot 0.6 m; 0.6 – 0.7 ton per hectare). De bodem in de koffievelden was vruchtbaarder dan die erbuiten, dankzij de toepassing van organisch materiaal door de boeren in het verleden. De koffieopbrengst was significant hoger (1.8 tot 1.92 ton per hectare) met *Tephrosia* in de koffievelden. *Tephrosia* in de koffievelden reageerde sterk als kunstmest werd toegepast op de koffie, daarmee resulterend in en hogere koffieopbrengst, een grotere economische opbrengst, en een hogere arbeids-efficientie. De groei van *Tephrosia* werd vooral beperkt door P en K tekorten, en in mindere mate ook door tekorten aan Ca en Mg.

De hoge heterogeniteit van bodemvruchtbaarheid in kleine boerenbedrijven maakt dat generieke adviezen voor bedrijfsbeheer niet functioneel zijn. Een studie werd uitgevoerd om het effect van de gewasresten van *Calliandra calothyrsus* (in 4 niveaus: 0, 30, 60 en 90 kg per hectare) gecombineerd met verschillende toepassingnveaus van P (0 en 44 kg P per ha) op de gewasopbrengst, de efficientie van nutrient gebruik en de economische opbrengst van mais te kwantificeren. De uitkomsten van zo’n studie kunnen dan gebruikt worden om lokatie specifieke beheersadviezen te kunnn ontwikkelen. Het experiment werd uitgevoerd op drie bedrijven van de BT1- en BT3-ategorieen in 2 contrasterende velden (binnen en buitenvelden), over drie seizoenen in Simbi en 2 seizoen in Kageyo. Maisopbrengsten waren hoger in het korte regenseizoen van 2008 (1.45 ton per hectare) dan in het lange regenseizoen van 2008 (0.95 ton per hectare) en het korte regenseizoen van 2009 (0.9 ton per hectare). Dit werd veroorzaakt door verschillen in de regenval in elk seizoen; deze resulteerden in een hogere nutrient opname in mais in het korte regenseizoen in 2008. De resultaten lieten zien dat de efficientie van N opname en de agronomische efficientie van N gebruik het hoogst waren in binnenvelden en in velden van BT3, en afnamen bij een toenemend applicatie niveau van N. Onze resultaten gaven een indicatie dat een iets lager N toevoegingsniveau (60 kg N per hectare) optimaal was dan het huidige adviesniveau (65 kg N per hectare). De economische opbrengst was hoger in Kageyo dan in Simbi, en deze nam toe bij toevoeging van P. Een sterke relatie tussen bodemvruchtbaarheid, maisproductiviteit en economische winstgevendheid was zichtbaar dankzij de hogere opbrengsten in Kageyo en in binnenvelden. Bovendien leiden hogere N toevoegingsniveaus tot grotere economische winstgevendheid door de hogere maisopbrengsten. Het simulatiemodel QUEFTS simuleerde de maisopbrengsten voor de beste seizoenen, daarmee bevestigend dat het model potentie heeft om toegepast te worden in complexe experimenten en op grote schaalniveaus.

Vee vormt een belangrijk deel in de kleine boerenbedrijven in Afrika ten zuiden van de Sahara en vee kan een belangrijke bijdrage leveren aan de voedsel zelfvoorziening. Om de huidige en potentiele rol van *agroforestry* soorten voor veeproductie in Rwanda beter te begrijpen, werd een studie uitgevoerd om de hoeveelheid voer te kwantiferen dat op dit moment beschikbaar is op de verschillende bedrijfstypen (BT1, BT2, B3) in het zuidwesten van Rwanda.

Ook de potentiele voerbeschikbaarheid op seizoensbasis werd gekwantificeerd onder verschillende scenarios. Dit maakte een evaluatie van de capaciteit van voerproductie voor het houden van vee mogelijk voor de verschillende bedrijstypen. De resultaten lieten zien dat het land dat beschikbaar is voor voerproductie het grootst was in BT3 boerderijen (1.71 ha) en het laagst in BT1 boerderijen. Veevoer was meer divers met vooral *Pennisetum* op de wat rijkere boerderijen. BT1 boeren compenseerden het tekort aan voer op het bedrijf zelf met het voeren van grote hoeveelheden moeras-kruiden en gewasresten. *Napier* en *Calliandra* waren beschikbaar in grotere hoeveelheden in de regenseizoenen dan in de droge seizoenen, terwijl dit precies omgekeerd was voor pseudo-stam materiaal van bananen. Vergeleken met de standaard voerbenodigdheden heeft een arme (BT1) boer onder geen van de scenarios genoeg voer beschikbaar om jaarrond een koe te houden. BT2 en BT3 boeren kunnen een koe van een lokaal ras of van een verbeterd ras houden, maar alleen onder een specifiek voerproductie scenario. Gedurende het droge seizoen laten de voorspellingen zien dat er een extreem gebrek is aan veevoer.

Concluderend kunnen we zeggen dat *agroforestry* een aanpak is die goed beschikbaar is voor kleine boeren, en een grote varieteit aan voordelen biedt. *Agroforestry* is geen unieke oplossing voor alle agrarische beperkingen, maar is een optie die in combinatie met andere technologieën, de levensstandaard en de zelfvoorziening in voedsel van kleine boeren met specifieke socio-economische en biofysische karakteristieken kan verbeteren. De multidimensionele aanpak die in deze studie gebruikt is kan bijdragen aan het beter specificeren en toespitsen van de *agroforestry* technieken die beschikbaar zijn voor de kleine boerenbedrijven in Rwanda. De aanwezigheid van een grote diversiteit aan boerenbedrijven in de verschillende agro-ecologische zones, de verscheidenheid aan benodigdheden van boeren, en de verschillende voorkeuren van diverse boeren voor technieken roept om een zorgvuldige overweging en adaptatie van bestaande onderzoeksmethoden. Onderzoek naar *agroforestry* moet niet alleen de belangrijkste bepalende factoren voor productie in isolatie analyseren, maar moet een meer integrale aanpak nemen. Die aanpak kan resulteren in aantrekkelijkere opties, en meer geïntegreerde strategieen voor boeren. Om dit te bereiken zullen onderzoekers actiever de dialoog moeten aangaan met de belangrijkste doelgroep, de kleine boeren in Afrika ten zuiden van de Sahara.

