Cassava and soil fertility in intensifying smallholder farming systems of East Africa

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Voor Eva en Guido: mama’s boek is af!

Stand unshod upon it.
For the ground is holy,
Being even as it came from the Creator.
Keep it, guard it, care for it.
For it keeps men, guards men, cares for men.
Destroy it and man is destroyed.

Alan Paton, *Cry the beloved country*

Abstract

Cassava is an important crop in Africa. This thesis focuses on cassava production in the mid altitude zone of East Africa, an area characterized by high population densities, bimodal rainfall patterns and relatively poor soils. The overall aim was to better understand the roles and production constraints of cassava in order to explore opportunities to improve the productivity and sustainability of intensifying cassava-based smallholder farming systems in East Africa. Increasing land pressure has changed agricultural landscapes from traditional millet-, cotton-, sugarcane- or banana-based systems with an important fallow component to continuously, cultivated cassava-based systems. Cassava cultivation on cropped fields increased from 1-11 to 16-55% in three to four decades as farmers believe that cassava improves soil fertility for the subsequent crop and increasingly target cassava to low fertility soils when land pressure increases. The substantial increase in cassava cultivation has allowed farmers to postpone intensification of crop management, but it seems that the elasticity of the traditionally low-input systems is coming to an end as production of the two most important crops (cassava and maize) is limited by nutrients. Farmers in areas of high land pressure have started to adopt fertilizer and manure and to improve crop management.

Contrary to existing generalizations, cassava is not a food security crop for poorer farmers in East Africa, but an important food and cash crop for farmers from all wealth classes. Average farm income was not less than in other farming systems in the region, while average food security was higher (>10 months year^{-1}) than in maize-based systems. Cassava is also not predominantly grown as an intercrop, as is often thought, nor is it grown without inputs, because farmers commonly use hired labour and improved genotypes. In addition, its labour requirements are higher than commonly assumed (287 man days ha^{-1}), due to large requirements for weed control. Existing generalizations concerning cassava are therefore either false or half truths and a continued belief in them will hamper the effectiveness of policy and development efforts aimed at improving cassava production. Efforts to increase cassava production in cassava-based farming systems will, for example, improve its scope for commercialization, but will not significantly enhance food security.

Average farmer yields for cassava (7-12 t ha^{-1}) are far below attainable yields on farm (30-50 t ha^{-1}). Still, on-farm yields are highly variable. Largest yields were obtained on farms with high labour availability, fertile soils, good weed management and timely (not too early) harvesting. An improved technology package more than doubled average yields in farmer fields, whereby the largest yield increase for a single technology was observed with 100-22-83 kg ha^{-1} N-P-K fertilizer. Multivariate analysis identified soil fertility, rainfall and weed management as the most important production constraints, while biotic factors were less important. Many fields were affected by multiple and interacting production constraints. Fertilizer responses were governed by the same, interacting factors influencing unfertilized cassava production. Genotype and biotic factors did not influence fertilizer response. Closing the considerable yield gap between actual and attainable cassava yields at farm level, can not be achieved by integrated pest management and breeding alone. Instead, research and development organizations should focus on addressing the whole range of interacting production constraints through the development and evaluation of integrated management packages. Improving cassava production will be more difficult for poorer than for wealthier farmers, as the first have less social and financial capital and less fertile soils and are therefore more likely to face multiple production constraints.

The positive impact of cassava on soil fertility perceived by farmers is supported by model simulations and nutrient balances that indicate that cassava may improve SOC contents of low fertility soils compared with maize and contribute to higher N recycling through crop residues. Adoption of higher yielding genotypes and improved production practices will improve yields and increase nutrient removal rates, but may simultaneously have a positive effect on SOC contents and nutrient recycling rates. Improving cassava stem management after harvesting seems an interesting option to improve sustainability of the system.

This thesis concludes that there is an urgent need to invest in agronomy and ISFM research and to reform existing research for developments programmes with a strong emphasis on breeding and IPM into integrated programmes that are able to address the multiple production constraints of cassava and thereby significantly contribute to improving the livelihoods of smallholder cassava farmers.

Keywords: Cost-benefits, Crop management, Farming systems, Fertilizer, Food security, Generalizations, Income, Labour, Land pressure, Niche, Rainfall, Sub-Saharan Africa, System analysis, Yield gap.

Contents

Chapter 1

General introduction

1. Background

In large parts of sub-Saharan Africa soil fertility is low as a result of inherently infertile parent materials and/or due to continuous cropping without external inputs. Soil fertility depletion has been described as one of the most important constraint to food security in sub-Saharan Africa (Sanchez et al., 1997; Smaling et al., 1997). Rapid population growth throughout Africa increases land pressure and aggravates the strain on natural resources. Traditional strategies to maintain soil fertility (shifting cultivation, bush fallows) are no longer feasible and farmers often do not have the resources or skills to effectively use new strategies (cattle manure, fertilizer, legumes). Consequently many farmers rely largely on crop rotation in their efforts to maintain crop productivity.

Farming systems in sub-Saharan Africa can be characterized as small-holder systems which are highly diversified, heterogeneous and dynamic. Spatial soil variability across regions and farms, but also within farms, is high as result of inherent differences in soil properties related to parent materials and position on the toposequence and differential nutrient, crop and water management (Crowley and Carter, 2000; van Asten, 2003; Zingore, 2006; Tittonell, 2008). Consequently, management strategies that may work in one part of the farm, may not work in another part (Vanlauwe et al., 2006). Access to resources varies strongly between farm households. Wealthier households generally have more land, labour and cattle than poorer households and therefore have a wider choice of management options. Small-holder livelihood strategies are composed of a wide range of crop and livestock activities and off-farm income sources (unskilled labour, business, permanent employment), while production objectives may range from strongly market oriented to completely subsistence oriented (Tittonell, 2008). Regional crop production depends on a combination of agro-ecological conditions, market demand and food preferences. Market demand is highly dynamic, but food preferences may also change over time.

Cassava (*Manihot esculenta* Crantz) is an important crop in many African farming systems. It plays an important role in food security, but also as a cash crop. It was introduced to Africa in the 16 to 18th century, but it took until the 20th century for production to seriously take off (Jones, 1959; Hillocks, 2002). During the last five decades, total production in Africa has almost quadrupled from c. 31 to 118 million tons per year (FAO, 2009). In the last three decades, this has been rather due to increases in land area under production than increases in yield (Figure 1). Cassava is frequently cultivated on marginal soils (FAO, 2004b; Dixon et al., 2002; Fresco, 1986). Hillocks (2002), therefore, suggests that the observed increase in acreage is

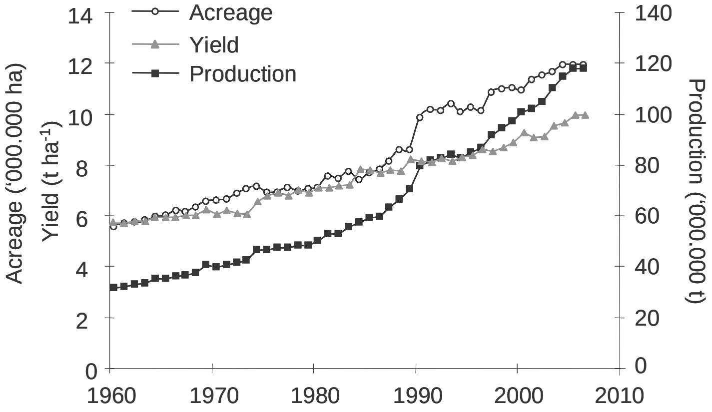


Figure 1: Cassava acreage, yield and production in Africa from 1961 to 2007 (FAO, 2009).

related to declining soil fertility levels in Africa. According to the FAO (2009), average cassava yields in Africa have gradually increased from c. 6 to 10 t ha^{-1} over the past five decades. At present, the average African farmer harvests approximately 20% less cassava per hectare than the world average of 12.2 t ha^{-1}. Nevertheless, there is potential for higher yields in Africa: in on-farm germplasm trials average yields of 15 to 40 t ha^{-1} are obtained (Ntawuruhunga et al., 2006; Fermont et al, 2007). However, little is known about the importance of various production constraints.

2. An introduction into cassava

Cassava is a shrub of 1 to 4 m. height that produces large storage roots, which are harvested 6 to 30 months after planting (MAP). It produces yields in a wide variety of rainfall conditions ranging from less than 600 mm in unimodal rainfall areas to well over 2000 mm in bimodal rainfall areas. Due to its perennial nature, the crop experiences alternating periods of vegetative growth and storage of carbohydrates in the roots (Alves, 2002). Generally speaking, the plant develops most of its stems and leaves during the first 6 months after planting and maximum canopy size is reached at 6 MAP. Storage root formation is initiated between 2 to 3 MAP, when a few fibrous roots (between 3 to 14) develop into storage roots, but the bulk of carbohydrates is usually relocated from the leaves to the roots between 6 to 10 MAP. Final root yields are determined by both the source supply (the amount of carbohydrates available in the above ground biomass) and the sink demand (the amount of carbohydrates that can be stored in the storage roots). The first is related to the leaf area index and the net assimilatory rate, while the second is related to the number of storage roots and their mean weight (Alves, 2002; El-Sharkawy, 2004).

Cassava has a rather sparse rooting system, with most roots concentrated in the topsoil and only a few roots descending beyond 2 m (El-Sharkawy, 2004). Compared with other crops, it forms extensive associations with mycorrhizal fungi in the soil. These assist the plant in the uptake of especially phosphorus, a low mobile element in the soil, by increasing the explored soil volume. Consequently, cassava has a much lower critical level for available P than less mycorrhizal dependent crops like maize and beans and is able to grow relatively well on soils with a weak capacity to supply P (Howeler et al., 1987). In addition, cassava is well adapted to acidic soils due to its tolerance to low pH and exchangeable aluminium (Howeler, 2002). The crop has a higher water use efficiency and can tolerate more water stress than many other crops (El-Sharkawy and Cock, 1986). This tolerance is related to several physiological mechanisms that cassava plants use to avoid drought stress by reducing transpiration losses and maintaining reasonable photosynthetic rates. These include partially stomata closure in response to both atmospheric and soil water stress, leaf folding in order to reduce leaf temperatures, a reduction in total leaf area and the ability to recover from water stress through an increase in leaf area and higher photosynthetic rates in the newly-formed leaves (El-Sharkawy, 2004; 2007). The above traits offer cassava comparative advantages in marginal environments and the ability to produce reasonable yields in places where other crops do not produce well (Howeler, 2002; Fresco, 1986; Cock and Howeler, 1978). Added advantages of cassava are its high productivity per unit of land and labour compared with other crops and a good in-ground storability. This, in combination with a wide choice of genotypes with early to late root bulking and high flexibility in its planting, weeding and harvesting times, enable farmers to maintain an almost continuous food supply throughout the year (Fresco, 1986; Nweke, 1994b). Cassava is either grown as a monoculture or intercropped with mainly cereals and/or legumes.

As the result of recurrent droughts and subsequent food shortages in southern Africa, the New Partnership for Africa’s Development (NEPAD) identified cassava as one of its key commodities in order to reduce dependence on maize. NEPAD has developed a Pan Africa Cassava initiative, which is attracting the attention of donors and governments (e.g., presidential initiatives in Nigeria and Ghana). According to Abdulai et al. (2005) investing funds into research and development activities on cassava is expected to create some of the comparatively highest Gross Domestic Product (GDP) gains from improved crop production.

3. Cassava-based farming systems in East Africa

East Africa (Tanzania, Kenya, Uganda, Rwanda and Burundi) accounts for 11% of total production of cassava in Africa. Yield estimates range from 6.5 to 12.0 t ha^{-1} between countries (FAO, 2009). Within the region, cassava is the most important staple food crop in terms of total production, followed by maize, sweet potato and cooking bananas. Production of cassava is concentrated in two contrasting agro-ecological zones: the mid-altitude area in the Great Lakes Region and the coastal zone of Tanzania and Kenya (Figure 2). This thesis concentrates on the largest of these two production zones, the mid-altitude area. This region is characterized by a wide diversity in agro-ecological and socio-economic conditions and market access and demand. As a result of large initial settlements attracted by the originally fertile soils western Kenya has one of the highest population densities in sub-Saharan Africa (> 250 persons km^{-2}) and land pressure is high (Braun et al., 1997; Soule and Shepherd, 2000). On the contrary, in Uganda one can still find regions with relatively low population densities (< 25 persons km^{-2}). Farming systems in the mid-altitude zone of

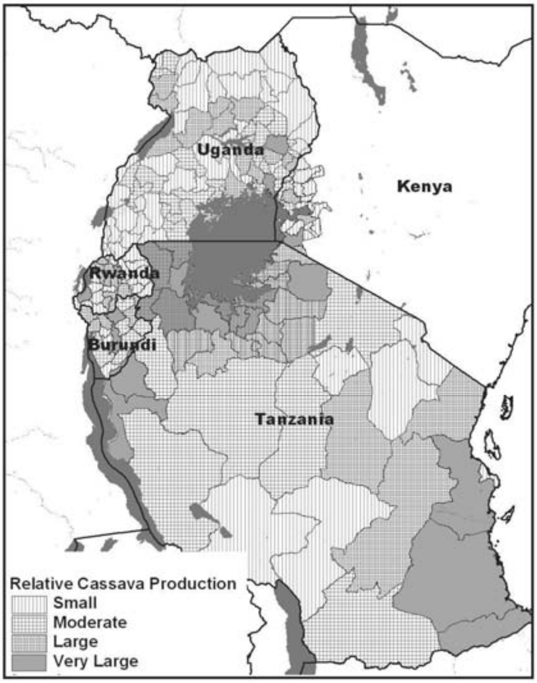


Figure 2: Relative importance of cassava production in East Africa. Production is classified on a per-country basis. No data were available for Kenya, except for western Kenya. Map is courtesy of Cassava Great Lakes Initiative (CGLI) project and provided by C. A. Legg.

East Africa are dominated by smallholder farmers, though in several areas large plantations of sugarcane and tea, sometimes using smallholder outgrowers, can be found. Most of the area has a bimodal rainfall pattern. Farm households generally grow a wide variety of crops, but intercropping systems are simple with generally only two crops.

Cassava is grown throughout the mid-altitude region, but production is concentrated in a wide band around Lake Victoria, northern/eastern Uganda and central Rwanda and Burundi (Figure 2). Production has been and still is severely affected by the cassava mosaic disease (CMD) pandemic that developed in Uganda in the early 1990s and has subsequently spread out. The pandemic is caused by simultaneous infections of cassava plants by the existing African Cassava Mosaic Virus and the new East African Cassava Mosaic Virus-Uganda, in combination with the super-abundance of the *B. tabaci* whitefly vector. The pandemic causes yield losses up to an average 72% in CMD affected, widely grown landraces (Legg et al., 2006). To control the pandemic, the International Institute of Tropical Agriculture (IITA) and the cassava programs of the National Agricultural Research and Extension Systems (NARES) in the region developed CMD resistant genotypes that were introduced on a wide scale. Initially promoted genotypes, including the widely adopted TMS 30572 (Nase 3) and SS4, were primarily selected on basis of CMD resistance, while genotypes promoted later were selected on a broader set of criteria that included yield.

4. Soil fertility in East African farming systems

The majority of agricultural soils in the mid-altitude zone of East Africa are Ferralsols, Acrisols and Nitisols; old, weathered soils that contain predominantly kaolinite and are virtually free of weathering minerals (Jaetzold and Schmidt, 1982; Andriesse and van der Pouw, 1985; Braun et al., 1997). Their fertility, in terms of available N and P, is closely related to soil organic matter content and, therefore, to the presence or absence of fallow periods (Foster, 1981; Padwick, 1983). To maintain soil fertility, Jones (1972) reported that a three year resting phase was required to restore the soil organic carbon and nutrients that were depleted in a three year growth phase. This is no longer feasible in most parts of East Africa as rapid population growth has provoked an evolution of farming systems towards more intensive systems with less and less fallow periods (Fresco, 1993; Nandwa and Bekunda, 1998). Nutrients are commonly not replaced to the degree that they are removed in crop harvests and other losses (Stoorvogel and Smaling, 1990; Hilhorst and Muchena, 2000;). This has resulted in a general trend of soil fertility decline, particularly in western Kenya. Nutrient balances for all cropping systems - apart from banana in Uganda which benefits from nutrient transfer from other land uses - were found to be negative, though at individual field level balances may be positive (Wortmann and Kaizzi, 1998; De Jager et al., 2001; Smaling et al., 2002). In the Lake Victoria Basin, nitrogen (N) and phosphorus (P) have been identified as the main limiting nutrients, but potassium (K) deficiency is locally important (Foster, 1981; Shepherd and Soule, 1998; Wortmann and Ssali, 2001; Vanlauwe et al., 2006).

To maintain soil fertility in cassava fields, Ugandan farmers commonly intercrop cassava with legumes (Nweke et al., 1999; Table 1). Less commonly used practices include incorporating or burning crop and weed residues, burning and grazing, whereas few farmers will apply mulch or (in)organic fertilizer to cassava fields. Overall, these strategies are not sufficient to offset nutrient losses. This situation is not much different from other staple food crops, such as cereals and sweet potato. However, throughout Africa farmers argue that cassava regenerates soil fertility (Kristjanson et al., 2002; Obiero, 2004; Saidou et al., 2004; Adjei-Nsiah et al. 2007).

Table 1: Soil fertility practices in cassava fields in Uganda (% of villages)[1].

Practice	Near fields	Distant fields
Intercropping with legumes	100	95
Incorporation of residues	59	56
Burning of residues	54	56
Grazing	36	28
Mulching	15	13
Manure	15	3
Inorganic fertilizer	5	3

[1] Based on data from Nweke et al. (1999)

5. Growing market opportunities for cassava

Cassava is well known as a food crop throughout the developing world that feeds both the rural and growing urban population. For the latter, an array of food products has been developed (Ferris et al., 1997; Nweke et al., 2002). These have been widely adopted in West Africa, but in East Africa the food markets remain limited to fresh and dried cassava. Still, the food markets are substantial: in 1991, approximately 25% of the cassava in Uganda was planted for the (fresh) market (Nweke et al., 1999). Since Thailand started exporting large quantities of cassava to the European Union in the nineteen eighties, cassava has become an important component of animal feed. Although the potential demand in the feed industry in Africa is high (e.g. 500,000 tons of cassava in Kenya), efforts to replace maize with cassava flour in chicken feed have not been very successful until now due to both supply and production problems and low prices offered to farmers (Karuri et al., 2001; Graffham et al., 2003). In Brazil and

Asia, cassava has more recently gained momentum as an industrial crop in the form of starch and ethanol for biofuel production (Henry and Hershey, 2002; Charoenrath, 2008; Fadel, 2008). With strong government support and so-called E10 programmes, that require replacing 10% of normal gasoline with ethanol, Thailand and Vietnam are capitalizing on the recent interest in biofuels. The recent increase in the average price of major cereals, which might continue to increase in the next decade as OECD/FAO (2008) predicted, will improve the competitiveness of cassava and may significantly increase the use of cassava as an alternative for maize and wheat flour in the food, feed, starch and biofuel industries. Expanding markets for cassava may turn cassava into a cash crop for smallholder farmers, while maintaining food security, and thus become a driver for rural change in Africa (FAO, 2004b). Outgrower schemes, whereby farmers are contracted by industries to produce cassava, are likely to become increasingly important. As production costs in Africa are high compared with Asia, most market opportunities need to be sought at local and regional level (FAO and IFAD, 2004).

The FAO (2004b) has identified three main prerequisites for cassava to become a successful trade commodity within Africa: (i) a substantial reduction of its production costs; (ii) a constant supply throughout the year; and (iii) a consistent high quality of cassava products. The first is required to increase the competitiveness of cassava in relation to maize and can be achieved by increasing production and/or decreasing labour demands. The second and third will require improved harvesting, post harvesting and processing technologies.

6. Cassava agronomy research

The growing markets for cassava, coupled with concerns about system sustainability in relation to the introduction of higher yielding genotypes, generally poor soils and low input use, have recently led to a growing interest in cassava agronomy and integrated soil fertility management (ISFM) in Africa. Cassava is among the least researched crops among the major crops in the world. Until the establishment of the International Institute of Tropical Agriculture (IITA) and the Centre Internacional de Agricultura Tropical (CIAT) in the late 1960s the global knowledge base on cassava was meagre. In order to control the major pests and diseases that threatened food security for millions of farmers (e.g. mealy bug, green mites, mosaic virus and more recently brown streak virus), IITA and its NARES partners focused on breeding and integrated pest management (IPM). Although this has resulted in improvements in cassava productivity (Figure 1), yields increased much less than for cereals and legumes. It is slowly becoming clear that breeding and IPM alone cannot bring about the production increases required to develop cassava into a strong food and cash crop. With less, or even no, serious pest and disease threats, well developed cassava markets and strong government support, cassava research in Latin America and especially in Asia has focused much stronger on agronomy, ISFM and crop physiology than in Africa.

Comparing cassava with other crops, Howeler (1991a) and Putthacharoen et al. (1998) found that nitrogen (N) and phosphorus (P) removal per hectare by cassava roots was lower than for the harvest products of most other crops, while potassium (K) removal was substantially higher in case of high cassava yields (36 t ha^{-1}) and similar to other crops in case of moderate cassava yields (11 t ha^{-1}). Although cassava still yields in infertile soils, it is responsive to fertilizer (Howeler, 2002). Inorganic fertilizer recommendations generally have a ratio of 2-1-2 or 2-1-3 of $N\text{-}P_2O5\text{-}K_2O$ and are sometimes applied in combination with manure (Nguyen et al., 2000; CIAT, 2009). Cassava, like any root crop, requires large amounts of potassium for optimal production. Continuous cassava production, without fertilization, will inevitably result in K becoming the most limiting nutrient (Howeler, 2002). In case of vigorous cassava genotypes, an excess of N fertilizer may over stimulate top growth at the expense of root production. Responses to P fertilizer depended on the available P supply, the mycorrhizal infection potential of the soil and the fine root length and shoot/tuberous root balance of the cassava genotype (Pellet and El-Sharkawy, 1993). In different agro-ecologies, N, P and K have all been identified as the most limiting nutrient for cassava production. Cassava is sensitive to zinc (Zn) deficiency, especially during early growth stages (Howeler, 2002). Cassava’s initial slow growth renders the crop sensitive to erosion problems if grown on sandy soils on sloping land and/or to weed competition during the first 3 to 4 months after planting. Management options to control erosion and sustain long-term cassava productivity include fertilizer use to stimulate early growth, intercropping with legumes and live barriers. The success of erosion control strategies is, however, highly site-specific as it depends on local conditions and farmer’s traditional practices (Howeler, 2008). Weed competition in the first months after planting may result in yield reductions of approximately 50% (Leihner, 2002). Good weed control during the first months after planting, either by hand or mechanical weeding, herbicide use or agronomic practices, is essential to obtain good yields and may, in itself, help to reduce erosion. Though cassava can generally tolerate drought stress better than other crops, the most critical period for a water-deficit in cassava is from 1 to 5 MAP – the stages of root initiation and tuberization. A water deficit during at least 2 months of this period can reduce root yields up to 60% (Connor et al., 1981). Management practices to reduce the impact of drought stress during this period include the selection of genotypes with a slightly more than optimal leaf area index (LAI) and timely planting with respect to the rains (El-Sharkawy and Cock, 1987; Fauzan and Puspitorini, 2000). In our efforts to increase yields and profitability of cassava production in Africa, while maintaining or improving system sustainability, we can take advantage of lessons learned in Asia and Latin America.

7. Aims and outline of the thesis

The overall aim of this research was to better understand the roles and production constraints of cassava in order to explore opportunities to improve the productivity and sustainability of intensifying cassava-based smallholder farming systems in East Africa. Specific objectives were to:

1. Evaluate the different roles of cassava in the livelihoods of smallholder farmers in relation to existing generalizations to improve interventions aimed at improving cassava production
2. Investigate the impact of increasing land pressure on the importance and temporal and physical niches of cassava
3. Quantify the factors that contribute to the yield gap of cassava
4. Quantify the response of cassava to mineral N, P and K and assess the factors that affect fertilizer response
5. Explore the impact of identified management options on the sustainability of cassava based systems

To address these objectives a combination of farming systems analysis using participatory rural appraisals (PRA's) and on-farm surveys, on-farm and on-station agronomic trials and a modelling approach was used (Figure 3). A farming systems approach allowed for the development of the bigger picture as it studied roles and crop management of cassava in relation to other crops, within the socio-economic settings of smallholder farm households and the larger socio-economic and historical context. Installing agronomic trials, both with farmers in their own fields and on research station fields over two years, enabled data collection in a range of environments and proved very useful to objectives 3 and 4. We extrapolate the obtained understanding of the dynamics in cassava-based farming systems to the future by using a modelling approach. Figure 3 shows the overall framework of this research and depicts the relation between the general context of this research, research locations, research activities and tools and the chapters of this thesis.

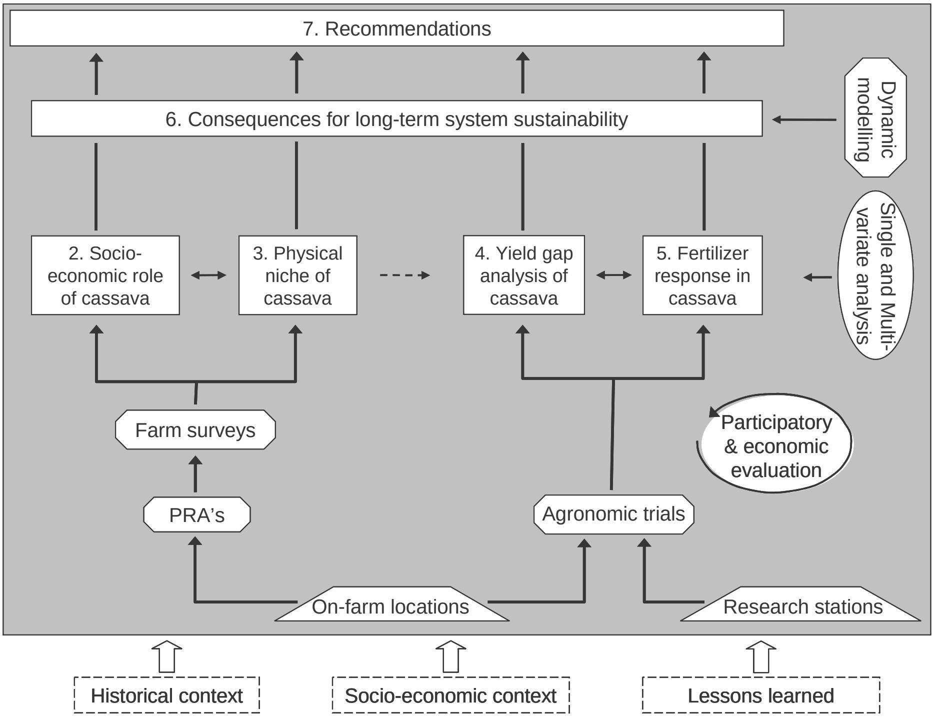
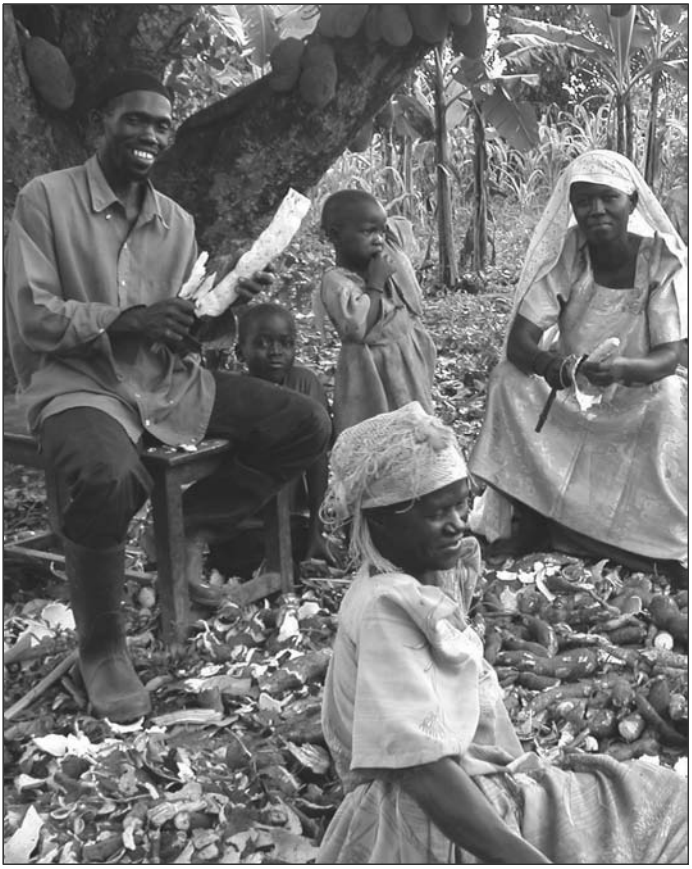


Figure 3: General framework of this thesis. Relation between the general context (dashed squares), research locations (trapeziums), research activities (rectangular octagons), analytical tools (ovals) and thesis chapters (solid, numbered squares – numbers correspond to the thesis chapters).

Chapter 2 and 3 examine cassava at the level of the farming system and beyond. Chapter 2 studies the truth behind several socio-economic generalizations that exist concerning cassava and evaluates the consequences of such generalizations for interventions aimed at improving cassava production. Chapter 3 studies the historical development of crop importance in farming systems that are currently classified as cassava-based systems to understand the physical niches that cassava occupies within these farming systems. Chapter 4 and 5 zoom in to the field level of cassava production. In chapter 4 farm surveys and agronomic data from 8 sites in Uganda and Kenya are used to identify and quantify the most important production constraints for cassava in the region using multi-variate analysis techniques. Chapter 5 studies the potential of NPK fertilizer to overcome soil fertility constraints and investigates factors affecting the yield response to fertilizer. Chapter 6 and 7 zoom out again to a farming systems perspective, whereby chapter 6 concentrates on exploring the consequences of changes in crop management for the sustainability of farming systems through modelling and chapter 7 elaborates on lessons learned, changing roles of cassava in the future and a way forward for agronomy research in Africa.

Chapter 2

Testing generalizations about cassava in East Africa and consequences for policy and development interventions



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Abstract

This study evaluates five generalizations that exist concerning the socio-economic role and management of cassava and discusses consequences for interventions designed to improve cassava production. Cassava is said to be: (i) a subsistence crop; (ii) grown by poor farmers; (iii) predominantly as an intercrop; (iv) requiring less labour than other crops; and (v) grown without inputs. Farm surveys in cassava-based farming systems in Uganda and Kenya showed that households from all wealth classes planted, consumed and marketed important amounts of cassava. Food self-sufficiency was high and positively associated with the land area on which cassava was grown. Cassava generated, on average, a larger part of crop income than any other crop. Farm income was not less than in other farming systems in East Africa. Poorer households planted more cassava as an intercrop than wealthier households, but still planted approximately half as a sole crop. Due to frequent weeding, total labour demand (287 man days ha^{-1}) was large compared with other crops. One third of the households hired labour for cassava weeding and half applied manure in cassava-maize intercropping systems. We conclude that for our study area the tested generalizations are either half truths or untrue and identify the following consequences for sustainable development of cassava-based farming systems. Efforts to increase cassava production will improve its scope for commercialization, but will not enhance food self-sufficiency. Cassava is well positioned to improve the livelihoods of smallholder farmers, but it is more challenging than commonly assumed to use cassava as an entry point to reach the poor. To develop the opportunities cassava offers, requires site-specific targeting of projects and development of management packages and regional markets.

Keywords: Food security, Income, Input use, Labour, Wealth classes, Weed management

1. Introduction

Since its introduction in Africa in the 16th century, cassava (*Manihot esculenta* Crantz) has become one of the most important crops on the continent. Production has more than tripled in the last four decades (Hillocks, 2002) and the crop is currently grown on approximately 12 million hectares. As food, feed and industrial markets are promising (FAO, 2004b), there is an increasing focus on cassava by governments, research and development institutes in Africa.

Over the centuries, many generalizations about cassava have evolved in sub-Saharan Africa. Cassava is said to be a subsistence crop, grown by resource poor, small farmers (Jameson, 1970; Alves, 2002; FAO, 2004b), who plant it preferably as an intercrop to reduce the risk of crop failure, while maximizing returns to land and labour (Otim-Nape et al., 1997; Leihner, 2002). Further, cassava is thought to require less labour than other crops (Cock, 1985; Berry, 1993) and to be grown without inputs (Leihner, 2002). Such generalizations will influence policy and project development and implementation, and if wrong, may have far-reaching consequences for the success and sustainability of interventions.

Few studies provide solid data to verify these generalizations about the role of cassava in African farming systems. The Collaborative Study of Cassava in Africa (COSCA) reported the most comprehensive information on cassava based cropping systems, but labour use and crop management issues are poorly described and the socio-economic role of cassava has not been investigated. Few other studies are available to confirm findings of the COSCA studies and these are from West and Central Africa (Fresco, 1986; Philips et al., 2006) with none from East Africa.

The objectives of this study were to investigate to what extent common generalizations about cassava are valid in East Africa and to evaluate consequences for the design and implementation of cassava policies and projects. We carried out a series of detailed farm surveys among smallholder farmers to evaluate the socio-economic role of cassava, crop management and labour use in relation to other crops. The selected study sites are representative for large parts of the cassava area in the mid altitude zone of East Africa as they exhibit a wide range in agro-ecological and socio-economical conditions. With average fresh yields of 10.6 in Kenya and 12.0 t ha^{-1} in Uganda, cassava yields are just above the African average of 9.9 t ha^{-1}.

2. Materials and methods

2.1 Site selection

This study focused on smallholder farming systems in central and eastern Uganda and western Kenya. Site selection was based on the importance of cassava, the degree of poverty, population density and agro-ecological characteristics (Thornton et al., 2002; Fermont et al., 2008 – Chapter 3). The farm surveys were carried out in three sites in western Kenya and three sites in Uganda. In Kenya, the sites included Kwang'amor (0^{o}29'N, 34^{o}14'E), Mungatsi (0^{o}27'N; 34^{o}18'E) and Ugunja (0^{o}10'N; 34^{o}18'E) in Teso, Busia and Siaya districts, respectively. In Uganda, the sites included Kisiro (0^{o}67'N; 33^{o}80'E), Kikooba (1^{o}40'N; 32^{o}38'E) and Chelekura (1^{o}14'N; 33^{o}62'E) in Iganga, Nakasongola and Pallisa district, respectively. Altitude in these sites varies between 1100 to 1260 masl, while the topography ranges from gently undulating to undulating. The climate is sub-humid with a bimodal rainfall distribution. In central Uganda less than 40% of the households falls below the poverty line, while parts of western Kenya have the highest poverty rates (> 60%) in East Africa (Thornton et al., 2002). High population pressure in most sites (160-387 persons km^{-2}) has resulted in continuous farming systems with limited fallow (Fermont et al., 2008 – Chapter 3).

2.2 Farm selection and characterization

Households at the six farm survey sites were categorized by local key informants according to their resource endowment into three wealth classes: poorer, medium and wealthier. Criteria used for the categorization were site-specific and included farm size, number of animals, off-farm income and education of children. Within each site twenty households were randomly selected with a minimum representation of three households per wealth category. Structured interviews in combination with a visit to all fields within each farm were used to characterize each household in detail in terms of land use, socio-economic importance of crops, food self-sufficiency, crop management and labour aspects. Household income was calculated from income generated by crop activities, other farm activities (livestock, honey, hiring land), casual work, permanent income sources (salary or pension), business and remittances or 'money sent home'. Interviews were held with the family member taking most of the decisions on farming activities, but information was cross-checked with other family members. Information was triangulated through multiple questions on sensitive topics, combining interview and field data, confirmation by key informants and subsequent visits. Income data were used to cross check the wealth class of the households, whereby 2 households were reclassified. The farm characterizations were carried out from June to September 2004 in western Kenya and from October 2005 to April 2006 in Uganda.

2.3 Labour use, food self-sufficiency and gross margin analysis

Available labour per farm was calculated from the number of family members in different age categories, assuming that children between 8-12 and 12-16 years contributed 0.15 and 0.45 man years respectively and an adult person year was comprised of 312 working days (information from resource persons). Available family labour was corrected for labour hired in and hired out. To compare total labour requirements of cassava with other crops, farmers ranked total labour required for one crop cycle of cassava versus total labour required for one crop cycle of selected other sole crops on a same size field. Relative monthly labour requirement was calculated using the average harvest age of cassava as supplied by farmers and a crop cycle of 4, 5.5, 4, 4, 3, 8, 5 and 18 months for maize, millet, sorghum, groundnut, beans, sweet potato, cotton and sugarcane respectively. To evaluate the contribution of cassava to staple food consumption, all households ranked the relative importance of cassava and other starchy staple crops. To quantify food self-sufficiency, households indicated the number of months per year their farm supplied sufficient food.

For each farmer who supplied yield estimates for cassava and maize, partial gross margins for cassava and maize production were calculated. Costs taken into account were labour for ploughing, planting and weeding and purchase of maize seeds and fertilizer. Prices for hired labour were used to mirror the opportunity costs of labour (CIMMYT, 1998) as farmers hired labour for agricultural activities in the study areas. Labour costs did not vary significantly between sites within a country and average values per country were used. The number of weed operations and quantity of fertilizer used were obtained from the farm surveys, whereas constant values were used for ploughing and maize seeds. Harvest and post-harvest labour costs expressed per ton of maize or cassava harvested were measured in Uganda and took into account labour for harvesting, transport, peeling, chipping and drying. Average retail and wholesale market prices during the survey periods were used for maize seeds and fertilizer, cassava chips (250 Uganda Shillings kg^{-1}; Ugsh and 15 Kenya Shillings kg^{-1}; Ksh) and maize (290 Ugsh kg^{-1} and 17 Ksh kg^{-1}) respectively (1 US$ = 1818 Ugsh or 80 Ksh).

2.4 Data analysis

Significance of differences between sites and wealth classes for selected socio-economic, food self-sufficiency, crop acreage, crop income and profit parameters were tested using univariate analysis of variance with subsequent Tamhane test for post-hoc comparison or non-parametric Kruskal-Wallis one-way ANOVA where appropriate. One sample t-tests were used to test whether relative total and monthly labour requirements of various sole cropped crops differed significantly from those of sole cropped cassava. Paired t-tests were used to test whether weed management, weeding preference and hired labour differed between cassava and other crops. Chi square tests were used to compare the percentages of households for whom cassava was the most important staple food or for whom cassava generated more income than other crops by wealth class. Chi square tests were also used to compare the percentages of households making profit from cassava and maize. The statistical significance of relations between acreage under cassava and food self-sufficiency and income generated by cassava were assessed by two tailed Pearson correlations. All statistical analyses were carried out using GenStat Discovery for Windows (edition 3) and SPSS for Windows (version 10.0).

3. Results

3.1 Description of the farming systems

The amount of cropped land, hired labour, income, food self-sufficiency, natural resource management and crop yields varied strongly between sites and wealth classes (Table 1). The cropped land ranged from 1.0 to 3.9 ha between sites. Hiring labour for agricultural work was very common in some sites, but limited to a few farmers in others. Cattle, mostly local Zebu (*Bos indicus)* breeds, were more important ($P<0.01$) in Kikooba and Kwang'amor (7.0 and 4.8 cows per household, respectively) than in the other sites (2.0-2.5 cows per household). Average annual household income ranged from US$ 633 to US$ 1,283 between sites and was generated for a large part (42-88%) through farm activities. Wealthier households had more access to land, labour and cattle and earned nearly ten times more income than poorer households ($P<0.001$). Farms produced at least five to six different types of crops (Table 2). In all sites, the most important food crops were cassava and maize (*Zea mays* L.), while groundnuts (*Arachis hypogaea* L.), sweet potato (*Ipomoea batatas* L.), finger millet (*Eleusine coracana* L.) and sorghum (*Sorghum bicolor* (L.) Moench) were generally less important, though not in all sites. Cash cropping was restricted to cotton (*Gossypium hirsutum* L.) in one Ugandan site and sugarcane (*Saccharum officinarum* L.) in two Kenyan sites. Cassava yields ranged from 6.6 to 12.7 t ha^{-1}, while maize yields ranged from 0.7 to 1.4 t ha^{-1} between sites. Cassava yielded significantly ($P<0.001$) less in Kenya (7.0 t ha^{-1}) than in Uganda (11.3 t ha^{-1}), but maize yields did not vary between countries. Land preparation was either done by hand, or by a combination of oxen and

Table 1: Selected mean characteristics of households in the six study sites in Uganda (U) and Kenya (K) by site and wealth class

		n -	Cropped land (ha)	Hired labour (man days yr^{-1})	Land:labour ratio (ha adult equivalent^{-1})	Household income $(\$\ \mathrm{yr}^{-1})$	Farm income (% HH income)	Food self-sufficiency (months yr^{-1})	Manure use (kg ha^{-1})	Fertilizer use (kg ha^{-1})	Cassava yield (t ha^{-1})	Maize yield (t ha^{-1})
Site												
Kisiro	(U)	19	3.9 ± 3.3	438 ± 653	0.7 ± 0.2	1266 ± 1120	88 ± 15	11.1 ± 2.0	46 ± 192	5 ± 16	8.3 ± 2.7	1.4 ± 0.4
Kikooba	(U)	21	1.7 ± 1.5	29 ± 53	0.6 ± 0.5	961 ± 895	50 ± 34	11.7 ± 1.3	0	0	11.2 ± 3.5	0.7 ± 0.2
Chelekura	(U)	20	1.7 ± 1.2	482 ± 654	0.2 ± 0.1	868 ± 855	51 ± 34	10.2 ± 2.5	391 ± 583	0	11.7 ± 3.7	1.0 ± 0.3
Kwang'amor	(K)	20	1.9 ± 1.8	205 ± 351	0.5 ± 0.4	835 ± 1170	73 ± 26	11.5 ± 1.5	269 ± 283	15 ± 26	7.7 ± 2.5	1.1 ± 0.6
Mungatsi	(K)	20	1.7 ± 1.3	294 ± 379	0.4 ± 0.2	1283 ± 1497	55 ± 35	11.5 ± 1.6	400 ± 383	40 ± 48	6.7 ± 2.3	1.2 ± 0.6
Ugunja	(K)	20	1.0 ± 0.6	70 ± 147	0.3 ± 0.2	633 ± 703	42 ± 28	11.0 ± 1.4	904 ± 1054	34 ± 59	6.1 ± 1.9	1.0 ± 0.4
P		-	*<0.01*	*<0.01*	*<0.001*	*ns*	*<0.001*	*ns*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
Wealth class												
Wealthier		26	4.0 ± 3.0	670 ± 650	0.6 ± 0.5	2456 ± 1295	51 ± 34	11.6 ± 1.1	458 ± 679	35 ± 55	9.9 ± 3.9	1.4 ± 0.7
Medium		39	2.1 ± 1.2	264 ± 425	0.4 ± 0.2	948 ± 537	70 ± 30	11.5 ± 1.5	354 ± 713	17 ± 37	9.1 ± 3.1	1.2 ± 0.4
Poorer		55	1.0 ± 0.5	40 ± 84	0.4 ± 0.3	287 ± 138	56 ± 33	10.7 ± 2.2	263 ± 464	5 ± 15	7.7 ± 3.4	0.9 ± 0.3
P		-	*<0.001*	*<0.001*	*<0.05*	*<0.001*	*<0.05*	*ns*	*ns*	*<0.001*	*<0.05*	*<0.001*
Overall means		120	2.0 ± 2.0	249 ± 457	0.4 ± 0.3	972 ± 1073	60 ± 33	11.2 ± 1.8	335 ± 602	16 ± 36	8.6 ± 3.5	1.0 ± 0.5

Table 2: Mean acreage (ha) for selected crop in the six study sites in Uganda (U) and Kenya (K) by site and wealth class

			Root and tubers		Cereals			Legumes	Cash crops	
		n	Cassava	Sweet potato	Maize	Sorghum	Millet	Groundnuts	Cotton	Sugarcane
Site										
Kisiro	(U)	19	0.59 ± 0.6	0.19 ± 0.2	1.82 ± 2.7	0.03 ± 0.1	0.05 ± 0.1	0.74 ± 0.6	0.07 ± 0.1	0
Kikooba	(U)	21	0.93 ± 0.8	0.27 ± 0.2	0.18 ± 0.4	0	0.02 ± 0.1	0.12 ± 0.1	0	0
Chelekura	(U)	20	0.56 ± 0.6	0.10 ± 0.1	0.09 ± 0.1	0.08 ± 0.1	0.21 ± 0.2	0.13 ± 0.2	0.21 ± 0.3	0
Kwang'amor	(K)	19	0.71 ± 0.7	0.04 ± 0.1	0.53 ± 0.7	0.04 ± 0.1	0.09 ± 0.1	0.03 ± 0.0	0	0.29 ± 0.7
Mungatsi	(K)	21	0.34 ± 0.2	0.03 ± 0.0	0.36 ± 0.3	0.03 ± 0.0	0.01 ± 0.0	0.02 ± 0.0	0.01 ± 0.0	0.81 ± 0.9
Ugunja	(K)	20	0.32 ± 0.2	0.09 ± 0.1	0.41 ± 0.2	0.14 ± 0.2	0.02 ± 0.1	0.03 ± 0.1	0	0.00 ± 0.0
P		-	*<0.01*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
Wealth class										
Wealthier		26	1.14 ± 1.0	0.22 ± 0.2	1.21 ± 2.4	0.10 ± 0.2	0.11 ± 0.2	0.25 ± 0.4	0.03 ± 0.1	0.44 ± 1.0
Medium		39	0.55 ± 0.4	0.12 ± 0.1	0.61 ± 0.7	0.05 ± 0.1	0.07 ± 0.2	0.24 ± 0.4	0.10 ± 0.2	0.21 ± 0.4
Poorer		55	0.33 ± 0.2	0.07 ± 0.1	0.2 ± 0.2	0.03 ± 0.1	0.04 ± 0.1	0.09 ± 0.2	0.03 ± 0.1	0.05 ± 0.2
P			*<0.001*	*<0.001*	*<0.01*	*ns*	*ns*	*ns*	*ns*	*<0.05*
Overall means		*120*	*0.58 ± 0.6*	*0.12 ± 0.2*	*0.55 ± 1.2*	*0.06 ± 0.1*	*0.07 ± 0.1*	*0.17 ± 0.3*	*0.05 ± 0.1*	*0.19 ± 0.5*

hand ploughing. Manure use was common in four sites, but fertilizer use was limited to the Kenyan sites and generally low. Wealthier households made up 4 to 16% of the population in all sites, while poorer households constituted between 37 to 64% of the population (Table 3).

Table 3: Households (% total population) by wealth class in the six study sites in Uganda (U) and Kenya (K)

		Wealth classes		
		Wealthier	Medium	Poorer
Kisiro	(U)	7	50	43
Kikooba	(U)	16	42	42
Chelekura	(U)	4	32	64
Kwang'amor	(K)	15	42	44
Mungatsi	(K)	9	55	37
Ugunja	(K)	10	46	44

3.2 Crop acreage, food consumption and marketing

On average, cassava and maize were planted on 0.58 and 0.55 ha or 34 and 24% of the cropped land, respectively (Table 2). Wealthier households generally planted larger acreages of the most commonly grown food crops (cassava, maize, sweet potato) and cash crops than poorer households (*P*<0.01). On a relative scale, however, poorer households in Kenya planted more (+14%) of their cropped land with cassava (*P*<0.05) and less (-14%) with sugarcane than farmers with a better resource endowment, while Ugandan households of all wealth classes dedicated similar proportions of their cropped land to the major crops.

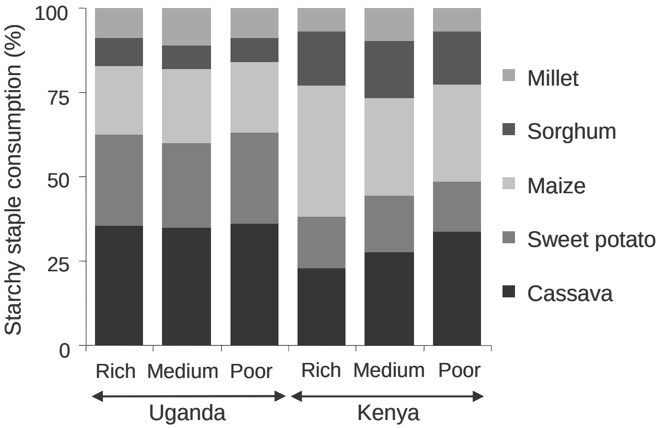


Figure 1: Contribution of selected crops to the starchy staple food consumption of households by country x wealth class for the six study sites in Uganda and Kenya.

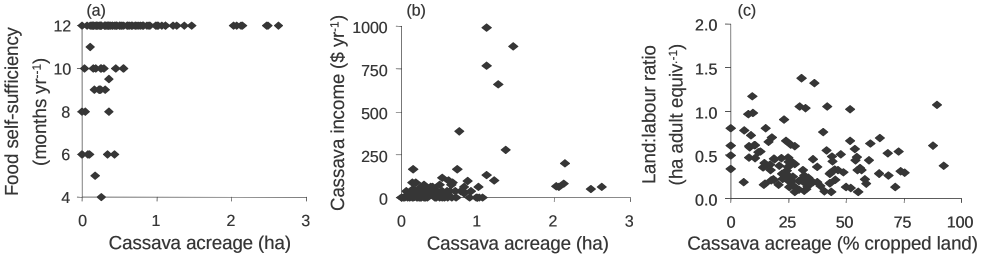


Figure 2: Cassava acreage versus a) household food self-sufficiency; b) annual income generated by cassava and; c) land:labour ratio for the six study sites in Uganda and Kenya.

The contribution of food crops to the starchy staple food consumption of households varied between sites ($P<0.01$). Cassava contributed between 27 and 41% of the starchy staple food consumption, while maize and sweet potato contributed between 14 and 33% and 11 and 39%, respectively. For 55% of all households, cassava contributed the largest proportion of the starchy staple food consumption, but this ranged from 35% to 90% between sites. In Uganda, wealth class did not influence staple food consumption patterns, whereas in Kenya cassava was the most important staple food for 67% of the poorer farmers versus 8% of the richer farmers ($\mathrm{P}<0.01$) and poorer farmers ate on average 11% more cassava ($P<0.001$) and 10% less maize ($P<0.05$) than wealthier farmers (Figure 1). Average food self-sufficiency was high (Table 1) and only 15% of all surveyed households were food insufficient for more than 2 months per year. Households with more than 0.6 ha of cassava were always completely self-sufficient in food (Figure 2a).