Curriculum vitae

Charles BUCAGU was born on September, 5, 1970 in Butare (currently Huye District), Rwanda. He attended secondary school at St Albert College (Bujumbura, Burundi) from 1984 to 1990. He received an associate degree in Agricultural Science from the University of Burundi in 1992. He completed a BSc in Agricultural Science (option: Crop Science and Horticulture) at the National University of Rwanda with distinction (> 70%) in 1998. He was appointed Tutor in the same department in April 1999. From 2001 to 2003, he pursued an MSc (Agronomy) at the University of Pretoria, South Africa, specializing in crop physiology. On completion of the MSc degree, he was promoted to the rank of Lecturer in the Department of Crop Science and Horticulture. He was involved in various activities including teaching, research, administration and community services. From 2004 to 2006, he was tasked to coordinate high value crops programme within the PEARL project, a USAID funded project operating as a community outreach Initiative at the National University of Rwanda. Through NUFFIC (Netherlands University Foundation for International Cooperation) funding, he started a PhD at Wageningen University with the Plant Production Systems Group in 2006 focusing on the integration of agroforestry within small scale farming systems in Rwanda.

List of Publications

1. Journal papers

Bucagu, C., Vanlauwe, B., Van Wijk, M.T., Giller, K.E. (2013). Assessing farmers' interests in agroforestry in two contrasting agroecological zones of Rwanda. *Agroforestry Systems* 87:141–158.

Bucagu, C., Vanlauwe, B. and Giller, K.E. (2013). Managing *Tephrosia mulch* and fertilizer to enhance coffee productivity on smallholder farms in Eastern African Highlands. *European Journal of Agronomy* 48: 19– 29.

Klapwijk, C.J., Bucagu, C., van Wijk, M.T., Vanlauwe, B., Munyanziza, E. and Giller, K.E., Assessing current and potential fodder availability within smallholder farming systems in southwest Rwanda. Submitted to *Agricultural Systems*.

Mbonigaba, J.J., Nzeyimana, I., Bucagu, C., Culot, M. (2009). Caractérisation physique, chimique et microbiologique de trois sols acides tropicaux du Rwanda sous jachère naturelle: contraintes à leur productivité. *Biotechnology Agronomy Society and Environment* 13 (4) : 545-558

3. Participation in conferences

Bucagu, C., Metzger, M., Giller, K.E. (2007). "Environmental stratification of Rwanda and Burundi in support for regional studies" A poster presented at the International Symposium on Innovations as Key to the Green Revolution in Africa: Exploring the Scientific Effects' organised by Afnet. Arusha, September 29 to October 2, 2007.

Bucagu, C., van Wijk, M.T., Giller, K.E. (2007). Typology and productivity of agroforestry based farming systems of Rwanda. Paper presented at the International workshop on Agroforestry and Soil management held in Butare (Rwanda), 20-23 October 2008.

Bucagu, C. (2009). Analysis and strategies for improving productivity of farming systems in Southern Rwanda. A paper presented at the International Research Conference at the National University of Rwanda (NUR), Butare/Rwanda around the theme: "Enhancing food and Nutrition Security and Integrated Pest Management in Developing Countries".

PE&RC PhD Education Certificate

PE&RC PhD Education Certificate

With the educational activities listed below the PhD candidate has complied with the educational requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of literature (4 ECTS)

- The role of agroforestry in smallscale farming systems (2006)

Writing of project proposal (5 ECTS)

- Contributions of agroforestry legumes on smallscale farms in Rwanda (2006)

Post-graduate courses (7.3 ECTS)

- Advanced statistics; PE&RC (2006)
- International training workshop on decision support systems and crop modelling; Moroco (2006)
- Participation AfricaNUANCES workshop: impact and FARMSIM analytical tools; Arusha, Tanzania (2007)
- Participation to CIRAD/CIALCA training workshop; Butare, Rwanda (2008)
- Analysing farming systems and rural livelihoods in a changing world: vulnerability and adaption; WGS (2008)

Deficiency, refresh, brush-up courses (6 ECTS)

- System analysis: simulation and system management (2006)

Competence strengthening / skills courses (2.1 ECTS)

- Learning ArcGIS 9; ESRI (2006)
- Techniques for writing and presenting a scientific paper; CENTA (2008/2009)
- Working with EndNote X4; WUR/Library (2011)

PE&RC Annual meetings, seminars and the PE&RC weekend (1.2 ECTS)

- PE&RC Weekend (2006)
- PE&RC Days (2006-2009)
- Ad hoc PE&RC seminars (2006-2009)

Discussion groups / local seminars / other scientific meetings (4.5 ECTS)

- Soil nutrients dynamics discussion group; Wageningen (2006)
- Rwanda PhD discussion group; both in Wageningen and Rwanda (2006-2009)

International symposia, workshops and conferences (3.5 ECTS)

- AfricaNUANCES project workshop (2006)
- Workshops/conferences on agroforestry in farming systems ; ICRAF (2007)
- Sustainability of smallscale farm management practices (2008/2009)

Supervision of a MSc student (3 ECTS)

- Klapwijk, Lotte: availability of animal feed resources at farm village scale in Umurera, Rwanda

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