Average income generated by crops varied strongly between sites (Table 4). Cassava and maize were marketed in all sites and generated on average 84 and 90 US\$ yr^{-1}, respectively. Groundnut marketing was limited to the Ugandan sites. Sweet potato, millet and sorghum generated small amounts of income only, while cash crops generated income in individual sites only. Overall, 63% of the households sold cassava, 58% sold maize and 48% sold groundnuts, while all other crops were sold by less than one third of the households. Cassava generated, on average, 23% of the total crop income, whereas maize and groundnuts generated 14 and 16%. All other crops contributed significantly ($P<0.05$) less to the crop income (data not shown). For 26% of all households, cassava generated more income than any other crop. Cassava was sold in quantities ranging from a few tins of dried chips on the local market to whole fields sold to traders. On average, households sold 23% of their cassava production. Marketing of cassava was not restricted to households with larger acreages of cassava: households with as little as 0.1 ha of cassava earned some income from cassava

Table 4: Income ($ per year) generated by selected crops in the six study sites in Uganda (U) and Kenya (K) by site and country x wealth class

			Root and tubers		Cereals			Legumes	Cash crops	
		n	Cassava	Sweet potato	Maize	Sorghum	Millet	Groundnuts	Cotton	Sugarcane
Site										
Kisiro	(U)	19	59 ± 226	0	446 ± 586	0	0	485 ± 428	71 ± 139	0
Kikooba	(U)	21	312 ± 527	4 ± 10	20 ± 51	0	0	48 ± 88	0	0
Chelekura	(U)	20	13 ± 25	2 ± 8	4 ± 8	0	25 ± 47	98 ± 180	74 ± 99	0
Kwang'amor	(K)	20	54 ± 46	6 ± 12	46 ± 36	17 ± 24	36 ± 63	5 ± 10	7 ± 22	116 ± 274
Mungatsi	(K)	20	24 ± 25	12 ± 24	39 ± 95	3 ± 7	6 ± 22	4 ± 15	5 ± 24	263 ± 300
Ugunja	(K)	20	27 ± 23	14 ± 19	8 ± 10	12 ± 18	1 ± 5	5 ± 11	0	2 ± 7
P			*<0.001*	*<0.05*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
Country x Wealth class										
Uganda										
Wealthier		13	439 ± 650	5 ± 12	393 ± 752	0	8 ± 23	338 ± 442	55 ± 138	0
Medium		20	92 ± 214	3 ± 9	154 ± 189	0	17 ± 49	319 ± 385	91 ± 133	0
Poorer		27	18 ± 358	0	34 ± 62	0	2 ± 6	62 ± 98	14 ± 24	0
P			*<0.001*	*ns*	*<0.05*	*ns*	*ns*	*<0.01*	*ns*	*ns*
Kenya										
Wealthier		13	37 ± 54	5 ± 8	55 ± 93	17 ± 32	31 ± 77	5 ± 10	0	312 ± 448
Medium		19	37 ± 31	16 ± 27	37 ± 68	12 ± 14	16 ± 31	7 ± 17	11 ± 31	153 ± 176
Poorer		28	33 ± 27	9 ± 15	16 ± 18	7 ± 11	5 ± 13	3 ± 8	2 ± 7	18 ± 44
P			*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*<0.05*
Overall means		120	84 ± 256	6 ± 15	90 ± 280	5 ±14	12 ± 36	104 ± 251	26 ± 76	63 ± 190

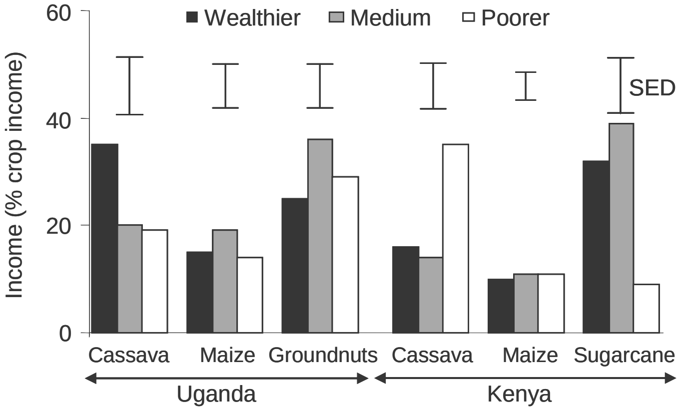


Figure 3: Contribution of selected crops to crop income by country x wealth class for the six study sites in Uganda and Kenya. SED = Standard Error of Difference.

(Figure 2b). In Uganda, wealthier households earned considerably more income from cassava, maize and groundnuts than poorer households (P<0.05; Table 4). Also in relative terms, cassava contributed a larger share of crop income for wealthier than for poorer households, though the contribution of maize and groundnuts to crop income was similar across wealth classes (Figure 3). In Kenya, all wealth classes earned similar amounts of income from all crops, except sugarcane (Table 4). Nonetheless, in relative terms cassava contributed more to the crop income of poorer than of wealthier households, while maize contributed similar shares across wealth classes (Figure 3).

Cassava production was overall more profitable in Uganda than in Kenya (195 *vs* 78 US$ ha^{-1}; P<0.001), while maize production in both countries generated similar profits (34 *vs* 33 US$ ha^{-1}; Table 5). In both countries the profits for cassava were higher than those for maize and a larger share of the households made a profit from cassava than from maize production (86 *vs* 64%; P<0.001). Nonetheless, due to relatively high maize yields and low cassava yields (Table 1), Kenyan households with a medium and good resource endowment earned similar profits from cassava and maize production (Table 5).

3.3 Intercropping, input use and labour

Cassava intercropping was a less common practice in Uganda than in Kenya, with 30% of the cassava acreage intercropped in Uganda and 51% in Kenya (P<0.001). Maize was the most common intercrop (> 50% of the cassava intercropping systems) in all but one site while beans, sorghum and to a lesser extent groundnuts and cotton were locally important intercrops. In Uganda poorer farmers planted more (+29%) of

Table 5: Partial gross margin analysis for cassava and maize for the six study sites in Uganda and Kenya by country x wealth class

Site	Cassava Total costs ($\$$ ha^{-1})	 Revenue ($\$$ ha^{-1})	 Gross margin ($\$$ ha^{-1})	Maize Total costs ($\$$ ha^{-1})	 Revenue ($\$$ ha^{-1})	 Gross margin^1 ($\$$ ha^{-1})
Uganda						
Wealthier	305 ± 61	563 ± 174	258 ± 117	146 ± 51	165 ± 79	20 ± 68 ***
Medium	307 ± 59	523 ± 131	216 ± 77	132 ± 17	196 ± 67	64 ± 54 ***
Poorer	271 ± 61	431 ± 165	160 ± 109	128 ± 16	150 ± 46	22 ± 39 ***
Kenya						
Wealthier	366 ± 76	489 ± 153	123 ± 103	269 ± 83	351 ± 139	82 ± 106
Medium	370 ± 91	467 ± 137	97 ± 74	205 ± 54	260 ± 74	55 ± 86
Poorer	320 ± 56	364 ± 123	44 ± 86	180 ± 40	173 ± 78	-7 ± 83 *
P	*< 0.001*	*< 0.001*	*< 0.001*	*< 0.001*	*< 0.001*	*< 0.01*
Overall means	320 ± 76	451 ± 156	131 ± 115	172 ± 63	205 ± 100	33 ± 78

Gross margins for maize followed by an asterisk are significantly different from gross margins for cassava in same row at * = $P<0.05$ or *** = $P<0.001$.

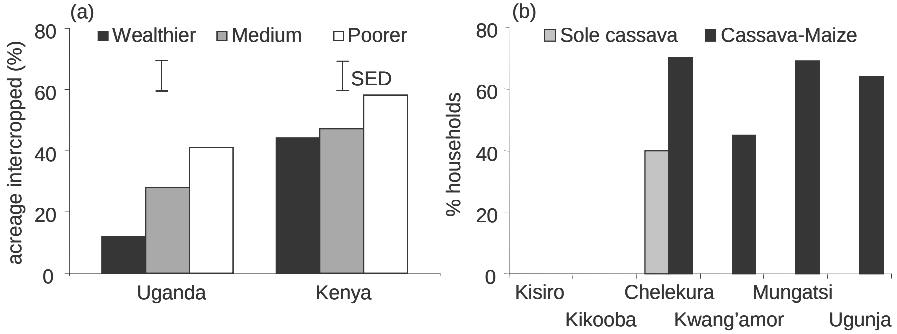


Figure 4: Cassava intercropping (% cassava acreage) by country x wealth class (a) and percentage of households using manure in sole cassava and cassava-maize intercropping systems by site (b) for the six study sites in Uganda and Kenya.

their cassava acreage with an intercrop than wealthier farmers did ($P<0.05$), a similar trend (+ 14%), though not significant, was observed in Kenya (Figure 4a). Still, in Uganda poorer households planted on average a larger part of their cassava acreage as a sole crop (59%) than as an intercrop (41%), while in Kenya figures were exactly opposite (42% sole and 58% intercropped). Households that sold more than half of their cassava production intercropped less (-16%) of their cassava acreage than households that sold a lower proportion of their cassava production ($P<0.05$).

Planting material for cassava was obtained from either the own farm (63%) or exchanged with neighbours (37%). Manure and chemical fertilizers were primarily applied to cereals and beans and sporadically to groundnuts and tobacco. Chemical

Table 6: Weed management for selected sole planted crops for the six study sites in Uganda (U) and Kenya (K) by site[1,2]

	Root & tubers		Cereals			Legumes	Cash crops	
	Cassava	Sweet potato	Maize	Sorghum	Millet	Groundnuts	Cotton	Sugarcane
# weedings per growth cycle								
Kisiro (U)	4.3 ± 0.9	1 ± 0 ***	2.7 ± 0.5 ***		1 ± 0 **	1 ± 0 ***	4.3 ± 1.0	-
Kikooba (U)	3.3 ± 1.0	1 ± 0 ***	1.7 ± 0.5 **		-	1 ± 0 ***	-	-
Chelekura (U)	4.5 ± 1.1	1.1 ± 0.3 **	2.4 ± 0.5 **	1.1 ± 0.4 ***	1.7 ± 0.6 ***	2 ± 0.5 ***	4.1 ± 0.6	-
Kwang'amor (K)	6.0 ± 1.7	1.5 ± 0.6 ***	2.6 ± 0.6 ***	1.1 ± 0.3 *	1.3 ± 0.5 ***	2 ± 0 *	7.3 ± 0.5	6.1 ± 1.5
Mungatsi (K)	5.2 ± 1.1	1.5 ± 0.8 **	2.7 ± 0.6 **	1.5 ± 0.6 *	1 ± 0 **	-	-	6.8 ± 1.1 ***
Ugunja (K)	3.9 ± 1.0	0.8 ± 0.4 ***	1.6 ± 0.6 *	1.4 ± 0.5 ***	-	-	-	-
P	<0.001	<0.001	<0.001	ns	<0.05	<0.001	<0.01	ns
Overall means	4.5 ± 1.4	1.1 ± 0.4 ***	2.4 ± 0.7 ***	1.2 ± 0.4 ***	1.4 ± 0.6 ***	1.4 ± 0.5 ***	4.6 ± 1.3	6.6 ± 1.3 **
Weed ranking								
Kisiro (U)	7.0 ± 2.5	8.9 ± 2.2	4.3 ± 2.3		6.6 ± 3.2	4.1 ± 1.2 *	5.7 ± 2.8	-
Kikooba (U)	7.9 ± 2.5	7.0 ± 2.6	6.4 ± 1.7		-	2.7 ± 0.4 ***	-	-
Chelekura (U)	5.2 ± 2.7	9.5 ± 1.1 ***	6.0 ± 2.6	7.8 ± 2.7	3.6 ± 1.4	6.3 ± 2.8	7.1 ± 2.8	-
Kwang'amor (K)	8.2 ± 2.2	0 ± 0	4.2 ± 2.3 ***	4.6 ± 1.1 ***	4.5 ± 2.2 *	6.9 ± 3.4	8.6 ± 1.7	8.2 ± 1.8
Mungatsi (K)	7.4 ± 2.7	8.2 ± 2.1	3.5 ± 1.2 ***	7.3 ± 0.9	8.5 ± 1.9 *	-	-	7.7 ± 2.4
Ugunja (K)	7.0 ± 2.0	8.6 ± 2.2	3.0 ± 0.4 ***	4.7 ± 2.5	-	-	-	-
P	< 0.001	ns	< 0.05	< 0.05	< 0.05	< 0.05	ns	ns
Overall means	7.2 ± 2.5	8.2 ± 2.3*	4.4 ± 2.1 ***	5.9 ± 2.4	5.0 ± 2.6 *	4.5 ± 2.4 ***	6.9 ± 2.7	7.9 ± 2.2

[1] Analysis based on households that planted the selected crops as a sole crop.

[2] Numbers within a row followed by an asterisk differ significantly from the cassava observation in the same row at * = P<0.05; ** = P<0.01; and *** = P<0.001 (paired t-test).

[3] Farmers ranked their preference to weed the 3-5 most important sole crops on their farm in case all fields had a similar age and similar weed pressure. Rankings were standardized for the number of crops. A low number indicates a higher preference for weeding.

Table 7: Hired labour used on selected sole planted crops for the six study sites in Uganda (U) and Kenya (K) by site and wealth class[1,2]

		Root & tubers		Cereals			Legumes	Cash crops	
		Cassava	Sweet potato	Maize	Sorghum	Millet	Groundnuts	Cotton	Sugarcane
Site									
Kisiro	(U)	53 ± 103	1 ± 4 *	158 ± 333	-	53 ± 55	175 ± 206 *	55 ± 69	-
Kikooba	(U)	11 ± 29	0	4 ± 13	-	-	0	-	-
Chelekura	(U)	129 ± 206	0 *	17 ± 41 *	6 ± 22 *	69 ± 98	81 ± 114 *	126 ± 171	-
Kwang'amor	(K)	19 ± 36	0 *	23 ± 47	2 ± 8	4 ± 15 *	5 ± 17	0	295 ± 370
Mungatsi	(K)	37 ± 63	0	36 ± 52	0 *	-	-	-	188 ± 217 **
Ugunja	(K)	6 ± 15	1 ± 3	11 ± 24	10 ± 28	-	-	-	-
P		<0.01	ns	<0.01	ns	<0.01	<0.001	<0.05	ns
Wealth class									
Wealthier		94 ± 127	1 ± 4 ***	137 ± 291	28 ± 39 *	63 ± 93	95 ± 149	138 ± 51	590 ± 221 *
Medium		51 ± 142	0 *	38 ± 75	0 **	57 ± 100	89 ± 173	153 ± 197	122 ± 111 *
Poorer		11 ± 27	0 *	2 ± 10 *	0 *	12 ± 23	11 ± 26	22 ± 28	0
P		<0.001	ns	<0.001	<0.001	ns	<0.05	<0.01	<0.001
Overall means		42 ± 106	0 ± 2 ***	45 ± 153	5 ± 19 ***	37 ± 74 **	57 ± 129	87 ± 138	222 ± 270 **

[1] Analysis based on households that planted the selected crops as a sole crop.

[2] Numbers within a row followed by an asterisk differ significantly from the cassava observation in the same row at * = $P<0.05$; ** = $P<0.01$and *** = $P<0.001$ (Paired t-test).

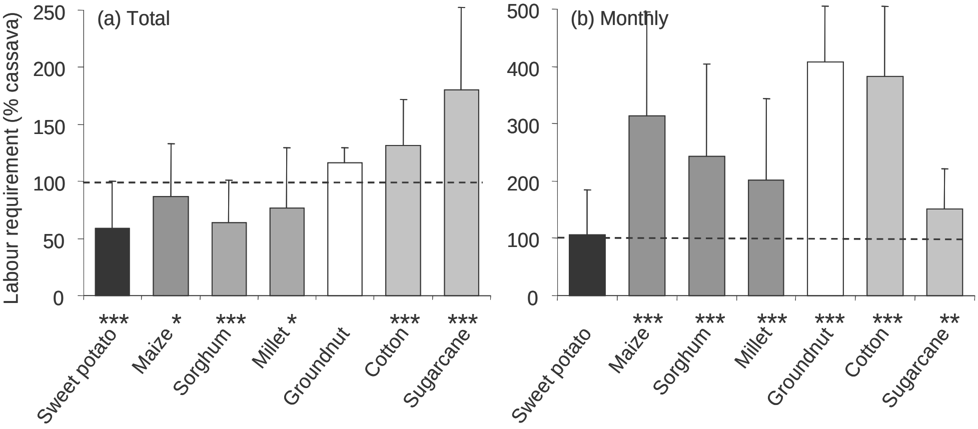


Figure 5: Total (a) and monthly (b) relative labour use of sole planted crops compared with sole planted cassava for the six study sites in Uganda and Kenya. Labour requirements for cassava are 100% in both graphs. Asterisks indicate whether crops had significantly different labour requirements than cassava at * = $P<0.05$; ** = $P<0.01$ and; *** = $P<0.001$. The number of households ranking labour for each crop was: cassava (108), maize (66), millet (32), sorghum (26), groundnuts (32), beans (11), sweet potato (67), cotton (26) and sugarcane (18).

fertilizers were never applied to cassava, while manure was only applied directly to cassava by 40% of the households in Chelekura. However, between 45 and 70% of the households in Chelekura and the Kenyan sites that intercropped cassava and maize, applied manure to the maize in these systems (Figure 4b). Overall, improved cassava genotypes were used by 60% of the households and planted on 36% of the cassava acreage, but this varied strongly between sites ($P<0.001$). Adoption of improved genotypes and the acreage planted to these genotypes was similar across wealth classes.

Although the number of weed operations per crop varied strongly between sites for all crops, except sorghum ($P<0.05$), in all sites cassava was weeded two to three times more than other crops ($P<0.001$), except sugarcane and cotton (Table 6). Intercropping cassava with maize reduced the number of weed operations from an average 4.5 to 3.8 times per crop cycle ($P<0.05$). On average, households gave preference to weeding maize, groundnuts and millet fields over weeding cassava fields ($P<0.01$), but other crops had a similar weeding preference as cassava (Table 6). Kenyan farmers had a much stronger preference to weed maize fields before cassava fields than Ugandan farmers. The number of weed operations and weeding preference was similar across wealth classes.

Overall labour use for cassava was 287 man days per hectare per crop cycle; i.e. 50 days for land preparation (two operations), 23 days for planting, 172 days for weeding and 42 days for harvesting. Per crop cycle, farmers used more labour per unit area on farm operations for cassava than for cereals, beans and sweet potato ($P<0.05$), but less labour than for cash crops ($P<0.001$; Figure 5a). Taking into account the length of the crop cycle, monthly labour use per unit area for cassava was 1.5 to 4 times less than for all other crops ($P<0.01$), except for sweet potato (Figure 5b). Labour limited households did not plant a larger part of their cropped land to cassava than households without labour constraints (Figure 2c). Use of hired labour for crop production varied strongly between sites and crops (Table 7). Overall, 36% of the households used hired labour for the production of cassava, mainly for weeding (36%), and less so for planting (10%) and harvesting (6%). Average hired labour for cassava amounted to 42 man days per year. This was more than labour hired for sweet potato, sorghum and millet ($P<0.01$), similar to the labour hired for maize and cotton and less than the labour hired for sugarcane ($P<0.01$). Hiring labour for most crops was strongly influenced by the resource endowment of the households. 60% of the wealthier households hired labour for cassava versus 25% of the poorer households ($P<0.01$). On average, poorer households hired more labour for cassava than for maize ($P<0.05$).

4. Discussion

4.1 Testing common generalizations

4.1.1 Cassava is a food security crop not a market crop

Cassava supplied approximately one third of the starchy staple food consumption in the study sites (Figure 1) and was the most important staple food in more than half of the surveyed households. Its importance as a staple food has undoubtedly increased over time. In colonial times, cassava was not popular in Uganda and Kenya and cassava planting was forced on farmers by the governments to prevent famine (McMaster, 1962). However, the importance of cassava has strongly increased in the last three decades due to increasing land pressure and farmers' perception that cassava improves soil fertility (Fermont et al., 2008 – Chapter 3). Due to the mixed nature of the farming systems, East African households depend less on cassava as a staple food than Central African households whose cropping systems are dominated by cassava (Fresco, 1986; Nweke and Enete, 1999). Still, food self-sufficiency in our study area was directly related to the absolute acreage under cassava (Figure 2a) and was generally much higher than in maize dominated farming systems in eastern and southern Africa (Ncube, 2007; Claessens et al., 2008).

In absolute terms maize, groundnuts, sugarcane and/or cotton generated more income than cassava in most sites (Table 4). However, cassava generated a larger part of crop income than any other crop. Even households with very small acreages of cassava still marketed a proportion of their harvest (Figure 2b). Similar trends were found in the COSCA study in Uganda (Nweke et al., 1999). Nonetheless, cassava is a less important cash crop in eastern Africa than in central and western Africa, where both large and small-scale farmer often derive more cash income from cassava than from any other crop (Fresco, 1986; Philips et al., 2006). Reasons for the larger market share of cassava in central and western Africa include the high urban and industrial demand for cassava products, the introduction of mechanical graters to reduce post-harvest labour requirements and the introduction of high yielding genotypes in Nigeria and Ghana (Nweke, 2005). Nevertheless, even without these advantages cassava can develop into a cash crop, which has profits that compare favourably with those of maize production (Table 5).

Cassava owes its reputation as a food security crop to: (i) its relative good yields under difficult growing conditions; (ii) its in-ground storability that allows farmers to harvest the crop progressively and bridge the food gap between growing seasons; and (iii) its resistance to locust attacks (Nweke, 2005). Our data confirm for East Africa the general perception that cassava is a food security crop and the notion that where cassava is grown there is no hunger (Hillocks, 2002; Gatsby, 2004). However, we also show that cassava is simultaneously an important income generator for the majority of the households, like it has been for several decades in western and central Africa (Phillips et al., 2006), albeit of lesser importance. Thus the lingering idea that cassava is primarily a subsistence crop, as Nweke (2005) already noted, is a myth.

4.1.2 Cassava is a poor man's crop

Households from all wealth classes planted, consumed and marketed important amounts of cassava and had adopted similar amounts of improved genotypes. In Uganda wealthier households planted larger cassava acreages and earned more income from cassava marketing than poorer households, while the share of cropped land planted to cassava and the importance of cassava as a food crop did not vary between wealth classes (Tables 2 and 3; Figure 1). Considering that in the 1950s Ugandan farmers still regarded cassava to be “food for very low people in their homes” or even “food for prisoners or dogs” (McMaster, 1962), there has been a considerable change in the way Ugandan farmers regard cassava. In Kenya, wealthier households also planted larger acreages of cassava than poorer households, but poorer households planted a larger share of cropped land to cassava, earned a larger share of crop income from cassava and consumed more cassava than wealthier households. The difference between the two countries is likely due to the presence of an important cash crop (sugarcane) in Kenya, which is preferentially grown and sold by wealthier households (Table 2 and 3, Figure 3) as it requires inputs and large fields. Within our study area, there was no relation between the general wealth of a site (% poorer households, average income) and the importance of cassava. At a regional level, the average annual income in our study sites (US$ 633 to US$ 1,283) is similar to income levels reported for banana-based cropping systems in Uganda (Bagamba, 2007) and maize-based cropping systems in Kenya (De Jager et al., 2001).

Cassava is typically perceived to be grown by resource poor, small farmers (Jameson, 1970; Alves, 2002; FAO, 2004b; Gatsby, 2004) as it can be produced with family labour and basic inputs only and has low production risks (Nweke, 2005). In addition, food policy analysts often assumed that cassava’s per capita consumption will decline with increasing per capita incomes. The COSCA study already showed that this is not true for urban consumers because they switch from dried flour forms to more convenient food forms such as gari, when income increases (Nweke, 2005). This study shows that, also in rural areas, cassava is not a poor man’s crop when evaluated on absolute acreages planted or absolute income earned and when evaluated on relative terms in Uganda, but it is when evaluated on relative terms in Kenya. At a regional scale we did not find evidence that cassava is produced in ‘poverty pockets’. It is thus too simplistic to classify cassava as a poor man’s crop. This may be a historical perception from colonial times, when farmers were forced to plant cassava.

4.1.3 Poor farmers intercrop cassava

Although poorer households planted a larger percentage of their cassava acreage as an intercrop than wealthier households, poorer households intercropped just 42 and 58% of their cassava acreage in Uganda and Kenya, respectively (Figure 4a). Thus, the perception that poorer farmers intercrop cassava to reduce the risk of crop failure, while maximizing returns to land and labour (Weber et al., 1979; Leihner, 2002) can be confirmed in the sense that poorer households intercrop cassava more than wealthier households, but is falsified in the sense that poorer households do not intercrop most of their cassava fields. Intercropping in our study area was less important than found by previous studies in Africa (Nweke et al., 1999), whereas intercropping systems are also simpler (only one intercrop, no relay cropping) than the complex intercropping systems described in West and Central Africa (Ezeilo, 1979; Fresco, 1986).

4.1.4 Cassava requires less labour than other crops

In our study site cassava production required an average of 287 man days ha^{-1}. This makes cassava production in eastern Africa very labour intensive compared with the 76 man days ha^{-1} used in Nigeria (Nweke, 1996) and the 50-150 man days ha^{-1} required in Asia, although in Vietnam labour requirements of up to 400 man days ha^{-1} are reported (Howeler et al., 2001). Most labour (60%) was used on weeding. This was also observed by Nweke and Enete (1999) and Melifonwu et al. (2000). Cassava is typically regarded as a crop with low labour demands as it is much less tightly constrained by seasonality than other crops due to its semi-perennial nature and the ability to tend it during periods of the growing season when more labour is available (Cock, 1985; Fresco, 1986; Berry, 1993). As such it is regarded as specifically suitable for labour-deficit and HIV/AIDS affected households (Nweke, 2005). We confirm that, even though farmers used more labour on cassava than in other parts of the world, monthly labour use of cassava per unit area in our study area was less than for other crops (Figure 5a). Nonetheless, total labour requirements per unit area for cassava were high (Figure 5b). While cassava fields were generally weeded later than maize, groundnuts and millet fields (Table 6), 36% of the households hired labour for weeding or cassava. This may be an indication that although farmers do not give a high preference to weed management of cassava, they still face a labour constraint for this particular task. It may also explain why households that faced a labour shortage did not increase the share of cassava on their farm (Figure 2c).

4.1.5 Cassava is grown without inputs

Farmers rarely targeted chemical fertilizer (if used) and manure to cassava. This is in line with findings from the COSCA study (Nweke, 1994a). Nonetheless, in western Kenya and Chelekura more than half the households applied manure to cassava-maize intercropping systems (Figure 4b). Sixty percent of the households planted improved genotypes, which had been obtained through development projects or farmer to farmer dissemination in concentrated efforts to control the cassava mosaic epidemic in the past 10 years (Legg et al., 2006). Farmers commonly hired labour for cassava (Table 7). The COSCA study also found that approximately one third of the households hired labour for cassava weeding (Nweke, 1994a). We can thus conclude that although input use in cassava is limited to improved genotypes and hiring of labour, the general perception that cassava is produced without inputs (Oyetunji et al., 2001; Leihner, 2002) is false.

4.2 Consequences for policies and development interventions

Over half of the rural population in Africa is living in poverty (Ravallion et al., 2007). The World Bank and African governments have recognized the role of agriculture to increase food security and reduce rural poverty (Worldbank, 2008) as each one percent increase in agricultural production in Africa has been shown to reduce poverty by 0.6 percent (IFPRI, 2002). Cassava is well positioned to improve the livelihoods of smallholder farmers in the cassava growing areas of East Africa, as it is consumed and marketed by a large majority of households (Table 4; Figures 1 and 3) and it has a good scope for yield improvement through improved agronomic practices (Fermont et al., 2009 – Chapter 4). Nonetheless, cassava can not be used to specifically reduce food insecurity and poverty amongst the poorest of farmers as has been the objective of several projects, because cassava is not a typical ‘poor man’s crop’. Experience from a ‘pro-poor’ root and tuber program in Ghana showed several other reasons why targeting cassava to the poorest farmers did not result in the anticipated reduction in poverty. These included a lack of land, labour and capital, clashes between labour requirements of cassava and other crops and insufficient capacity to be linked into developing markets (IFAD, 2004). Fermont et al. (2009 – Chapter 4) further argue that poorer farmers face a larger number of abiotic, biotic and associated management constraints than wealthier farmers and thus increasing cassava production for poorer farmers is more difficult than for wealthier farmers. To ensure that poorer households can profit from cassava cultivation, development programmes will have to offer solutions to the specific production constraints that these households face, perhaps in the form of labour-reducing technologies, high yielding genotypes and capacity building.

Food self-sufficiency in cassava-based farming systems is generally high, even for poorer households (Table 1). The introduction of technology packages to increase production in these farming systems will thus not significantly enhance food self-sufficiency. It will, however, improve the scope for commercialization of cassava. Nonetheless, in areas where cassava is not yet widely grown or areas affected by the cassava mosaic or brown streak epidemic, food self-sufficiency can be enhanced through the promotion of cassava and/or introduction of resistant genotypes.

To tap the huge potential of cassava to improve income for the majority of farmers in East Africa, there is a need to develop current and new cassava markets (animal feed, starch, biofuel) to increase opportunities for commercialization. The Ugandan government is dedicated to benchmarking international best practices to learn lessons from other countries that have escaped from poverty. Examples could be Vietnam and

Thailand, whose governments are actively promoting cassava starch and ethanol production through the development of an E10 policy (inclusion of 10% ethanol in normal gasoline) and attracting investors (Charoenrath, 2008; Kim et al., 2008). Cassava production prices in Africa are often not competitive with the low world market prices and markets need to be sought within Africa (FAO and IFAD, 2004). On the regional and national markets processed cassava products compete with grain products. Profitability per hectare was greater for cassava than maize using actual wholesale prices (Table 5). Experience in Uganda shows that animal feed industries normally offer 70% of the maize price for cassava. Under these conditions, cassava production still is more profitable than maize in Uganda but not in Kenya.

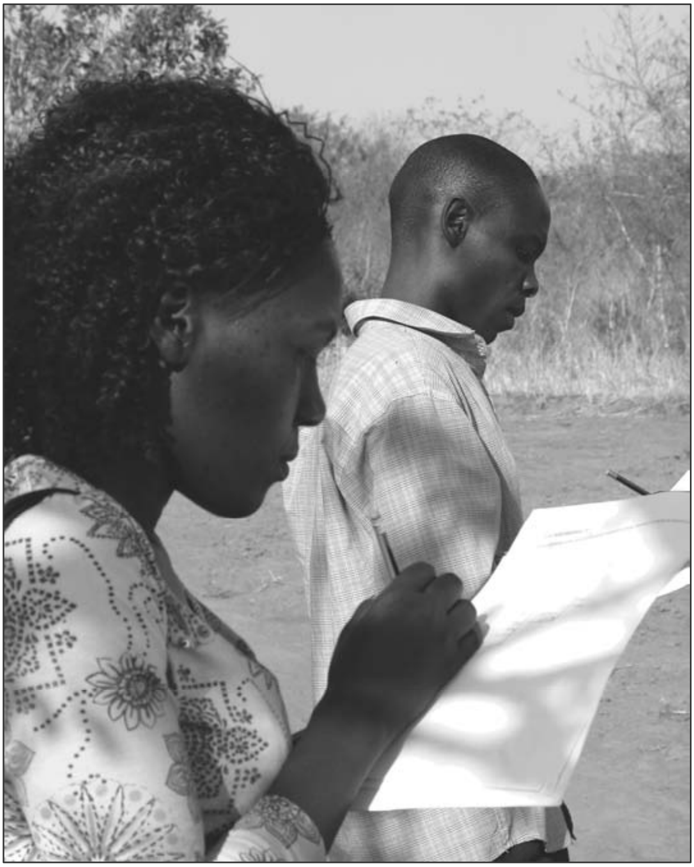
To increase the profitability of cassava production in order to facilitate its development as an industrial crop in East Africa and to improve its suitability for poorer and/or labour deficit and/or HIV/AIDS-affected households, attention should be given to the development of labour saving technologies and to yield improvement. The most important production constraints in East Africa are poor weed management, low soil fertility and a water-deficit during initial growth (Fermont et al., 2009 – Chapter 4). Removing these limitations by improved weed management, manure and/or fertilizer use and avoiding early drought stress by timely planting in combination with improved genotypes will increase cassava productivity and profitability. Labour saving technologies should focus on weeding as current weed management is very labour intensive. This may be related to the bimodal rainfall distribution, land preparation by hand resulting in late planting, low weeding preference for cassava (Table 6) and poor soils, leading to poor cassava growth and/or strong weed competition. Low-cost options to improve weed control include the use of higher plant densities and introduction of vigorous, early branching genotypes, while other possibilities include fertilizer use to promote early ground cover and herbicides (Fermont et al., 2009 – Chapter 4). The facts that farmers weed their fields more than recommended and commonly hire labour to produce cassava shows that farmers are willing to use inputs in cassava production (Tables 5 and 6), but most likely lack knowledge on improved production practices as shown by the generally restricted use of manure and fertilizer. Current weed management and manure use vary widely between sites, but much less between wealth classes, while land, labour and capital availability varied strongly between sites and wealth classes (Tables 1, 2, 5 and 6). When developing improved management packages these differences between areas should be taken into account, without losing sight of the variability in resources available to households.

5. Conclusions

We conclude from our study area that the five generalizations we tested are either half truths or untrue: (i) Cassava is not only an important food security crop, but also generates income for the majority of households; (ii) It is too simplistic to classify cassava as a poor man's crop as cassava farmers of all wealth classes plant, consume and market cassava and average farm income was similar to that in non-cassava based farming systems in East Africa; (iii) Although poorer farmers intercrop cassava more frequently than wealthier farmers, poorer farmers plant more or less similar proportions of sole and intercropped cassava; (iv) Cassava requires less labour per unit area than other crops, but only if expressed on a monthly basis. Total labour requirements of cassava are higher than for other crops due to frequent weeding; and (v) Farmers do use inputs for cassava production, mainly hired labour for weed management and improved genotypes, but also manure in cassava-maize intercropping systems. The continued belief in these generalizations will undermine a proper understanding of the socio-economic and management aspects of cassava production and may negatively impact on the sustainability of policy and development efforts aimed to improve cassava production. Thus, we identify three primary consequences for cassava interventions. First, efforts to increase cassava production in cassava-based farming systems will not significantly enhance food self-sufficiency, but will improve its scope for commercialization. Second, cassava is well positioned to improve the livelihoods of smallholder farmers, but it is more challenging than commonly assumed to use cassava as an entry point to reach the poor. Third, to develop the opportunities cassava offers to smallholder farmers to increase farm income will require, amongst others, site specific targeting of projects, development of management packages to improve yields and reduce labour requirements for weeding and regional market development.

Chapter 3

Increasing land pressure in East Africa: The changing role of cassava and consequences for sustainability of farming systems



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Abstract

Increasing land pressure during the past three to four decades has transformed farming systems in the mid-altitude zone of East Africa. Traditional millet, cotton, sugarcane and/or banana based farming systems with an important fallow and/or grazing component have evolved into continuously cultivated cassava or cassava/maize-based systems. Within three to four decades, cassava cultivation increased from 1-11% to 16-55% of cropped fields in our six study sites. Declining soil fertility, and not labour or food shortage, was apparently the primary trigger for this transformation. The land use changes have increased nutrient offtakes and reduced nutrient recycling rates. Cassava and maize now account for 50-90% of nutrient removal. Whereas single-season fallows were the most important source of nutrient recycling on cropped fields in the past, currently cassava litterfall and maize stover contribute roughly 70% of nutrient recycling, with 50-70% of N, P and K recycled in cassava litterfall. This may explain why many farmers reason that cassava ‘rests’ the soil. With increasing land use pressure farmers progressively use cassava as an ‘imitation fallow’ throughout their farm. Farmers increasingly target cassava to poor fertility fields characterized by low pH and available P. High cassava intensities are nonetheless maintained on more fertile fields, probably to guarantee regeneration of soil fertility on all fields. Once cassava is targeted to poor fertility soils, farmers have run out of low-input management options and need to intensify management to maintain system productivity. As cassava is now used by more farmers and on a larger acreage than fallowing in the studied farming systems, cassava cropping could perhaps serve as an excellent entry point to strengthen system sustainability.

Keywords: Cassava, East Africa, Soil fertility, Nutrient removal, System sustainability

1. Introduction

Cassava (*Manihot esculenta* Crantz) is an important crop in many farming systems in sub-Saharan Africa. Despite its world-wide importance, cassava arguably remains among the least researched staple crops in the world. In Africa, cassava research has primarily focused on breeding and management of pest and diseases; while relatively little agronomic research has been conducted. To identify major bottlenecks and appropriate management practices for cassava production systems, it is vital to understand the spatial and temporal roles that cassava takes within farming systems. In western Kenya, cassava is said to be grown preferentially in distant fields, while nearby fields are reserved for maize and groundnuts (Tittonell et al., 2005). Farmers cultivate cassava frequently on marginal soils (Fresco, 1986; Dixon et al., 2002; FAO, 2004b). At regional level, this is a consequence of increasing population densities leading to higher land pressure and successively shorter fallow periods, resulting in declining soil fertility and lower crop yields, which finally results in farmers resorting to allocate more of their land to cassava production (Berry, 1993; Hillocks, 2002). The substitution of cassava for other crops thus contributes to maintaining the total output of staple foodstuffs and reduces seasonal fluctuations in food supply (Jones and Egli, 1984). As such, the huge expansion of cassava production in Africa during the last decades of the 20th century may be linked to declining soil fertility (Hillocks, 2002) and is an indication that farming systems are rapidly changing.

With respect to the temporal role of cassava, opinions are somewhat divided. While Nweke et al. (1999) and Hillocks (2002) argue that cassava is planted just before land is left to fallow, Fresco (1986) observed that cassava is the first crop cultivated after fallow, and Silvestre and Arraudeau (1983) suggest that cassava is dominant both at the beginning and at the end of the cropping cycle. Farmers in Ghana and Benin use cassava as a ‘soil fertility regenerating strategy’ (Saidou et al., 2004; Adjei-Nsiah et al. 2007) and the West-African term for cassava cultivation ‘jachère manioc’ literally means ‘cassava fallow’. The role of cassava therefore appears to vary according to the dynamics of the farming system and in particular to the degree of intensification (Carter et al., 1992). However, our understanding of long-term changes in the relative importance of cassava in different agro-ecological regions remains limited (Fresco, 1993).

In East Africa, land pressure is generally high and has resulted in continuous farming systems with limited fallow: a situation which perhaps represents the future of most smallholder farming systems in Africa. Cassava is a major crop in the coastal zone of Tanzania and Kenya and the mid-altitude zone of Uganda, Kenya and Tanzania.

Average fresh yields vary from 9.1 t ha^{-1} in Kenya to 14.4 t ha^{-1} in Uganda (FAO, 2007). In cassava-based farming systems in Uganda and Kenya, cassava is the first or second most important staple food and generates on average one fifth of crop income (Nweke et al. 1998; Nweke et al., 1999), although industrial demand for cassava is limited.

This study explores the impact of increasing land pressure on the importance and spatial and temporal role of cassava in cassava-based farming systems in the mid-altitude area of East Africa. Secondly we analyse consequences of land-use changes on the sustainability of these farming systems. For this study we collected and analysed detailed farm and field information from six sites in Uganda and Kenya and compared them with historical data from the same areas.

2. Materials and methods

2.1 The study sites

Six study sites in western Kenya and central / eastern Uganda were selected to represent the cassava based cropping systems found in the mid-altitude zone of eastern Africa: in Uganda the parishes of Kisiro (0^{o}67'N; 33^{o}80'E), Kikooba (1^{o}40'N; 32^{o}38'E) and Chelekura (1^{o}14'N; 33^{o}62'E) in Iganga, Nakasongola and Pallisa district, respectively, and in western Kenya the sub-locations of Kwang'amor (0^{o}29'N; 34^{o}14'E), Mungatsi (0^{o}27'N; 34^{o}18'E) and Ugunja (0^{o}10'N; 34^{o}18'E) in Teso, Busia and Siaya district, respectively. Demographic and agro-ecological details are given in Table 1. Five of the sites have medium to high population densities (160-387 persons km^{-2}) and are representative for the intensive land use systems with little fallow that are developing in many parts of (East) Africa. A further site, Kikooba, which has a lower population density (20 persons km^{-2}) was included for contrast. The climate is sub-humid with a bimodal rainfall distribution. Average annual rainfall varies between 1078 and 1770 mm (Table 2). Crop production takes place during the long rains from March to June and the short rains from September to November. Cassava and Maize (*Zea mays* L.) are the main staple food crops grown in all sites. Other staple food crops grown include sweet potato (*Ipomoea batatas* L.), sorghum (*Sorghum bicolor* (L.) Moench), finger millet (*Eleusine coracana* L.), rice (*Oryza sativa* L) and groundnut (*Arachis hypogaea* L.). At each site, three to four key informants ranked all households in three wealth categories; poor, medium and rich. From this stratified wealth ranking, 20 households were randomly selected for the purpose of this study, with a minimum representation of three households per wealth category. Structured

Table 1: Main demographic and agricultural indicators in the six study sites in Uganda and Kenya

Variable	Unit	Uganda			Kenya			*P*
		Kisiro[1] Iganga[2]	Kikooba[1] Nakasongola[2]	Chelekura[1] Pallisa[2]	Kwang'amor[1] Teso[2]	Mungatsi[1] Busia[2]	Ugunja[1] Siaya[2]	
Population density sub-county[3]	Persons km^{-2}	160	20	230	325	291	387	-
Farm size	ha	4.8 (0.7-15.1)	7.0 (0.9-47.3)	1.8 (0.5-5.1)	3.0 (0.7-13.2)	2.6 (0.6-8.8)	1.5 (0.3-3.7)	*<0.05*
Arable land	ha	4.6 (0.6-14.8)	6.9 (0.8-47.1)	1.7 (0.5-5.0)	2.9 (0.7-12.8)	2.0 (0.3-5.0)	1.2 (0.3-3.3)	*<0.05*
Cassava	ha	0.6 (0-2.5)	0.9 (0.2-3.7)	0.6 (0.1-2.1)	0.7 (0.1-2.6)	0.3 (0-0.8)	0.3 (0.03-0.8)	*<0.01*
Cassava	% Farm	13 (0-28)	27 (3-55)	26 (8-50)	28 (7-68)	19 (0-63)	24 (3-66)	*<0.01*
Grass fallow (< 3 year)	% Farm	5 (0-27)	24 (0-87)	3 (0-14)	12 (0-28)	6 (0-31)	5 (0-44)	*<0.001*
Bush fallow (> 3 year)	% Farm	0 (0-2)	21 (0-89)	6 (0-79)	3 (0-49)	4 (0-39)	10 (0-65)	*<0.01*
Grazing	% Farm	6 (0-41)	3 (0-57)	3 (0-31)	8 (0-38)	14 (0-69)	4 (0-23)	*ns*
R[4]	-	93 (65-100)	66 (12-100)	94 (68-100)	78 (49-100)	90 (63-100)	86 (34-100)	*<0.001*
Fresh cassava yield	t ha^{-1}	8.3 (2.7-12.0)	12.7 (5.3-26.7)	11.7 (6.7-17.8)	7.7 (4.4-13.3)	6.7 (2.7-11.1)	6.6 (2.7-16.0)	*<0.001*
Maize yield	t ha^{-1}	1.4 (0.9-2.2)	0.7 (0.4-1.1)	1.0 (0.6-1.8)	1.1 (0.3-2.2)	1.2 (0.4-2.7)	1.0 (0.3-2.0)	*<0.001*
Cattle	Heads	2.1 (0-6)	7.0 (0-20)	2.0 (0-6)	4.8 (0-27)	2.5 (0-10)	2.1 (0-6)	*<0.01*
Manure use	t year^{-1}	0.3 (0-5.0)	0	0.5 (0-3.4)	0.6 (0-3.2)	0.8 (0-4.0)	0.8 (0-3.2)	*<0.05*
Fertilizer use	kg year^{-1}	28 (0-400)	0	1 (0-10)	47 (0-450)	101 (0-450)	34 (0-200)	*<0.01*

Anonymous (2005, 2007); http://www.cck.go.ke/html/final_annex1_cover_status.pdf

[1] Parish/sublocation.

[2] District.

[3] Population density per sub-county for Uganda was calculated from total population per sub-country divided by the estimated land area from the district map.

[4] R (land use intensity factor) = 100C / (C + F); C = number of cropping years per cycle and F = number of fallow years per cycle (Ruthenberg, 1976).

Table 2: Main biophysical characteristics of the six study sites in Uganda and Kenya

Variable	Unit	Uganda			Kenya			*P*
		Kisiro^1 Iganga^2	Kikooba^1 Nakasongola^2	Chelekura^1 Pallisa^2	Kwang'amor^1 Teso^2	Mungatsi^1 Busia^2	Ugunja^1 Siaya^2	
Altitude	m	1140	1100	1145	1220	1220	1260	-
Total annual rainfall	mm	1200	1078	1465	1420	1770	1620	-
Topography	-	Gently undulating	Gently undulating	Gently undulating	Gently undulating	Undulating	Undulating	-
Parent material	-	Lake deposits from granites and gneisses	Gneisses and Granites	Lake deposits from granites and gneisses	Granites	Granites	Mudstone	-
Dominant soil type (local/FAO name)	-	Mukyanga ferric Acrisol	Grey sand orthic Ferralsol	Aputon, haplic Ferralsol	Asinge, orthic Acrisol	Oluyekhe, ortic Acrisol	Kuoyo, ferric Acrisol	-
pH^3	-	6.5 (6.4-6.7)	6.0 (5.5-6.6)	5.8 (4.8-6.6)	5.7 (5.1-6.7)	5.2 (4.5-6.4)	5.4 (4.8-6.2)	*<0.001*
SOC^3	g kg^{-1}	7.6 (5.2-9.6)	8.9 (5.6-12.7)	6.5 (2.9-15.1)	8.4 (3.5-13.7)	10.6 (6.9-14.4)	8.9 (6.3-12.6)	*<0.001*
Total N^3	g kg^{-1}	0.72 (0.5-0.9)	0.67 (0.1-1.1)	0.57 (0.2-1.1)	0.49 (0.1-0.8)	0.75 (0.4-1.3)	0.62 (0.4-1.0)	*<0.01*
Avail. Phosphorus^3	mg kg^{-1}	12.2 (2.8-27.2)	6.9 (2.7-15.9)	9.8 (1.5-107)	6.5 (2.2-19.8)	8.6 (2.9-48.7)	3.2 (1.1-8.7)	*<0.001*
Exch. Potassium^3	cmol$_{(+)}$ kg^{-1}	0.42 (0.1-0.9)	0.46 (0.2-1.1)	0.43 (0.2-1.2)	0.43 (0.1-1.2)	0.44 (0.1-1.0)	0.34 (0.2-0.6)	*ns*

Jameson (1970); Jaetzold and Schmidt (1982); Andriesse and van der Pouw (1985); KARI (2000); Anonymous (2001, 2004); Ruecker (2005).

[1] Parish/sublocation.

[2] District.

[3] Soil analyses carried out on 16, 13, 25, 31, 25 and 27 composite top soil (0-20 cm) samples from cropped upland fields.

interviews were used to collect data on the cropping and livestock systems, average cassava and maize yields, manure and fertilizer use, labour availability and the perceptions of farmers on the physical and temporal role of cassava. Information was triangulated through multiple questions, field observations, key informants and subsequent visits.

2.2 Biophysical characterization of farms and sites

For each of the 121 selected households a biophysical characterization of the farm was carried out. This took place from June to September 2004 in western Kenya and from October 2005 to April 2006 in Uganda. At each farm, all fields were visited by the survey team with the farmer. A total of 1401 fields representing 425 ha were surveyed. For each field the following information was recorded: (i) field size (visual estimation); (ii) land use (including intercrops) in the previous, current and next season; (iii) local soil name and soil fertility status as perceived by the farmer in three classes (poor, average or good); (iv) distance to the homestead in four classes (near, medium, far or distant); and (v) land tenure status (owned, hired, borrowed). Total farm size, arable land, and absolute and relative areas under various land uses were then calculated. We distinguished fallows as: (i) grass-fallow - fields that were fallowed for less than 3 years, which included single-season fallows; and (ii) bush-fallow – fields that were fallowed for more than 3 years. For each site, the relative importance of each local soil type was determined. The intensity of cassava cropping, expressed as the percentage of fields grown with cassava during at least one of the three survey seasons, was computed for each soil type, fertility status, tenure status and distance class. We also calculated the relative cassava acreage that was found before and after selected crops and fallows using field information over three seasons.

At each site 4-5 representative transects were chosen to characterize the general biophysical environment. The transects covered the main land units and (local) soil types. Depending on the relative importance of each local soil type and its significance for cassava production, between 2 to 22 sampling points per local soil type were selected in cropped upland fields. Composite top soil (0-20 cm) samples were taken within a radius of 5 m from each main sampling point. Soil samples were air-dried, sieved through a 2 mm sieve and analysed for pH, available P, exchangeable K, total N and soil organic carbon, following standard methods described by Okalebo et al. (2002).

2.3 Changes in land use and partial nutrient budgets

Cropping patterns in 2004/5 were compared with cropping patterns of 1977 (Kenya) and 1964 (Uganda) using results of a detailed farm survey (Jaetzold and Schmidt, 1982) and results of the 1963/4 Uganda Census of Agriculture (Jameson, 1970). The relative importance of cassava, sweet potato, maize, millet, sorghum, common bean, groundnuts, sugarcane, cotton, sunflower, coffee and banana on annually cropped land was calculated for each site. The relative importance of 'single-season fallow' was included in the calculations as, especially in the past, large parts of the land were not cropped during the second rains. For the 1963/4 situation in Uganda, the relative importance of single-season fallows was estimated from descriptions of the farming systems. The agro-ecological zones LM1 and LM 2-3 in Busia district and LM 1 in Siaya district in Kenya were taken as representative for Mungatsi, Kwang'amor and Ugunja respectively, while the former districts of Busoga, East Mengo and Teso districts in Uganda were taken as representative for Kisiro, Kikooba and Chelekura respectively.

The above data were used to estimate the average amounts of nutrients (N, P, K) removed and recycled per ha of cropped land annually for the cropping patterns of 1977 and 2004 in Kenya and 1964 and 2005 in Uganda. Annual nutrient removal by export of crop products and residues was estimated from yield and residue production (kg ha^{-1}) and their N, P and K contents corrected for the land area occupied and the number of harvests per year. Annual nutrient recycling through crop and single-season fallow residues remaining in the field was estimated in a similar way from estimates of biomass (kg ha^{-1}) produced by two single-season fallows, the amount of cassava litterfall (kg ha^{-1}) produced during one growth cycle, estimates of crop residues returned to the field, N, P and K contents of all the residues and the land area occupied. Yields of sorghum, millet, sweet potato, groundnuts, cotton and sunflower were obtained from FAO (2007), Jaetzold and Schmidt (1982) and own field observations. Data on nutrient contents, dry matter and harvest indices for cassava, maize, millet and sorghum were taken from agronomic trials in the six sites and two on-station trials, while data for for sweet potato, groundnuts, cotton and sunflower were obtained from FAO (2004a). Data on crop residue management were estimated during the farm surveys and checked by direct field measurements. An estimate of cassava litterfall during the growth period was obtained from Carsky and Toukourou (2003). Biomass production and nutrient contents of a six month old natural fallow were obtained from Rutunga et al. (1999). Considering the appreciable degree of uncertainty in especially FAO data on yield and crop nutrient contents, the annual nutrient removal and recycling rates calculated are treated as rough estimates.

2.4 Statistical analysis

Significance of differences between sites and soil types for the various biophysical parameters and soil characteristics were tested using: a) univariate analysis of variance with subsequent LSD test for post-hoc comparison when required; and b) non-parametric Kruskal-Wallis test where appropriate. The CROSSTAB procedure using Pearson Chi square analysis or univariate analysis of variance where appropriate were used to test for significant effects of local soil type, fertility status, distance class and tenure status of fields on the intensity of cassava cultivation within sites and countries. The CROSSTAB procedure was also used to test whether farmers had significantly different opinions on the biophysical role of cassava in the farming system. Relative acreages of crops planted before versus after cassava were compared using the non-parametric Wilcoxon signed ranks test for 2 related samples. The statistical significance of relationships between selected farm and management parameters were assessed by two tailed Pearson correlations. All statistical analyses were carried out using SPSS for Windows (version 10.0).

3. Results

3.1 The biophysical environment and farming systems in the study sites

All sites were characterized by undulating landscapes where uplands were dissected by (non-permanent) rivers. Main soils in the region include ferric and orthic Acrisols and orthic and haplic Ferralsols, which have developed from strongly weathered granite or sedimentary parent material. Soil fertility was generally poor (Table 2). Soil organic carbon, total soil N, available P and pH varied significantly ($P<0.05$) between sites, while exchangeable K varied less. Average soil organic carbon values ranged from 13.5 to 18.3 g kg^{-1}, while average available P and exchangeable K ranged from 3.2 to 9.3 mg kg^{-1} and 0.34 to 0.46 $cmol_{(+)}$ kg^{-1}, respectively. With an average pH of 5.5, soils in Kenya and Chelekura were more acidic ($P<0.01$) than soils in Kisiro and Kikooba with a pH of 6.3. Farmers in the first sites perceived their soils to be less fertile ($P<0.001$) than farmers in the latter sites as they classified 20% of their fields as having a ‘poor’ fertility versus 7% in the latter sites. Local soil classification was generally based on texture, but sometimes included topography, stoniness, colour, and previous land use. Between two and five local soil types were distinguished at each site (Table 3); two to four upland soil types located on the crest, upper and middle slopes of the interfluves and one soil type on the valley fringes. According to the farmers, fertility levels of the upland soil types were different ($P<0.05$). At least one of the upland soil types in four out of the six sites had less available nutrients (total N,

Table 3: Cassava cultivation intensity and selected properties in the top soil (0-20 cm) of the main local soil units in the six study sites in Uganda and Kenya

Site	Local soil type	Survey data					Transect data					
		Main diagnostic feature according to farmer description[1]	Area[2] (%)	n	Intensity cassava cultivation[3] (%)	Farmer fertility score[4]	n	pH	SOC ($g\ kg^{-1}$)	Total N ($g\ kg^{-1}$)	Avail. P ($mg\ kg^{-1}$)	Exch. K ($cmol_{(+)}\ kg^{-1}$)
Kisiro	Mukyanga	Sandy	37	98	39 a[5]	2.0 a	8	6.5	7.4	0.69	10.8	0.32 a
	Kigoola	Loamy	32	88	48 a	2.4 b	8	6.5	7.8	0.75	13.5	0.52 b
	Kibali	Valley fringes	31	34	24 b	2.9 c	-	-		-	-	
Kikooba	Sandy	Sandy	64	116	64	2.1 a	7	6.2	7.1 a	0.47 a	7.9	0.36
	Clay	Clayey	36	119	62	1.8 b	6	5.9	10.9 b	0.90 b	5.8	0.57
Chelekura	Aputon	Sandy	32	81	66 a	2.3 a	8	5.6 a	4.0 a	0.38 a	2.3 a	0.25 a
	Orony	Fertile	26	61	56 a	2.6 bc	7	6.3 b	6.6 b	0.59 b	28.7	0.66 b
	Eitela	Loamy	14	30	67 a	2.3 ab	5	5.1 c	6.5 b	0.58 b	2.7 a	0.43 a
	Apokor	Clayey	12	28	51 a	2.3 ab	5	6.0 b	10.2 c	0.86 c	2.3 a	0.39 a
	Akawo	Valley fringes	16	15	0 b	2.8 c	-	-	-	-	-	
Kwang'amor	Asinge	Sandy	34	148	70 a	1.5 a	22	5.8	7.4 a	0.43 a	6.3	0.41
	Apokor	Clayey	26	48	56 a	2.5 b	6	5.7	11.5 b	0.62 b	7.6	0.52
	Enyunyur	Stony	10	17	71 a	1.7 a	3	5.5	10.0 ab	0.60 ab	5.5	0.40
	Akapian	Valley fringes	30	48	0 b	2.9 c	-	-	-	-	-	-
Mungatsi	Oluyekhe	Sandy	35	96	68 b	1.7 a	15	5.0 a	10.2	0.69	5.3 a	0.37
	Sirambasi	Clayey	19	58	43 a	2.6 b	8	5.4 b	11.3	0.79	15.5 b	0.56
	Sivare	Stony	9	19	58 ab	1.3 c	2	5.6 ab	11.0	0.99	5.7 ab	0.47
	Isa	Valley fringes	37	49	22 c	3.0 d	-	-	-	-	-	-
Ugunja	Kuoyo	Sandy	51	118	52 a	2.2 a	8	5.5		0.73	3.5	0.35
	Luala	Loamy	25	60	40 a	2.7 b	11	5.4	8.9	0.58	2.7	0.37
	Gee	Stony	21	51	51 a	1.6 c	7	5.5	9.1	0.61	3.1	0.29
	Pundo	Valley fringes	3	8	22 b	2.9 b	-	-	-	-	-	-

[1] Texture characterization by farmers does not correspond to FAO texture criteria as farmers use relative scale.

[2] Relative importance of each soil unit is calculated on basis of total acreage surveyed.

[3] Percentage of fields with cassava as a major crop in at least one of the three survey seasons.

[4] Farmers classified each field as having a poor (1), medium (2) or good (3) fertility level.

[5] Figures within the same column, for the same site, followed by different letters are significantly different at $P<0.05$.

available P, exchangeable K or SOC) than the other soil types ($P<0.05$). Valley fringes accounted for 20% of the surveyed agricultural area on average, but their importance for agriculture varied from 3 to 37% between sites (Table 3). By-laws often prohibited the cultivation of the valley bottom.

Farms were scattered in the uplands. Average farm sizes ranged from 1.5 to 7.0 ha (Table 1). Farming systems were diverse with farmers growing important acreages of four to six crops on average. During the survey period the majority (97%) of farmers grew cassava. Average cassava acreage per site ranged from 0.3 to 0.9 ha per cropping season, occupying 13 to 28% of the farm area. Grass-fallows (< 3 years) occupied on average 5 to 24% of the farm area and were found on 67% of the farms. With the exception of Kikooba, 64% of the grass-fallows were left for only a single season. Bush-fallows (>3 years) and grazing lands were found on 24 and 33% of the farms respectively and occupied from 0 to 21% and 3 to 14% of the farm area respectively. Bush-fallows and grazing lands were mostly located on waterlogged or shallow soils, on large farms and/or on farms with a labour deficit. Consequently bush-fallows and grazing lands were not used for cropping by 62 and 49% of the farmers respectively. The average number of cattle, mostly local Zebu (*Bos indicus*) breeds, ranged from 7.0 per household in Kikooba to 4.8 in Kwang'amor and between 2.0 to 2.5 for the other sites. As 31 and 70% of the farmers owing cattle in Kenya and Uganda respectively did not have private grazing land and no zero-grazing systems were found in these areas, cattle normally grazed in communal valley areas. Manure and fertilizer use ranged from none in Kikooba to 800 and 100 kg ha^{-1} respectively in Mungatsi and significantly more nutrient inputs were used in Kenya than in Uganda ($P<0.01$). Average fresh cassava yields ranged from 6.6 to 7.7 t ha^{-1} and 8.3 to 12.7 t ha^{-1} in Kenya and Uganda, while average maize yields ranged from 0.7 t ha^{-1} in Kikooba to 1.4 t ha^{-1} in Kisiro (Table 1). Cassava was more often intercropped in Kenya than in

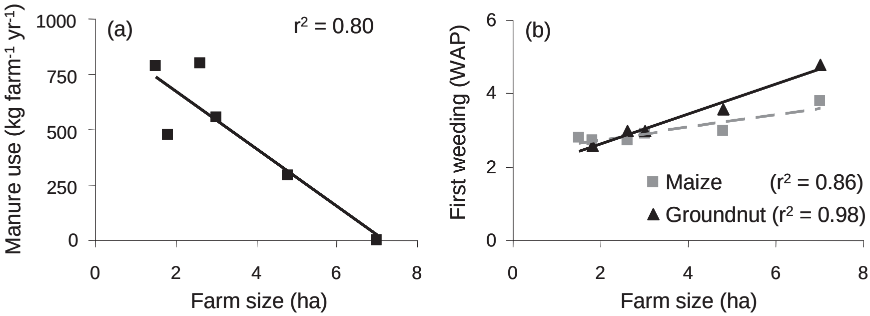

Figure 1: Correlations between average farm size and annual manure use (a) and average first weeding (weeks after planting) for maize and groundnuts (b) for the six study sites in Uganda and Kenya.

Uganda (*P*<0.001), with on average 51 and 30% of the cassava acreage being intercropped, mainly with maize. Other important intercropping systems were common bean intercropping in maize fields in Kenya (19% of maize area) and maize intercropping in groundnut fields in Uganda (21% of the groundnut area). Other crops were predominantly planted as sole crops. In sites with smaller farms, farmers used more manure (*P*<0.05; Figure 1a) and weeded maize and groundnuts earlier (*P*<0.01; Figure 1b).

3.2 Changes in farming systems over time

In western Kenya population densities at sub-county level increased from approximately 159-232 in 1982 to 291-387 persons km^{-2} in 2004 (cf. Table 1; Jaetzold and Schmidt, 1982). Nonetheless, average farm size had remained constant in Kwang'amor and decreased only by 0.2-0.3 ha in Ugunja and Mungatsi. At the same time, average household size had increased from 4.5-5.6 persons to 5.9-8.3 persons. The proportion of the average farm left fallow remained the same, while the proportion of the average farm used for grazing area was reduced by 22-34%, despite cattle numbers remaining stable. In 1977, between 40 to 85% of the cropped land was left fallow for a single season during the second rains, while in 2004 farmers had intensified land use to the extent that similar amounts of land were cultivated in both of the rainy seasons. The proportion of cropped land under cassava increased from 1-11 to 21-37% (Table 4a), whereas land cropped with cereals remained constant in Mungatsi and had increased in Kwang'amor and Ugunja. Cash cropping (i.e. cotton, sugarcane and sunflower) increased in Mungatsi, decreased in Kwang'amor and completely disappeared in Ugunja. In 2004/5 farmers used much more manure and fertilizer: average annual use had increased from 0-200 kg ha^{-1} to 300-900 kg ha^{-1} manure and from 6-30 kg ha^{-1} to 15-40 kg ha^{-1} fertilizer.

In Uganda population densities at district level increased from 14-98 in 1959 to 41-328 persons km^{-2} in 2005 (Table 1; Jameson, 1970). No detailed data on farm size and the relative importance of fallowing and grazing land are available, but Jameson (1970) states that land was cropped for two years and rested for two years in some areas, while in other areas the crop : fallow ratios tended to be much wider. Crop choice changed drastically over the four decades. Traditional cash crops such as coffee and cotton almost disappeared from the system (Table 4b), while at the same time a large shift in the predominant food crops had occurred: Banana, millet and sorghum had been replaced by cassava, sweet potato, maize and groundnuts. The proportion of cropped land under cassava had increased from 1-4 to 16-55%. No historical data on

Table 4: Comparison of cropped land under various crops (%)[1] in 1977[2] and 2004 for the Kenyan sites (a) and in 1963-64[3] and 2005 for the Ugandan sites (b)

		Root & tuber crops		Cereals				Legumes		Cash crops			Fallow
Site	Year	Cassava	Sweet potato	Maize	Sorghum	Millet	Rice	Common beans	Groundnuts	Cotton	Sugarcane	Sunflower	Single-season fallow[3]
(a) Kenya													
Kwang'amor	1977	11	-	16	1	8	-	-	-	13	-	8	43
	200	37	2	27	2	4	3	-	2	-	15	-	
Mungatsi	1977	9	-	16	5	4	-	2	1	8	12	7	36
	2004	21	2	21	2	1	-	-	1	1	49	-	
Ugunja	1977	1	-	42	3	-	-	5	-	-	27	2	20
	2004	31	9	40	13	2	-	-	3	-	1	-	

		Root & tuber crops		Cereals				Legumes		Cash crops			Fallow
Site	Year	Cassava	Sweet potato	Maize	Sorghum	Millet	Rice	Common beans	Groundnuts	Cotton	Coffee	Banana	Single-season fallow[3]
(b) Uganda													
Kisiro	1963	1	2	3	6	7	-	-	8	30	4	23	18
	2005	16	5	48	1	1	1	1	19	2	2	1	
Kikooba	1963	2	3	6	5	4	-	3	5	18	26	17	14
	2005	55	16	11	-	1	-	1	7	-	4	3	
Chelekura	1963	4	2	-	14	30	-	2	6	18	-	1	25
	2005	34	6	5	5	13	12	4	8	13	-	-	

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[1] Area with sole crop or with predominant intercrop.

[2] Data calculated from Jaetzold and Schmidt (1982) based on cropping pattern survey for first and second rains in corresponding agro-ecological zones (LM2-3 in Busia district for Kwang'amor; LM1 in Busia district for Mungatsi and; LM1 in Siaya district for Ugunja).

[3] Data calculated from Jameson (1970) using crop acreages per district (former Busoga district for Kisiro, former East Mengo district for Kikooba and former Teso district for Chelekura).

[4] Land not cultivated for one season. In Kenya (1977) farmers planted only a small portion of their farm to crops during the second rains. Data for Uganda (1963) were estimated from Jameson (1970).

input use are available, but in 2005 virtually no inputs were used in Kisiro and Kikooba, while average manure application rates in Chelekura were 400 kg ha^{-1}.

The intensification of cropping during the past three to four decades appears to have increased the offtake of nitrogen from around 15-25 to 30-40 kg ha^{-1} yr^{-1} (Figure 2a), while the offtake of phosphorus increased from around 3-6 to perhaps 4-8 kg ha^{-1} yr^{-1} (Figure 3a) and the offtake of potassium from around 10-15 to 20-50 kg ha^{-1} yr^{-1} (Figure 4a). Meanwhile, the recycling of nitrogen and potassium appears to have decreased by about 0-30 kg ha^{-1} yr^{-1} (Figures 2b and 4b) in most sites, while recycling of phosphorus has decreased slightly at half the sites (Figure 3b). At present about 50-90% of all nutrients are removed in produce of cassava and maize. On an annual basis, one crop of cassava removes a similar amount of N (± 35 kg ha^{-1}) and P (± 5 kg ha^{-1}) as two crops of maize, but almost four times as much K (± 47 versus 12 kg ha^{-1}). Cassava roots account for approximately 55% of the nutrients removed at harvest time, while the stems account for the rest. Three-four decades ago single-season fallows contributed one to two thirds of N, P and K recycling, while currently three quarters of N, P and K recycling come from cassava litterfall and cassava and maize crop residues. On an annual basis, one crop of cassava recycles about three times as much N (± 54 versus 20 kg ha^{-1}), similar amounts of P (± 4 kg ha^{-1}), but about 30% less K

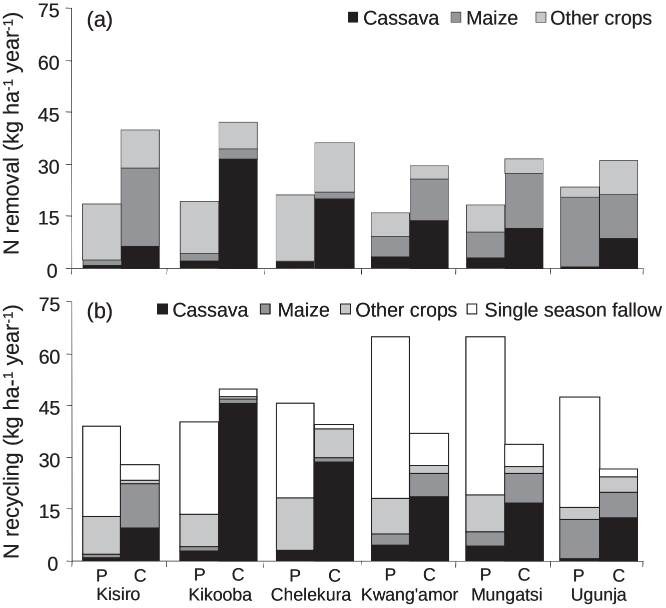

Figure 2: Estimated average past (P) and current (C) annual Nitrogen removal (a) and recycling (b) for Kenya (1977 and 2004) and Uganda (1963 and 2005).

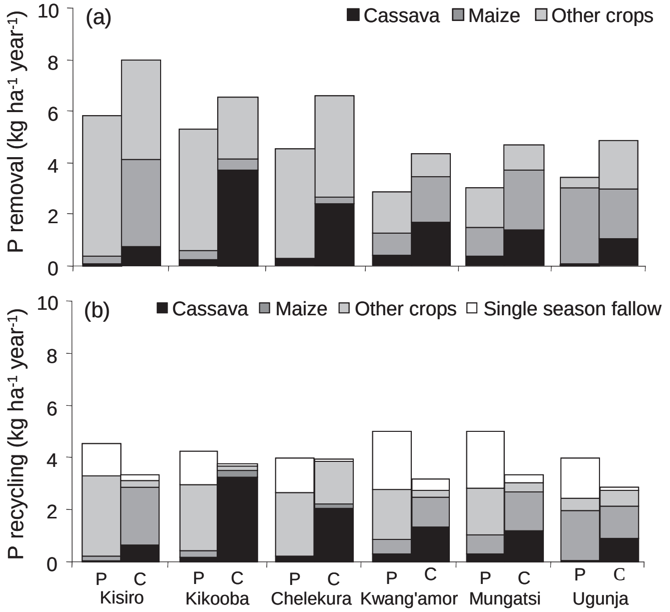

Figure 3: Estimated average past (P) and current (C) annual Phosphorus removal (a) and recycling (b) for Kenya (1977 and 2004) and Uganda (1963 and 2005).

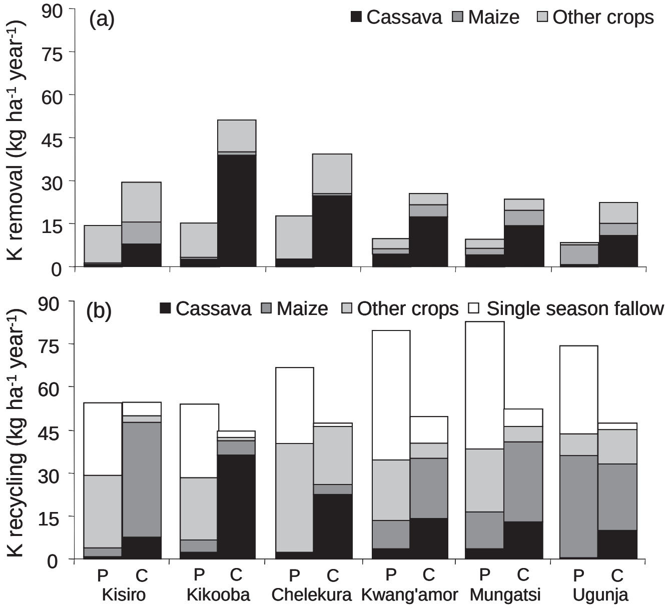

Figure 4: Estimated average past (P) and current (C) annual Potassium removal (a) and recycling (b) for Kenya (1977 and 2004) and Uganda (1963 and 2005).

(± 43 versus 62 kg ha^{-1}) as two crops of maize, while cassava recycles roughly half the amount of N, P and K that were recycled by two single-season fallows. Cassava litterfall contributes approximately 70% of N and P and 50% of K recycling by cassava.

3.3 Current spatial role of cassava

In the present farming systems, cassava cultivation was limited to upland fields in Kikooba, Chelekura and Kwang'amor (Table 3). In the other sites, cassava was found in the valley fringes but at a much lower frequency ($P<0.001$) than in the upland fields; i.e. 23 % of the valley fringe and 50% of the upland fields were planted with cassava as a major crop in at least one of the three survey seasons. Valley fringe cassava fields were reasonably well drained, were perceived as more fertile ($P<0.001$) than upland cassava fields, and were rarely intercropped (8%).

Taking maize yield as a proxy for overall soil fertility status, there was a strong negative relationship at regional level between the average soil fertility status of a site and the relative importance of cassava ($P<0.001$; Figure 5). At farm level, Kenyan farmers planted more cassava when they thought the average soil fertility status of their farm was poor than when they thought it was high ($P<0.01$; Figure 6). This was not the case in Uganda. The majority of farmers in Chelekura and the Kenyan sites said that they preferentially targeted cassava to their poorest fields, while farmers in Kisiro and Kikooba said they did not (Table 5), which was confirmed during the survey (Table 6). Although the soil fertility of local upland soil types varied significantly within all sites, cassava cultivation intensities were similar across upland

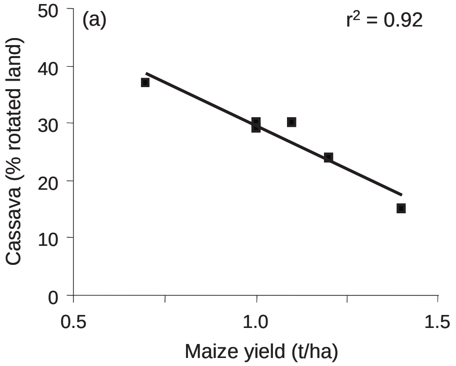

Figure 5: Correlation between average maize yield and relative cassava acreage in the six study sites in Uganda and Kenya.

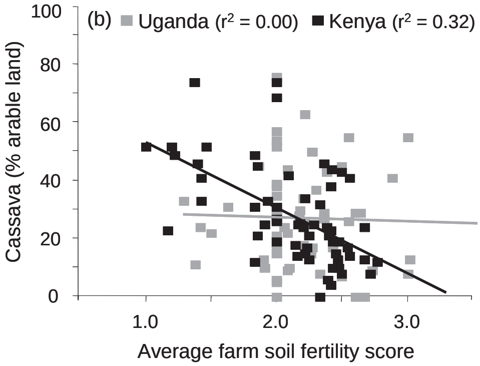

Figure 6: Correlation between soil fertility score by farmers and relative cassava acreage of surveyed farms in Uganda and Kenya.

soil types. Only in Mungatsi did farmers plant cassava preferentially (*P*<0.05) on the poorest soil type (Oluyekhe; Table 3). In Ugunja, Mungatsi and Chelekura, farmers considered upland fields close to their home as more fertile than upland fields that were located further away (*P*<0.01). Nonetheless, only the poor farmers in Ugunja planted less cassava (-37%) in their more fertile nearby fields in favour of maize (*P*<0.01).

Table 5: Agreement of farmers (% farmers agreeing) with statements on the role of cassava in the six study sites in Uganda and Kenya (n = 120)

Statements	Uganda			Kenya			*P*
	Kisiro	Kikooba	Chelekura	Kwang'amor	Mungatsi	Ugunja	
Cassava planted on poorest fields	22	5	60	70	79	95	*<0.001*
Cassava improves soil fertility	100	62	100	100	75	85	*<0.001*
Cassava used to rest the land	89	62	95	90	84	90	*<0.05*
Cassava is last crop before fallow	94	95	75	55	79	100	*<0.01*
Cassava is first crop after fallow	11	76	6	5	16	0	*< 0.001*
Never cassava after cassava	67	81	85	90	84	70	*ns*

P-value from 2 sided, asymptotic Pearson χ square test, testing for significant differences between sites

Table 6: Cassava cultivation intensity[1] (%) on upland fields per soil fertility status class (farmer perception) in the six study sites in Uganda and Kenya

Soil fertility status	Uganda				Kenya			
	Kisiro	Kikooba	Chelekura	Total	Kwang'amor	Mungatsi	Ugunja	Total
n	186	235	202	623	213	173	229	615
Poor	83 (6)	63 (27)	33 (12)	58 (45)	72 (87)	67 (51)	64 (39)	69 (177)
Medium	42 (143)	62 (195)	68 (103)	57 (441)	64 (98)	58 (77)	51 (111)	57 (286)
Good	43 (37)	77 (13)	52 (87)	52 (137)	57 (28)	49 (45)	38 (79)	45 (152)
P	*ns*	*ns*	*< 0.05*	*ns*	*ns*	*ns*	*< 0.05*	*< 0.001*

Between parentheses the number of surveyed fields within a soil fertility class is given. *P*-value from 2-sided asymptotic Pearson χ^2 test, testing for significant difference between fertility within sites and countries.

[1] Percentage of upland fields with cassava as a major crop in at least one of the three survey seasons.

Table 7: Relative cassava acreage (%) before (B) and after (A) fallow and selected crops[1] in the six study sites in Uganda and Kenya (n = 120)

	Fallow				Tuber crop		Cereals						Legumes		Cash crop	
	Bush		Grass		Sweet potato		Maize		Sorghum		Millet		Groundnut		Cotton	
	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A
Uganda																
Kisiro	0	0	0	10	18	27	49	33	1	0	2	2	31	18	0	5
Kikooba	4	0	23	5	24 *	78 *	15	12	0	0	1	0	33 *	5 *	0	0
Chelekura	0	0	0	2	12	17	13	10	9	8	33	21	18	25	11	16
Kenya																
Kwang'amor	0	0	25	20	4	8	42	42	6	8	10	13	13	8	1	0
Mungatsi	0	0	22	18	12	9	52	54	6	12	2	4	6	2	0	0
Ugunja	0	0	7	15	13	13	60	36	17	24	0	4	3	7	0	0

[1] Percentages are based on field information from three seasons, i.e. maximum two crop sequences per field.

* *P*< 0.05; Wilcoxon signed ranks test for 2 related samples, testing for differences between cassava acreage before and after crop within a site.

3.4 Current temporal role of cassava

No well-defined crop rotations were used at any of the sites. Cassava was most frequently planted before or after cereals (especially maize), except for Kikooba where farmers preferred to plant cassava after groundnuts and before sweet potato (Table 7). The majority of farmers indicated that they planted cassava as the last crop before a fallow and did not plant cassava immediately after a fallow (Table 5). Field data, however, show that in Kenya farmers planted as much cassava after as before grass-fallows, while in Kisiro and Chelekura cassava was rarely planted before or after a grass-fallow. Across sites, the majority of farmers (86%) believed that cassava improves soil fertility and therefore used cassava ‘to rest the soil’ (Table 5). Some farmers (17%) also believed that sweet potato improved soil fertility. Most farmers (48%) explained that the positive effect of cassava on the next crop was due to its ability to shed leaves continuously during its growth cycle. Other explanations offered by farmers are that uprooting cassava brings nutrients to the soil surface (12%) or that cassava extracts few nutrients (10%). Water conservation and less striga or weed pressure in the subsequent crop were mentioned by some farmers.

4. Discussion

4.1 The changing role of cassava in intensifying farming systems

4.1.1 Cassava on the increase

During the past three to four decades, increasing population pressure coupled with external changes, such as in markets, have caused striking changes in land use and led to an important intensification of the studied farming systems. In all sites, cassava has developed from being a crop of little importance, grown in odd corners or on small plots outside the main rotation (Jameson, 1970), to the first or second most important crop in terms of acreage cultivated. From being classified as millet, banana, cotton and/or sugarcane based farming systems with an important fallow and/or grazing land component (Jameson, 1970; Jaetzold and Schmidt, 1982) all systems have evolved into cassava or cassava/maize based farming systems under continuous cultivation (R > 65; Ruthenberg, 1976; Figure 7). Common reasons mentioned for an increase in cassava cultivation are related to either cassava being less-demanding on soil fertility and labour, to its high yield per unit area in intensifying agricultural systems (Berry, 1993; Hillocks, 2002; Baijukya et al., 2005), or to its role as food security crop during famine periods (e.g. the Ugandan West Nile famine as reported by McMaster (1962). That cassava yields well in poor soils was most probably a contributing factor in two

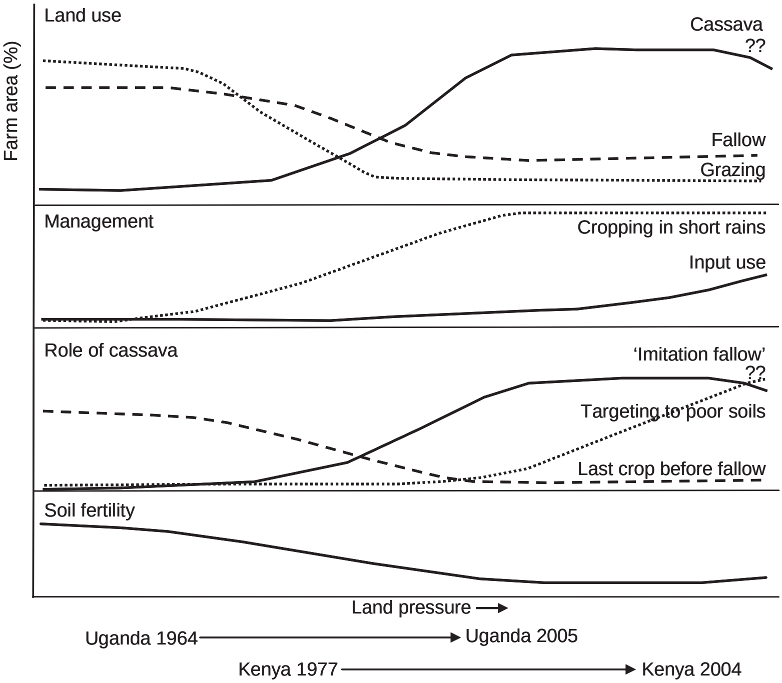

Figure 7: Observed or apparent changes in land use, management, the role of cassava and soil fertility in continuous cultivation systems in eastern Africa in response to increasing land pressure.

of the sites in Uganda where cassava has replaced banana, which requires fertile soils (van Asten et al., 2004) and in all Kenyan sites where farms with poorly fertile soils were found to plant more cassava. Due to the reduction of cash cropping, grazing land and a decline in fallowing in Uganda, the acreage under food crops has increased considerably over the past decades. It is therefore unlikely that farmers introduced cassava with the primary aim to maintain food productivity of their farms. Nonetheless, cassava is currently more important in sites with low maize yields. Over the past decades, labour availability per household has increased and households with less available labour did not grow more cassava in any of our study sites (data not shown). The above suggests that declining soil fertility, and not labour or food shortage, was apparently the primary trigger for the dramatic increase in cassava acreage in the last three to four decades.

4.1.2 The changing physical and temporal roles of cassava

In the past, long fallow periods were common in the millet-based farming areas in Uganda (Jameson, 1970) and most likely in all our study areas. Cassava is often grown as the last crop before a long fallow (Carter et al., 1992; Hillocks, 2002), as it gives relative good yields when soil fertility is poor (Fresco, 1986; Howeler, 2002). It is likely that this was also the case in our study sites, as the idea that cassava is planted at the end of a rotation was still firmly set in the minds of many farmers. Our detailed farming systems analysis revealed a different situation. In the continuous cultivation systems of today, farmers have no distinct rotations and consider cassava as an 'imitation fallow', or effectively as a substitute for fallow (Figure 7). In Ghana, Benin, Nigeria and Kenya extensive or sole cassava cropping is also regarded as a soil fertility regenerating strategy and referred to in Francophone Africa as 'jachère manioc' - literally 'cassava-fallow' (Kristjanson et al., 2002; Carsky and Toukourou, 2003; Obiero, 2004; Saidou et al., 2004; Adjei-Nsiah et al., 2007). In our study areas, farmers attached great value to the 'fallow' role of cassava as it was planted: (i) on soils of all textures, despite root development, yields and ease of harvesting being better on sandy soils (Carter et al., 1992; Ratanawaraha et al., 2000); (ii) on all field types – even in cases where cassava was preferentially grown on particular fields its cultivation intensity remained high on non-preferred field types; and (iii) as a sole crop in 50-70% of the fields, which represents an increase compared with earlier studies in Uganda (Jameson, 1970; Nweke et al., 1998). Sole cropping of cassava favours soil regeneration as nutrient removal by sole crops is less than from intercropped cassava (Leihner, 2002).

Many studies report that cassava is targeted away from fertile (homestead) fields (Fresco, 1986; Dixon et al, 2002; FAO, 2004b; Tittonell et al., 2005; Baijukya et al., 2005). In our study, targeting of cassava to less fertile upland fields was common in the Kenyan sites and Chelekura. These sites have a higher population density (>230 persons km^{-2}), smaller farm sizes (< 3 ha) and soils with lower pH values (< 5.8) than the other two Ugandan sites where cassava was not targeted to poorly-fertile fields. Targeting of cassava to poor fertility fields was strongest in Ugunja, which has the highest population pressure (387 person km^{-2}) and soils with very low available P (3.2 mg kg^{-1}), in combination with relatively low pH (5.4), In Mungatsi farmers preferred to plant cassava on Oluyekhe, a soil with a medium-low available P content (5.3 mg kg^{-1}) and a low pH (5.0). Cassava is known for its tolerance to acidic and low available P soils (Howeler, 1991b), as its highly effective symbiosis with mycorrhizas enables cassava to absorb P efficiently (Kang et al., 1980; Howeler et al., 1987; Howeler, 2002).

The above analyses are from upland fields where the majority of cassava production takes place. In three sites farmers also planted cassava in another part of the landscape, i.e. in fields on the fringes of the valleys. The use of these fields seems to be dictated more by local topography and drainage (potential) than by population density or the importance of cassava. Cassava cultivation intensity was lower on the valley fringe fields than on upland fields, likely due to either problems with waterlogging and/or the high fertility of these fields.

4.2 Consequences for system sustainability

Increasing land use intensities have drastically increased nutrient removal from annually cropped land in all sites over the past three to four decades (Figure 2a-4a). Current annual removal rates for cropped fields are estimated at 30-40 kg ha^{-1} N, 4-8 kg ha^{-1} P and 25-50 kg ha^{-1} K. Accounting for leaching and erosion, Roy et al. (2003) arrived at nutrient removal rates for Kenya that were two to three times higher than our estimates. Farmers in the Kenyan sites and Chelekura applied about 10-30 kg ha^{-1} N and 2-5 kg ha^{-1} P and K with manure and/or fertilizer, but only made limited use of leguminous crops. Farmers in Kisiro and Kikooba rarely used fertilizers and manure and although 9-20% of the cropped land was used for groundnut, which potentially contributes large amounts of nitrogen (Toomsan et al., 1995), groundnut stover was not returned to the fields. Farmers in our study areas with higher land use intensities thus partially offset N and P losses from crop harvests, but not in sites with lower land use intensities, while K losses were hardly compensated for in any of the sites.

Management of organic resources plays a critical role in both short-term nutrient availability and longer-term maintenance of soil organic matter (Palm et al., 2001), the more so in farming systems with little or no external input use. Jones (1972) and Jameson (1970) recommended that land is either rested for at least half the time or 10 tons manure per acre is applied every three years to maintain soil fertility in Uganda. Neither option is possible in the intensive farming systems of today, although farmers in Kikooba and Kisiro could without doubt increase manure use. Compared with three-four decades ago, recycling of organic resources appears to have decreased in most sites due to the decline in fallowing (Figure 2b-4b). Currently, most recycling of N and P occurs through cassava litterfall. According to criteria of Palm et al. (2001), cassava litterfall is an important source of easily mineralizable N due to its high nitrogen (2.5%) and low lignin content, leading to high decomposition rates (Hairiah et al., 2005). Maize stover supplies less N due to its poor N content that causes N immobilization. Considering the limited use of external nutrient inputs, the large scale adoption of cassava is likely to have been key in maintaining a reasonable supply of nitrogen and phosphorus to (cereal) crops. If the systems had intensified towards cereal-based systems, cereal yields in all likelihood would have decreased due to a lack of N and P, unless farmers had intensified management. Fresco (1993) postulated that by growing more cassava, farmers may be able to delay the intensification of management practices. This is confirmed by our results, but once farmers target cassava to the poorer soils, they have effectively run out of low-input management practices and will need to intensify management to maintain crop production (Figure 7). Such intensification is already happening in the sites with the highest land use intensities (Kenya and Chelekura): farmers commonly use manure and fertilizer and weed their crops earlier. The use of (in)organic inputs may result in soil fertility improvement in the long term and could translate into a reduced need for cassava as an 'imitation fallow', or an even stronger preference to plant cassava on poor fields as fertilizer response in cereals is often better on good soils (Vanlauwe et al., 2006; Tittonell et al., 2007a).

Cassava breeding programmes in East Africa have developed genotypes that yield 1-6 t ha^{-1} more than the local or the widely-adopted early released improved genotypes, while harvest indices have remained constant (unpublished results). The increasing demand for biofuels world-wide is expected to increase adoption of the new genotypes as it will promote industrialization of cassava and lead to increased prices (von Braun, 2007). Although nutrient recycling is expected to be augmented through more litterfall, it is likely that the widespread adoption of these genotypes will accelerate the depletion of nutrient stocks. In the long term, K inevitably becomes the limiting nutrient in farming systems with an important cassava component (Howeler, 2002; Adjei-Nsiah et al., 2007). Increasing K inputs is difficult as manure contains limited amounts of K, potassium fertilizers are currently not or poorly available in rural markets and Ugandan farmers lack experience of using fertilizers. K removal could be reduced by approximately half, if farmers would dry cassava stems on field edges (to prevent sprouting) and return them to the fields, or if they returned the ash generated when cassava stalks are burned for cooking.

5. Conclusions

This study confirms the versatile nature of cassava. We have demonstrated that both the importance and the temporal and physical roles of cassava within a farming system have changed drastically within a few decades as a consequence of increasing populations, higher land pressure, and less grazing land and/or fallow (Figure 7). Our results support the theory of Berry (1993) and Hillocks (2002) on this sequence of changes, while in addition we argue that the ability of cassava to recycle important amounts of nutrients through its litterfall is likely to be as important as its ability to grow on poor soils. Even when cassava is not a traditional food crop and/or there is no strong market demand for cassava, farmers have set aside cultural preferences for cereals and introduced cassava on a large scale. With land pressure increasing throughout Africa, similar changes may be expected in other parts of the continent. The fact that cassava production in Africa has more than tripled in the last four decades, mainly due to an increase in area cultivated (Hillocks, 2002), is an indication that this is already happening. As cassava is now used by more farmers and on a larger acreage than fallowing in the farming systems studied, cassava cropping could serve as an excellent entry point to strengthen system sustainability. There is thus a clear need to: (i) evaluate the capacity of cassava to sustain or improve nutrient recycling into the soil’s more labile nutrient pools: (ii) to understand the underlying mechanisms: to (iii) to evaluate differences between genotypes: and (iv) to develop management options that can maintain/improve the productivity of capital extensive cassava-based farming systems through integrated soil fertility management (ISFM) practices in Africa. Given the high land pressure and the observed trends, the increased use of external nutrient inputs seems inevitable in the near future.

Chapter 4

Closing the cassava yield gap: An analysis from small-holder farms in East Africa

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Abstract

Cassava yields in Africa are small and it remains unclear which factors most limit yields. Using a series of farm surveys and on-farm and on-station trials in Uganda and western Kenya, we evaluated the importance of abiotic, biotic and associated crop management constraints for cassava production in a range of socio-economic settings as found in smallholder farms in the region. Average yields under farmer management were 8.6 t ha^{-1}, but these were more than doubled to 20.8 t ha^{-1} by using improved crop establishment, improved genotypes and 100-22-83 kg ha^{-1} of single-nutrient N-P-K fertilizers. A farm survey revealed large yield differences between farms. Less endowed farmers harvested less cassava per unit area than better endowed farmers (difference of 5.9 and 9.7 t ha^{-1} in Kenya and Uganda, respectively); differences were associated with less access to labour, poorer soils, and premature harvesting by less endowed farmers. Analysis of 99 on-farm and 6 on-station trials showed that constraints for cassava production varied strongly between sites and years. Poor soil fertility, early water stress and sub-optimal weed management limited cassava production by 6.7, 5.4 and 5.0 t ha^{-1}, respectively, when improved crop establishment and genotypes were used. Pests and diseases were relatively unimportant, while weed management was particularly important in farmer fields during a dry year in Kenya (yield gap of 11.6 t ha^{-1}). The use of complementary analytical tools such as multiple regression and boundary line analysis revealed that many fields were affected by multiple and interacting production constraints. These should be addressed simultaneously if significant productivity improvements are to be achieved. This will be more difficult for less endowed than for better endowed farm households, since the former lack social and financial capital to improve management.

Keywords: Agriculture; Boundary line analysis; Drought; Nutrient management; Production constraints; Soil fertility; Weed management

1. Introduction

Cassava research and extension efforts in Africa have successfully focused on breeding and integrated pest management (IPM) strategies to control major pests and diseases, most notably mosaic virus, mealy bugs and green mites (Alene et al., 2006; Legg et al., 2006; Zanou et al., 2007). While the major focus of such efforts was placed on coping with biotic constraints, relatively little attention has been given to abiotic, crop management and socio-economic constraints. Understanding the relative importance of these factors to the yield gap is a necessary step to guide the design of relevant research for development interventions aimed at improving cassava productivity. This has been acknowledged by scientists who recently initiated a worldwide exercise to gather expert knowledge on the contribution of various constraints to the cassava yield gap in the main agro-ecological regions where cassava is grown (Generation Challenge Programme, 2008, p. 82). The yield gap is generally defined as the difference between actual farmer yields and potential yield, whereby potential yield is the maximum yield that can be achieved in a given agro-ecological zone. For practical purposes it is, however, more interesting to study the gap between the actual and attainable yield, whereby the attainable yield can be defined as the maximum yield observed in a given agro-ecological zone with a given management intensity.

The mid-altitude zones of East Africa constitute a major cassava-growing region in Africa and cover a wide range of agro-ecological conditions. Some of these are well represented in areas of Kenya and Uganda. Average fresh yields at country level in 2007 were 10.6 t ha^{-1} in Kenya and 12.0 t ha^{-1} in Uganda, which was just above the African average of 9.9 t ha^{-1} (FAO, 2009), but far below typical average fresh yields of 15-40 t ha^{-1} obtained in on-farm breeding trials in these countries (Ntawuruhunga et al., 2006; Fermont et al., 2007). According to Cock et al. (1979) the ideal cassava plant, consisting of a late branching genotype that possesses large leaves with a long leaf life, would have a potential yield of 25-30 t ha^{-1} dry roots, equivalent to fresh root yields in the range of 75-90 t ha^{-1}. Such fresh root yields have been attained in experimental conditions in Colombia and India (El-Sharkawy, 2004). The largest fresh root yields recorded under experimental conditions in East Africa are 50-60 t ha^{-1} (Obiero, 2004; Ntawuruhunga et al., 2006). In the past fifteen years, the most obvious constraint to cassava production in East Africa was the cassava mosaic virus disease pandemic. This virus caused a mean yield loss of 72% in landraces, but has been controlled due to the widespread introduction and adoption of resistant genotypes (Legg et al., 2006). Nonetheless, actual cassava yields have remained low. Therefore, the question remains what the most limiting factors are for cassava production.

This study thus aims to quantify the relative importance of abiotic, biotic and management constraints for cassava production across a range of socio-economic settings in smallholder farms in East Africa. The study is based on data from a series of farm surveys in Uganda and western Kenya, complemented with a range of on-farm and on-station trials for a period of two years. We first quantify average and attainable yields for smallholder farmers under increasingly improved crop management, comparing: (i) current farmer practice; (ii) improved crop establishment; (iii) regime ii + improved genotypes; (iv) regime iii + NPK fertilizer. Secondly, we explore which management practices, in relation to socio-economic settings, determine yields under current farmer practice (regime i). Thirdly, we study the abiotic, biotic and associated crop management factors limiting cassava productivity at management regime iii (improved genotypes and crop establishment). We use multiple regression and boundary line analysis (Shatar and McBratney, 2004) to identify the relevant yield loss factors, to explore possible interactions and to quantify their contribution to the yield gap. We conclude by discussing the scope to overcome the production constraints identified.

2. Materials and methods

2.1 Site description

The farm surveys and agronomic trials were carried out in a range of sites in western Kenya and central and eastern Uganda. The sites were chosen to represent a range of environments and management practices in cassava-based cropping systems in the mid-altitude zone of East Africa. The farm surveys were carried out in three sites in western Kenya, which included Kwang'amor (0^o29'N; 34^o14'E), Mungatsi (0^o27'N; 34^o18'E) and Ugunja (0^o10'N; 34^o18'E) in Teso, Busia and Siaya districts, respectively. In Uganda, the sites included Kisiro (0^o67'N; 33^o80'E), Kikooba (1^o40'N; 32^o38'E) and Chelekura (1^o14'N; 33^o62'E) in Iganga, Nakasongola and Pallisa district, respectively. On-farm trials in western Kenya were installed in the same sub-locations and in Nambale (0^o28'N, 34^o14'E) in Busia district, while on-farm trials in Uganda took place in Kisiro and Minani (0^o80'N; 33^o57'E) in Iganga district. In addition, on-station trials were installed at the Kenyan Agricultural Research Institute (KARI) in Alupe, Busia district (0^o30'N; 34^o08'E) and at the Ugandan National Crops Resources Research Institute (NaCRRI) in Namulonge, Wakiso district (0^o32'N; 32^o37'E). Main soils in the region include ferric and orthic Acrisols and orthic and haplic Ferralsols; soils that are derived from strongly weathered granite or sedimentary parent material (KARI, 2000; Jaetzold and Schmidt, 1982). The climate in all sites is sub-humid with a bimodal rainfall distribution. This allows for the production of most annual crops during both the long (March-June) and the short rains (September-November). Altitude ranges between 1100 and 1260 masl. Cassava is planted in the first two months of the short or long rains and remains in the field for about a year. Agricultural systems are diverse with farmers growing 4-6 main crops on average (Fermont et al., 2008 – Chapter 3).

2.2 Farm surveys

At the start of the farm surveys in Kenya (June-September 2004) and Uganda (October 2005-April 2006), three to four key informants per site ranked all households in three wealth categories; poorer, medium and richer. Twenty households per site were randomly selected, with a minimum representation of three households per wealth category. Structured interviews, in combination with a visit to all fields of each household, were used to collect data on main production constraints, socio-economic settings, farm management, and cassava crop management. Essential information was cross-checked by triangulating interview data with field measurements during a series of field visits. Farmers were asked to estimate average cassava yield in the past few years, by estimating the number of bags of fresh or dry cassava product per unit land. Dry matter yields were converted to t ha^{-1} fresh cassava yields, using an average dry matter content of 33% (Alves, 2002). More detail on the data collection methods is given in Fermont et al. (2008 – Chapter 3).

2.3 Trials

Two consecutive sets of on-farm cassava trials were planted in 2004 (49 farms) and 2005 (50 farms) across the six on-farm sites in Kenya and Uganda; we refer to them as the ‘2004 trials’ and ‘2005 trials’, respectively. In addition, six researcher-managed trials with similar treatments and four repetitions were installed at KARI (Kenya) and NaCRRI (Uganda) experimental stations. The 2004 trials were planted with two genotypes, TMS 30572 (released in Uganda as ‘Nase 3’) and TMSI92/0067 in Uganda and Nase 3 and MM96/5280 in Kenya, while the 2005 trials were planted with only TMSI92/0067 in Uganda and MM96/5280 in Kenya. Nase 3 has been widely adopted by farmers in both countries (Legg et al., 2006), while the other two genotypes are more recently developed by the national cassava breeding programmes. In all trials these genotypes were grown without and with fertilizer. Per crop cycle 100-22-83 kg ha^{-1} N-P-K (e.g. 100-50-100 kg ha^{-1} N-P2O5-K2O) was applied. P was applied as basal application of triple super phosphate at planting, and N and K as urea and potassium sulphate in two equally split broadcast applications at 1 and 3 months after planting (MAP). In all trials, a package of improved management practices at crop establishment was used that consisted of a 1 m x 1 m plant spacing, no intercropping, and early planting at the start of the rainy season. We refer to this package as ‘improved crop establishment’. Manual weeding was done by farmers, according to their own judgement, while on-station trials were kept weed-free by manual weeding. Total cassava storage roots fresh yield was determined at 11.5-13 and 12-15 MAP in the on-farm and on-station trials, respectively.

Composite soil samples (0-20 cm) were taken from each field. Samples were oven-dried, sieved through a 2 mm sieve, and analysed for pH, available P, exchangeable K, Ca, Mg, total N, soil organic carbon and texture following Okalebo et al. (2002). Daily precipitation data were recorded using rainfall gauges at all sites. Total precipitation (mm) and rain days were calculated for the entire crop cycle duration and the periods of 0-3, 3-6, 6-9, 9-12, 12-15, and 0-6 MAP. Research technicians scored overall weed management (WM) in each field on a scale from 1 (very poor) to 5 (very good). Twenty plants in the centre of each plot were scored at 3, 6 and 9 MAP for incidence (yes/no) and severity (1-5 scale; IITA, 1990) of cassava mosaic disease, bacterial blight, green mites, anthracnose disease and mealy bugs; no disease data were recorded in the 2004 on-farm trials in Uganda. Severity scores at 3, 6, and 9 MAP were used to calculate the area under severity index progress curves (AUSiPC) for all pests and disease, except for mealy bug, which was not found in any of the trials. AUSiPC values range from 0 for a pest/disease-free plot to 750 for a plot where all plants were consistently rated severely infected.

2.4 Data analysis

2.4.1 Management regime i: current farmer management

To explore the relationship between crop management, farm management, and socio-economic variables with average farm yields under current farmer management, we first calculated Pearson bivariate correlations. Explanatory variables that had a correlation coefficient (r) larger than 0.25 with yield and/or exhibited a pattern of co-variation with cassava root yields were included in the further analysis. We then classified average farm yields into three groups per country: lowest yielding farms (first quartile), average yielding farms (second and third quartile) and highest yielding farms (fourth quartile). For each yield class, average values for the retained explanatory variables were calculated. Chi-square tests (SPSS 12.0) were carried out to explore significant differences between yield classes.

2.4.2 Management regime iii: explaining yield variability

To identify the variables that best explain yield differences at management regime iii (improved crop establishment and improved genotypes), we carried out a linear regression analysis on data from the 2004 and 2005 trials, whereby abiotic, biotic and management factors were taken as independent variables and cassava root yield of the two genotypes MM96/5280 and TMSI92/0067 as the dependent variable. Analyses were done for the entire data set and for each country separately, using GenStat (version 10.1). Where required, variables were transformed to normality using Box-Cox power transformations. Subsequently, Spearman's and Pearson's correlation analyses were used. For any pair of abiotic, biotic and management variables with inter-correlations (r) greater than 0.7 only one variable was retained in the regression model. The all subsets regression routine in GenStat and Mallow's criteria were used in addition to other model diagnostics to select the best model. We computed the square of the semi-partial correlation coefficients to approximate the relative contribution of each explanatory variable to yield variability, while controlling for other variables in the equation (Snedecor and Cochran, 1980; Cohen et al., 2003). As many variables were highly variable, we checked that the impact of the measurement error for each explanatory variable on the regression coefficients was <10% (Warton et al., 2006).

2.4.3 Management regime iii: identifying yield gaps

To explore in more detail the contribution of individual abiotic, biotic and management factors to the yield gap at management regime iii, we slightly adapted the boundary line approach as used by Webb (1972), van Asten et al., (2003) and Shatar and McBratney (2004). Our approach consisted of following steps:

1. After sorting the independent variables in ascending order and removing outliers, we defined boundary lines that represented the maximum yield response (the dependent variable) to the various independent variables (e.g. rainfall). Boundary lines were fitted through selected boundary points (Schnug et al., 1996) following the model:

$$y_l = \frac{y_{\max}}{(1+(K \times EXP(-R \times x)))} \tag{1}$$

   whereby ymax is the observed attainable yield level at management regime iii, x is the independent variable and K and R are constants. The best boundary line model was obtained by minimizing the root mean squared error (RMSE) between the fitted boundary line (yl) and the boundary points (yp).

2. Individual boundary lines were used to calculate for each field and each independent variable the maximum cassava yield that could have been obtained if production would only have been limited by the independent variable in question (y_max_{ij})
3. Individual boundary lines were then combined in order to create a multivariate model, assuming responses according to von Liebig's law of the minimum (von Liebig, 1863; Shatar and McBratney, 2004). The model was used to predict yields for each field.
4. Lastly, we determined the yield gap caused by each independent variable in each field as the attainable cassava yield minus y_max_{ij}.

3. Results

3.1 Yield steps between intensifying regimes of management

Average cassava yields under current farmer practice (regime i) in Kenya and Uganda ranged from 6.1 to 11.7 t ha^{-1} (Table 1). The complete management package (regime iv), consisting of improved crop establishment, an improved genotype and NPK fertilizer use, more than doubled average yields on farmer fields, from ca. 9 to 21 t ha^{-1} ($P<0.001$) and increased attainable yields from ca. 18 to 37 t ha^{-1} (Figure 1). This effect was observed in both Kenya and Uganda, albeit with somewhat different patterns of response at each individual site (Table 1). Improving crop establishment (regime ii) increased average yields by 1.5 t ha^{-1}, but the effect varied strongly (-0.9 to +4.4 t ha^{-1}) across sites. Replacing the widely adopted Nase 3 with the improved genotypes MM96/5280 or TMSI92/0067 (regime iii) increased average yields further by 3.5 t ha^{-1} ($P<0.001$), with a range of 0.9 to 6.1 t ha^{-1} between sites. Adding NPK fertilizer (regime iv) increased average yields by another 7.2 t ha^{-1} ($P<0.001$), with a range of 5.8 to 9.2 t ha^{-1} between sites, except for the fertile NaCRRI site. Whereas average yields varied between sites under farmer practice ($P<0.001$), with improved crop establishment ($P<0.01$) or using improved genotypes ($P<0.05$), the application of NPK fertilizers tended to equalize yields across sites (Table 1). Whereas boundary lines could be identified under unfertilized conditions that showed increasing yields with increasing SOC, available P and exchangeable K, no functional relationships (i.e. boundary lines) could be derived when fertilizer was applied (Figure 2a-c).

Table 1: Effect of increasing management on average cassava yields (t ha-1) in Kenya and Uganda

Regime	i Farmer management[1]	ii + improv. crop establishment[2]	iii + improved genotype[3]	iv + NPK fertilizer[4]	SED
Kenya					
Kwang'amor	7.9 (4.4-13.3)	9.9 (5.5-17.3)	10.8 (3.0-16.2)	20.0 (8.5-34.3)	2.02
Mungatsi	6.4 (2.7-9.8)	10.8 (6.0-15.5)	14.4 (5.8-22.7)	20.2 (10.3-35.2)	2.39
Nambale	-	7.4 (2.7-14.3)	13.5 (3.5-25.5)	21.0 (8.5-35.0)	2.88
Ugunja	6.1 (2.7-8.9)	5.2 (1.0-14.3)	10.1 (2.8-23.8)	19.3 (6.4-37.3)	2.62
KARI	-	10.8 (3.3-17.6)	12.7 (4.3-20.6)	17.9 (7.7-25.4)	2.36
Uganda					
Minani	-	13.0 (9.0-19.3)	16.4 (9.8-24.5)	25.3 (20.5-31.0)	1.78
Kisiro	8.3 (2.7-12.0)	11.9 (6.4-18.0)	15.1 (6.5-22.8)	23.2 (7.1-35.5)	2.72
Kikooba	11.2 (5.3-17.8)	-	-	-	-
Chelekura	11.7 (6.7-17.8)	-	-	-	-
NaCRRI	-	15.5 (11.6-18.9)	21.3 (15.5-27.3)	21.5 (14.8-30.4)	3.13
Overall mean	8.6	10.1	13.6	20.8	0.93
SED	0.89	2.54	2.78	3.32	

[1] Farmer estimates of average cassava yield in their farm. Data from 108 household surveys

[2] Yield of Nase 3 in the 2004 trials with improved crop establishment (1 m x 1 m spacing, no intercrop, timely planting). Data from 57 fields. Nase 3 had similar yields as landraces (Fig. 3d)

[3] Yield of improved genotypes MM96/5280 (Kenya) and TMSI92/0067 (Uganda) in the 2004 and 2005 trials with improved crop establishment. Data from 111 fields.

[4] Yield of improved genotypes MM96/5280 (Kenya) and TMSI92/0067 (Uganda) in the 2004 and 2005 trials with improved crop establishment and fertilizer use (100-22-83 N-P-K). Data from 112 fields.

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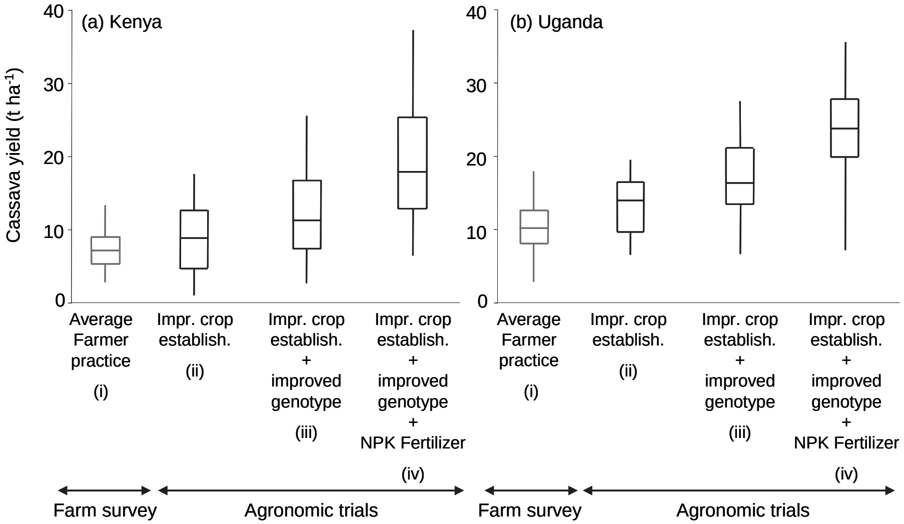


Figure 1: Cassava yields in (a) Kenya and (b) Uganda at four regimes of increasing management. See footnotes at Table 1 for more details. Box-whisker diagrams include the range of 50% of the observations (rectangular box), the median (cross bar) and the min. and max. values (vertical lines).

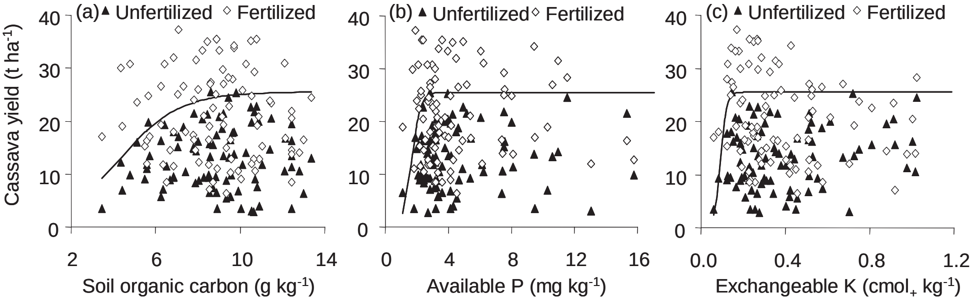


Figure 2: Cassava yields under management regime iii (improved crop establishment and genotypes) and regime iv (level iii + NPK fertilizer use) in the 2004 and 2005 trials versus (a) soil organic carbon; (b) available P and; (c) exchangeable K.

Yield variability at each management regime was large (Table 1). In the next paragraphs management regime i (current farmer practice) and regime iii (improved crop establishment + improved genotypes) are analysed in more detail to evaluate which factors contributed to the observed yield variability.

3.2 Management regime i: socio-economic diversity, management and cassava yield

The farm surveys showed that socio-economic conditions varied broadly between sites (Table 2); the average amount of arable land per household ranged from 1.2 ha to 4.0 ha ($P<0.01$), average annual household income ranged from US$ 663 to US$ 1,283 ($P<0.001$), while average labour availability ranged from 3.3 to 8.8 adult equivalent per year per household ($P<0.001$) between sites. Farm and crop management also varied strongly between sites; farmers planted on average 0.3 to 0.9 ha of cassava ($P<0.01$), planted an average 0 to 80% of this acreage with improved genotypes ($P<0.001$) and between 38 to 70% as a sole crop ($P<0.01$), while the number of weed operations per field ranged from 3.3 to 5.9 ($P<0.001$) between sites. Farmers rarely applied (in)organic nutrient inputs in cassava fields, but hired labour for cassava varied ($P<0.001$) from 6 to 129 man days per year per farm. These differences were reflected in the average cassava yields as estimated by farmers across sites (Table 1). Yields were significantly larger in Uganda than in Kenya ($P<0.001$).

Average cassava yields of the lower quartile farms were 6.1 and 9.7 t ha^{-1} less than average cassava yields of the upper quartile farms in Kenya and Uganda, respectively ($P<0.001$; Table 3). In both countries, greatest yields were observed on farms with a high annual household income, large amounts of available labour, large acreages of

Table 2: Selected details on socio-economic settings, farm and cassava management in the six farm survey sites in Kenya and Uganda

		Kenya			Uganda			
		Kwang'amor	Mungatsi	Ugunja	Kisiro	Kikooba	Chelekura	SED
Socio-economic								
Arable land	(ha)	2.9 ± 3.4	2.0 ± 1.3	1.2 ± 0.8	4.0 ± 3.5	2.7 ± 1.8	1.8 ± 1.3	0.7
Labour availability[1]	(Adult equivalent year^{-1})	5.1 ± 3.2	4.6 ± 2.2	3.7 ± 1.7	5.4 ± 3.7	3.3 ± 2.8	8.8 ± 6.9	1.2
Household income	(US$ year^{-1})	835 ± 1170	1283 ± 1497	633 ± 703	1266 ± 1120	961 ± 895	868 ± 855	334
Cassava income	(US$ year^{-1})	54 ± 46	24 ± 25	27 ± 23	59 ± 22	313 ± 527	13 ± 25	75
Farm management								
Cassava acreage	(ha)	0.7 ± 0.7	0.3 ± 0.2	0.3 ± 0.2	0.6 ± 0.6	0.9 ± 0.8	0.6 ± 0.6	0.2
Soil fertility score[2]	(-)	2.2 ± 0.4	2.2 ± 0.5	2.2 ± 0.4	2.3 ± 0.3	2.0 ± 0.3	2.4 ± 0.3	0.1
Cassava management								
Improved genotypes[3]	(% Cassava acreage)	44 ± 28	43 ± 31	0 ± 0	46 ± 27	5 ± 12	80 ± 18	7
Sole cropping	(% Cassava acreage)	38 ± 18	51 ± 33	57 ± 32	70 ± 33	70 ± 34	70 ± 32	10
Harvested < 1 year	(% Farms)	33	42	25	61	33	35	-
First weed operation	(Weeks after planting)	3.6 ± 1.4	4.1 ± 1.4	4.0 ± 0.6	3.5 ± 0.6	5.5 ± 2.7	2.9 ± 0.7	0.5
# weed operations	(-)	5.9 ± 1.7	5.2 ± 1.1	3.9 ± 1.0	4.3 ± 0.9	3.3 ± 1.0	4.5 ± 1.1	0.4
Last weed operation	(Months after planting)	8.5 ± 1.1	7.9 ± 1.4	7.5 ± 1.5	7.5 ± 1.9	10.1	7.7 ± 1.7	0.6
Hired labour	(Man day year^{-1})	19 ± 37	37 ± 62	6 ± 15	53 ± 103	11 ± 29	129 ± 206	31

[1] Labour availability expressed as adult equivalent per year is based on family labour + hired labour.

[2] Farmers scored the soil fertility status of each field from poor (1) to good (3). Using individual field size, a weighted soil fertility score for the farm was calculated.

[3] Mainly Nase 3 and SS4.

Table 3: Comparison of farmer estimates of cassava yield under current farmer management (regime i) and selected details on socio-economic settings and farm and cassava management for the first quartile, second + third quartile and fourth quartile yields in Kenya and Uganda

		Kenya				Uganda			
		1st quartile	2nd + 3rd quartile	4th quartile	*P*	1st quartile	2nd + 3rd quartile	4th quartile	*P*
n		11	31	17		11	27	11	
Cassava yield	(t ha^{-1})	3.8 ± 0.8	6.4 ± 0.8	9.7 ± 1.5	*< 0.001*	6.3 ± 1.7	10.2 ± 1.3	16.0 ± 1.9	*< 0.001*
Socio-economic									
Arable land	(ha)	1.0 ± 0.5	1.7 ± 1.9	3.2 ± 2.9	*< 0.001*	1.3 ± 0.6	3.5 ± 3.3	2.9 ± 2.0	*< 0.05*
Labour availability[1]	(Adult equivalent year^{-1})	2.2 ± 1.3	4.0 ± 1.5	6.6 ± 2.7	*< 0.001*	4.7 ± 4.9	5.5 ± 3.8	9.6 ± 8.5	*ns*
Household income	(US$ year^{-1})	267 ± 187	907 ± 1108	1289 ± 1517	*< 0.001*	389 ± 146	1151 ± 1074	1226 ± 956	*< 0.1*
Cassava income	(US$ year^{-1})	21 ± 23	34 ± 38	50 ± 33	*< 0.05*	9 ± 14	128 ± 252	105 ± 213	*ns*
Farm management									
Cassava acreage	(ha)	0.3 ± 0.2	0.4 ± 0.4	0.7 ± 0.7	*< 0.01*	0.3 ± 0.2	0.7 ± 0.6	1.0 ± 1.0	*< 0.1*
Soil fertility score[2]	(-)	1.9 ± 0.3	2.2 ± 0.4	2.4 ± 0.3	*< 0.01*	2.1 ± 0.3	2.3 ± 0.4	2.4 ± 0.3	*ns*
Cassava management									
Improved genotypes[3]	(% Cassava acreage)	12 ± 23	25 ± 29	49 ± 32	*< 0.01*	51 ± 31	43 ± 39	53 ± 38	*ns*
Sole cropping	(% Cassava acreage)	52 ± 27	49 ± 32	46 ± 25	*ns*	60 ± 36	71 ± 35	73 ± 32	*ns*
Harvest < 1 year	(% Farms)	82	37	0	*< 0.001*	55	31	24	*ns*
First weed operation	(Weeks after planting)	3.7 ± 1.0	3.7 ± 1.0	4.3 ± 1.4	*ns*	4.4 ± 3.2	3.8 ± 1.5	3.5 ± 1.0	*ns*
# weed operations	(-)	4.3 ± 1.0	4.6 ± 1.3	6.2 ± 1.7	*< 0.01*	3.5 ± 1.1	4.0 ± 1.0	4.4 ± 1.2	*ns*
Last weed operation	Months after planting)	8.3 ± 1.4	7.8 ± 1.5	8.1 ± 1.3	*ns*	7.0 ± 2.0	8.6 ± 2.8	9.3 ± 2.2	*< 0.1*
Hired labour	(Man days year^{-1})	14 ± 31	13 ± 26	37 ± 67	*ns*	20 ± 46	54 ± 105	168 ± 254	*< 0.05*

[1] Labour availability expressed as adult equivalent per year is based on family labour + hired labour.

[2] Farmers scored the soil fertility status of each field from poor (1) to good (3). Using individual field size, a weighted soil fertility score for the farm was calculated.

arable land, large acreages of cassava and generally more fertile soils. Yields were positively correlated with these variables ($P<0.05$), but most strongly with labour availability ($P<0.001$; Figure 3a). Household income was positively correlated with availability of labour and arable land ($P<0.01$) in both countries, and with cassava acreage ($P<0.001$) in Uganda. Kenyan farms with high yields more frequently used improved cassava genotypes, never harvested their cassava fields before 12 MAP, and weeded their cassava fields 2.5 times more than farms with low yields. Ugandan farms with high yields hired more labour for cassava activities and weeded their cassava fields one extra time and for 2 months longer than farms with low yields. Household income was positively correlated with hired labour on cassava in both countries ($P<0.01$) and with the use of improved genotypes in Kenya ($P<0.05$). In Kenya, the number of weed operations was positively associated with higher cassava yields up to 6 weedings per crop cycle (Figure 3b). In both countries, late first weeding (> 4 weeks after planting) was associated with small cassava yields as estimated by farmers (Figure 3c). The use of improved genotypes that were available to farmers at the time of the survey (primarily Nase 3 and SS4) was not correlated with yields in Uganda, and only slightly ($R^2 = 0.1$; $P<0.05$) correlated with yields in Kenya (Figure 3d).

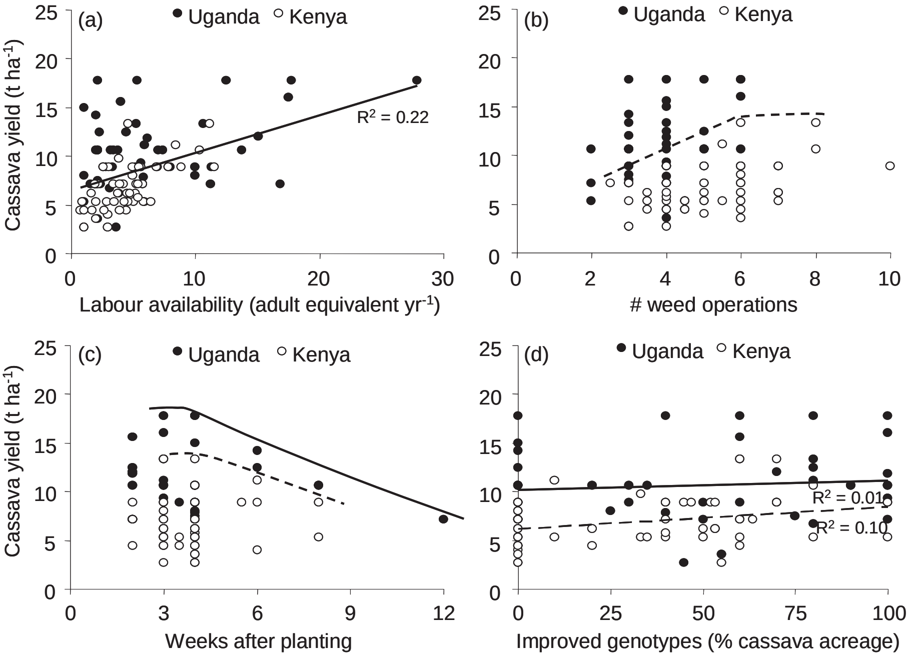


Figure 3: Relationship between cassava yield under management regime i (farmer practice) and (a) labour availability per household; (b) number of weed operations during the growth cycle; (c) timing of first weed operation and; (d) adoption of improved genotypes (primarily Nase 3 and SS4); n = 108.

Table 4: Selected characteristics of the 2004 and 2005 cassava trials at Management regime iii in Kenya (K) and Uganda (U) by site and year

			Soil fertility[2]					Soil texture		Rainfall[2]			Management[2]		Pests & Diseases[2]		
		Yield (t ha^{-1})	pH -	SOC (g kg^{-1})	P (mg kg^{-1})	K (cmol$_{(+)}$ kg^{-1})	∑cat	Sand (%)	Silt (%)	RFtot (mm)	RF0_6 (mm)	#RFd (-)	WM (-)	DH (-)	CBB (-)	CGM (-)	CAD (-)
2004																	
Kwang'amor	(K)	11.6	6.0	6.9	4.5	0.33	1.4	76	8	1447	902	127	3.6	339	116	51	26
Mungatsi	(K)	14.0	5.5	11.4	5.8	0.56	3.0	54	18	1781	1054	144	4.4	338	75	36	2
Nambale	(K)	9.4	5.4	10.6	3.8	0.37	2.5	59	14	1830	1076	146	3.1	345	146	55	43
Ugunja	(K)	6.4	5.7	8.7	3.0	0.40	1.9	50	21	1316	675	115	3.4	342	75	21	12
Minani	(U)	19.1	6.2	10.0	5.6	0.78	9.0	67	7	1771	692	93	3.5	398	11	15	0
Kisiro	(U)	15.7	6.5	8.0	12.3	0.46	4.0	76	8	1478	966	107	3.2	384	10	15	0
KARI	(K)	12.4	5.2	14.7	3.1	0.42	7.6	42	21	2200	1001	213	5.0	445	157	10	12
NaCRRI	(U)	17.0	6.2	20.5	7.1	1.32	17.8	54	11	1065	532	154	5.0	375	92	91	1
Average		*12.2*	*5.8*	*10.7*	*5.1*	*0.53*	*5.0*	*60*	*14*	*1644*	*878*	*137*	*3.8*	*369*	*89*	*34*	*14*
2005																	
Kwang'amor	(K)	9.7	5.8	7.2	8.5	0.33	2.6	72	11	2187	1126	164	2.9	390	117	136	3
Mungatsi	(K)	14.7	5.4	9.0	5.3	0.33	1.1	55	19	2377	1306	165	3.6	398	142	129	25
Nambale	(K)	18.7	5.3	8.7	3.4	0.19	1.4	57	15	2460	1107	144	3.2	397	129	149	2
Ugunja	(K)	14.4	5.7	7.8	2.7	0.22	1.5	45	23	1677	801	167	3.6	390	125	46	1
Minani	(U)	14.5	6.1	9.4	2.5	0.55	5.5	67	9	1292	464	90	3.5	370	51	6	0
Kisiro	(U)	14.8	6.3	8.5	4.6	0.32	5.2	74	8	1270	490	88	3.4	370	53	38	0
KARI	(K)	13.0	5.1	16.7	3.1	0.43	8.9	41	20	1853	824	87	5.0	389	172	34	12
NaCRRI	(U)	25.7	6.4	18.9	5.7	0.97	12.4	51	11	1152	538	142	5.0	398	120	42	0
Average		*15.0*	*5.7*	*10.2*	*4.3*	*0.38*	*4.2*	*57*	*15*	*1825*	*850*	*131*	*3.7*	*387*	*114*	*74*	*6*
SED sites		2.1	0.1	0.8	1.1	0.11	0.8	3.0	1.5	11	14	2	0.4	3	13	14	7
SED year		0.9	0.1	0.3	0.5	0.05	0.3	1.3	0.6	5	6	1	0.2	1	6	6	3

[1] Improved crop establishment and improved genotypes (MM96/5280 in Kenya and TMS I92/0067 in Uganda.

[2] SOC = soil organic carbon; P = available P; K = Exchangeable K; ∑cat = sum of exchangeable K + Ca + Mg; RFtot = Total rainfall; RF0_6 = rainfall in first six months after planting; #RFd = number of rain days during growth cycle; WM = Weed management, ranges from very poor (1) to very good (5); ; DH = number of days from planting to harvesting; CBB = Cassava Bacterial Blight; CGM = Cassava Green Mites; CAD = Cassava Antracnose Disease.

3.3 Management regime iii: (a)biotic and management factors and cassava yields

Abiotic and biotic stresses and management in the 2004 and 2005 trials varied strongly between sites and years (Table 4). Cumulative rainfall ranged from 1065 to 2460 mm between sites (P<0.001) and from 1644 to 1825 mm between years (P<0.001). On-farm soil fertility was generally poor, but SOC and exchangeable cations were better at the on-station sites (P<0.001). Average SOC ranged from 6.9 to 20.5 g kg^{-1} (P<0.001), average available P from 2.5 to 12.3 mg kg^{-1} (P<0.001) and exchangeable K from 0.19 to 1.32 cmol$_{(+)}$ kg^{-1} (P<0.001) between sites and years. The soils in the Kenyan on-farm trials had less exchangeable K and cations and lower pH than the soils in the Ugandan on-farm trials in both years (P<0.05). Soil texture ranged from sandy loam to clay loam. Average weed management score per site ranged from 2.9 to 5.0 (P<0.001), while days to harvest ranged from 338 to 445 (P<0.001). Bacterial blight and green mite pressure was higher in Kenya than in Uganda, and higher in 2005 than in 2004 (P<0.001). These differences were reflected in the average yields under management regime iii (improved crop establishment and improved genotypes) that ranged from 6.4 to 25.7 t ha^{-1} between sites and from 12.2 to 15.0 between years (Table 4; P<0.001).

3.3.1 Factors explaining yield variability

Of the 58% yield variability explained by the linear model for the entire data set (RMSE = 4.0 t ha^{-1}), approximately one-third of the explained variability was associated with rainfall between the 9th and 12th month of the growth cycle, while variables pertaining to soil fertility (exchangeable Mg, available P and pH), weed management and soil texture variables explained the remaining variability in approximately equal parts (Table 5). Of the 38% yield variability explained by the Kenyan model (RMSE = 5.0 t ha^{-1}), about half was associated with total rainfall, and the rest with weed management and soil pH, while of the 82% yield variability explained by the Ugandan model (RMSE = 2.5 t ha^{-1}), most was associated with crop management variables, notably with weed management, and only a small percentage with soil fertility variables. Exchangeable Mg was strongly correlated with SOC (R^2 = 0.77; P<0.001), while rainfall between the 9th and 12th month of the growth cycle was significantly correlated to total rainfall during the growth cycle (R^2 = 0.28; P<0.001).

3.3.2 Factors contributing to cassava yield gaps

Clear boundary lines were identified in the scatter plots relating soil fertility, soil texture, pest and disease, weed management and selected rainfall variables to cassava

Table 5: Linear regression models of cassava yield under management regime iii1 in the 2004 and 2005 trials for the entire data set (a) and Ugandan (b) and Kenyan (c) data sets separately

Variable	Regression coefficient	Square of semi partial correlation coefficient	*P*	% variance explained
(a) Entire data set[2] (R^2 = 0.58)				
Rainfall 9-12 MAP	0.57	0.20	*<0.001*	30.2
Weed management	0.52	0.15	*<0.001*	23.6
Silt	-0.43	0.10	*<0.001*	14.9
Exchangeable Mg	-0.38	0.07	*<0.001*	11.2
Available P	0.36	0.07	*<0.001*	10.1
Clay	0.30	0.04	*<0.003*	6.2
pH	0.24	0.03	*<0.017*	3.8
Constant	-2.66	-	*<0.745*	-
(b) Kenya data set[3] (R^2 = 0.38)				
Total rainfall	2.44	0.15	*<0.001*	48.4
Weed management	0.13	0.10	*<0.003*	32.2
pH	2.48	0.05	*<0.034*	16.1
Days to harvest	-0.00	0.01	*<0.349*	3.2
Constant	-20.1	-	*<0.001*	-
(c) Uganda data set[4] (R^2 = 0.82)				
Weed management	1.25	0.22	*<0.001*	51.2
Days to harvest	0.33	0.19	*<0.001*	44.0
Exchangeable Ca	-1.20	0.02	*<0.086*	4.7
Rainfall 9-12 MAP	0.04	0.00	*<0.844*	0.1
Constant	-111.3	-	*<0.001*	-

[1] Improved crop establishment and improved genotypes (MM96/5280 in Kenya and TMSI92/0067 in Uganda)

[2] $y = -2.66 + 0.57 \times RF_{9-12} + 0.52 \times WM - 0.43 \times Silt - 0.38 \times Exch.Mg + 0.36 \times P + 0.30 \times Clay + 0.24 \times pH$

[3] $y = -20.1 + 2.44 \times RF_{tot} + 0.13 \times WM + 2.48 \times pH - 0.001 \times Days\_harv$

[4] $y = -111.3 + 1.25 \times WM + 0.33 \times Days\_harv - 1.20 \times Exch.Ca + 0.04 \times RF_{9-12}$

yield under management regime iii (improved crop establishment and improved genotypes) in the 2004 and 2005 trials (e.g. Figures 2a-c; 4a and b). The observed attainable yield (y_{max}) at management regime iii was 27.3 t ha^{-1}. No boundary lines could be identified for amongst others total rainfall, rainfall from 0 to 3 MAP, and days to harvest. Both genotypes responded similarly to all studied variables. Following von Liebig's law of the minimum, predictive multivariate models for cassava yield were developed using the identified boundary lines. This resulted in moderately good estimations for the yields measured in 2004 and 2005 in Uganda (R^2 = 0.42 and 0.47; RSME = 4.5 and 5.2 t ha^{-1}) and in 2005 in Kenya (R^2 = 0.38; RMSE = 5.5 t ha^{-1}), but in poor estimations in 2004 in Kenya (R^2 = 0.06; RMSE = 8.2 t ha^{-1}). In the scatter plots of yield versus weed management and yield versus rainfall during the first six months after planting, the 2004 Kenya data showed a distinctly different pattern from the rest of the data (Figures 4c and d). Developing a separate predictive model for the 2004 Kenya data, whereby the general boundary lines for weed management and

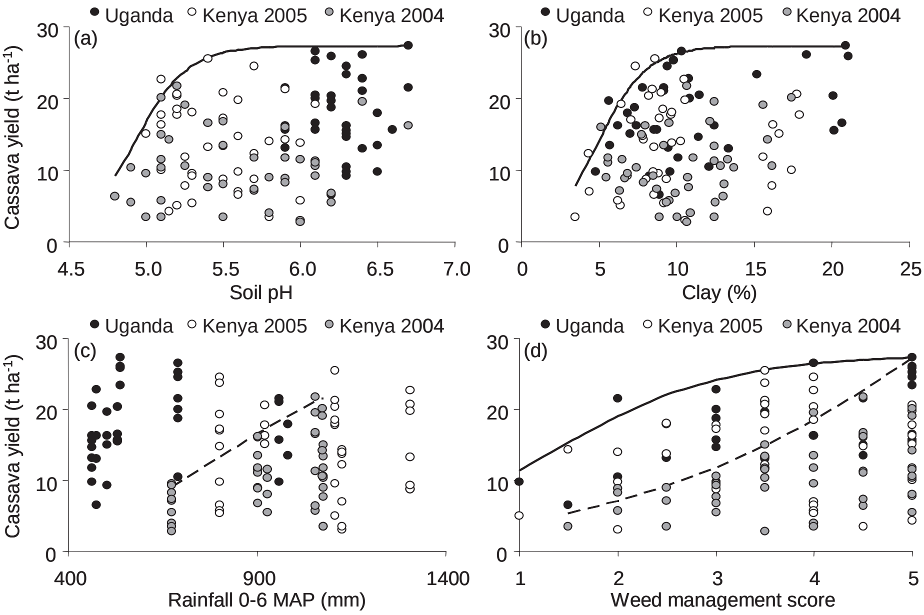


Figure 4: Boundary lines for cassava yield under management regime iii (improved crop establishment and genotypes) in the 2004 and 2005 trials for (a) soil pH; (b) clay content; (c) rainfall from 0 to 6 MAP and; (d) weed management. Black and dotted lines represent boundary lines for the overall and 2004 Kenya data sets, respectively. Weed management was scored from very poor (1) to very good (5).

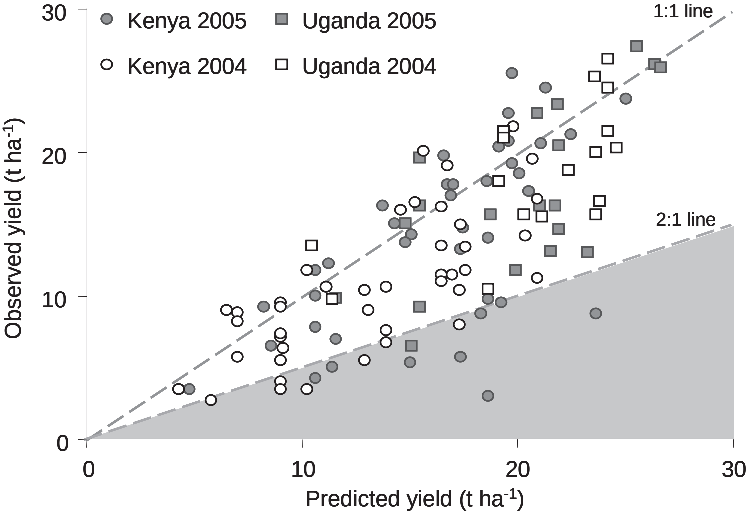
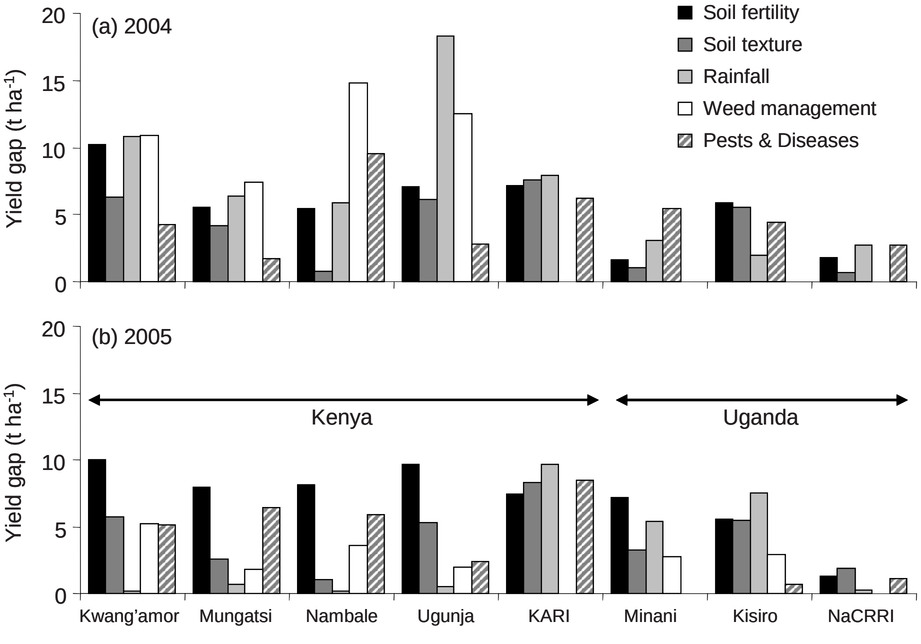


Figure 5: Predicted versus observed cassava yields under management regime iii (improved crop establishment and genotypes) for the 2004 and 2005 trials. Predictions are made using the multivariate boundary line model. Dashed lines represent the 1:1 and 2:1 lines.

rainfall during the first six months after planting were substituted with the boundary lines for the 2004 Kenya data, resulted in good yield estimations for this data set with an R^2 of 0.56 and RMSE of 3.8 t ha^{-1} (Figure 5).

The factors responsible for the identified yield gaps varied strongly between years and sites (Figure 6 and Table 6). Overall, poor soil fertility was the most important constraint and limited yields by an average difference of 6.7 t ha^{-1} with respect to the attainable yield. However, soil fertility limited production more strongly in Kenya (7.9 t ha^{-1} difference) than in Uganda (4.3 t ha^{-1} difference). Available P, total N and SOC limited yields in approximately one third of all fields. Yield limitations due to soil pH, total N, K and the sum of cations were either restricted to, or stronger, in Kenya than in Uganda. Rainfall limited yields by an average difference of 5.4 t ha^{-1} with the attainable yield. Observed yield limitations due to rainfall were associated with too



(c)	Soil fertility	Soil texture	Rainfall	Weed Management	Pests & Diseases
Overall	6.7 ± 4.9	4.3 ± 4.7	5.4 ± 5.5	5.0 ± 6.2	3.8 ±3.7
Kenya	7.9 ± 4.9	4.7 ± 5.0	6.1 ± 6.2	6.0 ± 6.4	5.3 ± 3.5
Uganda	4.3 ± 4.2	3.2 ± 4.0	4.2 ± 3.1	3.0 ± 5.4	0.6 ± 1.3

Figure 6: Identified yield gaps for cassava planted under management regime iii (improved crop establishment and genotypes) in the 2004 and 2005 trials due to soil fertility, soil texture, rainfall, weed management and pest & disease constraints in (a) 2004; (b) 2005 and; (c) average yield gap per constraint per country. Yield gaps are based on the multivariate boundary line model.

Table 6: Percentage of fields in the 2004 and 2005 trials at Management regime iii[1] where cassava production was affected[2] by abiotic and/or biotic stresses and/or weed management in Kenya (K) and Uganda (U) by year and site

			Soil fertility[3]						Soil texture[3]			Rainfall[3]		Mgm[3]	Pests & Diseases[3]		
		n	pH	SOC	N	P	K	Σcat	Sand	Clay	Silt	RF0-6	#RFd	WM	CBB	CGM	CAD
2004																	
Kwang'amor	(K)	9	0	78	67	22	11	67	0	67	0	100	0	100	11	11	44
Mungatsi	(K)	7	43	0	0	0	0	29	14	14	29	100	0	100	0	0	29
Nambale	(K)	9	33	22	0	22	11	33	0	11	0	100	0	100	67	22	100
Ugunja	(K)	9	22	33	11	67	0	44	33	0	44	100	0	100	11	0	33
Minani	(U)	8	0	13	0	0	0	0	0	13	0	0	100	38	0	0	0
Kisiro	(U)	6	0	50	50	0	0	0	0	83	0	0	0	50	0	0	0
KARI	(K)	8	88	0	0	75	0	0	88	0	63	100	0	0	88	0	88
NaCRRI	(U)	4	0	0	0	25	0	0	0	0	0	0	0	0	0	50	25
2005																	
Kwang'amor	(K)	9	0	57	86	14	14	29	0	57	0	0	0	57	14	71	14
Mungatsi	(K)	8	25	25	63	13	25	63	13	13	25	0	0	38	38	75	88
Nambale	(K)	7	44	22	67	33	67	67	0	0	0	0	0	44	33	100	11
Ugunja	(K)	10	0	50	90	70	10	50	70	0	40	0	0	20	10	10	10
Minani	(U)	8	0	25	13	50	25	13	0	25	0	0	100	50	0	0	0
Kisiro	(U)	8	0	63	0	38	13	0	0	63	0	0	100	38	0	25	0
KARI	(K)	8	100	0	0	63	0	0	88	0	50	0	50	0	88	0	63
NaCRRI	(U)	4	0	0	0	25	0	0	25	0	0	0	0	0	0	0	0

[1] Improved crop establishment and improved genotypes (MM96/5280 in Kenya and TMSI92/0067 in Uganda)

[2] $y\_max_{ij} < 90\%\ y_{max}$

[3] SOC = soil organic carbon; N = total N; P = available P; K = Exchangeable K; ∑cat = sum of exchangeable K + Ca + Mg; RF0_6 = rainfall in first six months after; #RFd = number of rain days during growth cycle; WM = Weed management, ranges from very poor (1) to very good (5); CBB = Cassava Bacterial Blight; CGM = Cassava Green Mites; CAD = Cassava Antracnose Disease.

little rainfall during the first six months after planting in 2004 in Kenya and with a too low number of rain days in Uganda during the crop cycle, whereby the number of rain days is positively correlated to cumulative rainfall (mm) during the first six months after planting ($P<0.001$). Weed management caused an average yield gap of 5.0 t ha^{-1} and restricted production most in farmer fields in Kenya in 2004 (yield gap of 11.6 t ha^{-1}), whereas soil texture caused an average yield gap of 4.3 t ha^{-1}. Observed limitations due to soil texture were associated with high silt contents (> 20%) and/or low clay content (<19%). Although 62% of the Kenyan fields in 2005 were affected by green mites, the absolute contribution to the yield gap (3.8 t ha^{-1}) from pests and diseases was the least important of all constraints recorded in this study.

In approximately 14% of the fields, yields predicted by the multivariate model were at least 100% higher than observed yields (Figure 5 – grey triangle). All but one of these fields were located in Kenya and over 25% were located in Ugunja. In all these fields, yields were limited by a multitude of constraints (3-8), but in none of these fields could the observed yield be accurately predicted by the single most limiting constraint.

4. Discussion

4.1 Constraints to cassava production in eastern Africa

Cassava production in most fields in our study was affected by multiple abiotic and biotic constraints that differed strongly between fields, sites and years. Their impact was aggravated by sub-optimal management practices (e.g. Table 3-5; Figures 4 and 6). Consequently, current farmer yields are less than one-fifth of the maximum yields recorded in the same region (Figure 1). Although the full management package (regime iv) more than doubled average yields, maximum yields in our trials were still ca. 14 to 25 t ha^{-1} lower than the maximum recorded yields in Kenya and Uganda (Figure 1). To achieve maximum yields, cassava requires high solar radiation, high mean day temperature, sufficient supply of all required nutrients, good rainfall distribution during crop establishment and possibly a dry period before harvesting (El-Sharkawy, 2004). Evidently, agro-ecological conditions in 2004 and 2005 were not optimal for cassava production.

Within the agro-ecological conditions prevalent during our trials, the farm survey, linear regressions and boundary line analyses all identified poor weed management as an important constraint to cassava production (Tables 3, 5 and 6 and Figure 6). Other studies (Melifonwu, 1994; Doll et al., 1982, quoted in Leihner, 2002) underline the importance of weed management for good cassava production. Uncontrolled weed growth during the first three MAP may reduce yields by 50-65%. Although three weed operations per growing cycle are recommended, farmers in our study weeded their fields on average 3.3 to 5.9 times (Table 2). Nonetheless, yield increases were observed in Kenya when the total number of weed operations increased to 6 per crop cycle (Figure 3b). Interestingly, only 12% of the farmers considered weeds as an important production constraint (Fermont, unpublished).

Poor soil fertility was identified in the boundary line analysis as the most important constraint to cassava production – despite the general perception that cassava is tolerant to poor soil fertility (Howeler, 2002) – and affected the majority of farmers' fields in our study (Figure 6 and Table 6). The importance of poor soil fertility as a major yield limiting factor is well illustrated by the strong response to fertilization, which over-ruled yield differences between sites (Figure 1 and Table 1). This is further reinforced by the fact that 62% of the farmers perceived poor soil fertility as a production constraint, 22% perceived it to be the most important constraint (Fermont, unpublished), and the observation that the smallest yields were found on farms with soils that were perceived as the poorest by farmers (Table 3). Soil fertility constraints in western Kenya were generally more severe than in Uganda (Table 6 and Figure 6) due to lower amounts of cations and pH (Table 4); which is exacerbated by its higher land pressure (Fermont et al., 2008 – Chapter 3).

Low rainfall, either during the first 6 months after planting or during the total crop cycle, was identified as the most important factor explaining yield variability in Kenya in the linear regression analysis, and as the overall second most important constraint in the boundary line analysis (Figure 6 and Table 6). These findings are rather surprising as cassava is considered to be a drought tolerant crop that can produce acceptable yields with as little rainfall as 700 mm year^{-1}, while being able to endure several months of drought (De Tafur et al., 1997b; El-Sharkawy, 2006). In our trials, total rainfall during the growth cycle was 1065 mm or more (Table 4) and drought periods did not exceed 40 consecutive days. The identified rainfall variables may be proxies for insufficient soil water availability during the early growth stages of cassava. Water stress during the first six months after planting is known to reduce storage root initiation and negatively affect root yields (Connor et al., 1981). In medium-high rainfall areas, early water stress may be caused by poor rainfall distribution in combination with sealing and crusting of topsoils in case of high intensity rain storms on bare soils (Hoogmoed and Stroosnijder, 1984). The latter was particularly visible at sites with high silt contents.

Although 68% of the farmers considered pests and diseases to be a production constraint on their farms (Fermont, unpublished) and in some years and sites a single pest or disease could affect up to 100% of the fields (Table 6), green mites, bacterial blight and anthracnose were not identified as important constraints for cassava production (Table 5 and 6 and Figure 6). Due to the adoption of resistant genotypes and farmer selection of tolerant landraces, the cassava mosaic disease epidemic has been largely brought under control in East Africa (Legg et al., 2006). Biological control programmes have successfully reduced the impact of green mites and especially mealy bugs on cassava production, while tolerance to bacterial blight is a key component of all breeding programmes in East Africa. As was also found for banana production in East Africa, farmers may overemphasize the importance of pests and diseases as production constraints because damage by pests and diseases can be more easily observed than most abiotic stresses (van Asten et al., 2009).

4.2 Interactions between production constraints

In the analysis of our trials, we observed interactions between rainfall and weed management for the 2004 Kenya data (Figures 4c and d). Poor rainfall during crop establishment resulted in slower plant development and consequently more labour was required for weeding. This was most obvious in sites with high silt content, where soil crusting hindered infiltration of rainwater. Interactions between factors influencing cassava yields were also observed by Schultness et al. (2004) for pest pressure and crop management and by De Tafur et al. (1997a) for water stress and fertilization during early growth stages.

In the farm survey analysis, we observed interactions between household resource endowment, crop management and soil fertility (Table 3), with less endowed farmers having lower cassava yields, less access to labour (e.g. for weeding) and generally poorer soils than better endowed farmers. Similar links between poverty and low crop yields were found by Zingore et al. (2006) and Tittonell et al. (2007b) for maize and groundnuts, while Tittonell et al. (2007c) showed that soil heterogeneity not only determined water and nutrient limitations, but also influenced farmers' management decisions. It will be more difficult for less endowed than for more endowed households to increase cassava yields because: (i) less endowed households face multiple production constraints and lack the social and economic capital to intensify crop management, while (ii) in a multi-stress environment removing one stress will increase production less than in an environment facing only one or two stresses.

Whereas linear regression models allowed us to identify overall trends for the whole study taking into account variable interactions, the boundary line approach identifies limiting factors for each individual field while ignoring interactions. Both approaches ascribed similar importance to weed management, rainfall and pest and diseases, but indicated different degrees of importance for soil fertility as a yield-determining factor (Table 5 and Figure 6). The importance given to variables in the linear regression or boundary line models depended on whether or not the variables showed significant linear correlations with yield or clear boundary lines. Weed management displayed both a linear correlation with yield and a clear boundary line, while most soil variables only displayed a clear boundary line (Figures 2 and 4). Soil fertility data from farm surveys or farmer trials will generally show a wide scatter when plotted against yield and often exhibit a plateau above which no increase in yield is observed (Shatar and McBratney, 2004). In such cases, the explaining power of a boundary line approach, which identifies the maximum yield at each given level of an independent variable, may be better than the explanatory power of a linear regression analysis. On the other hand, ignoring interactions between variables, as is done in the boundary line approach, is an oversimplification that may result in over prediction of yields (Figure 5 – grey triangle). Both analysis tools performed poorly with the Kenya data set. This could be due to strong interactions between variables and/or omission of major variables affecting yields in Kenya. The performance of the boundary line model was improved by identifying separate boundary lines for the Kenya 2004 data set. This shows that in case variables do not interact strongly, data from various years and sites may be analysed together, but in case of interactions site/year specific boundary lines need to be identified to account for the interactions.

4.3 Closing the cassava yield gap through improved production practices

The identified yield gaps for cassava may be (partially) closed through improved production practices as shows from the doubling of cassava yields when the full technology package (regime iv) was used (Table 1). Nonetheless, even without introducing new genotypes and fertilizer there is scope for yield improvement, as is clear from the large variation in cassava yields under current farmer practice (Table 3). Underlying this variation are differences in financial and human capital between farmers translating into differences in labour availability, particularly for weed management. During the survey, many farmers indicated to first weed cereal and legume fields and weed cassava fields later as cassava is perceived to be more tolerant of weed pressure. The promotion of options to improve early weed control thus seems key to reducing weed constraints in cassava production. Average cassava plant densities on farmers' fields in the region are low (3200 to 6400 plants ha^{-1}; Nweke et al., 1998; 1999). Increasing plant density to the recommended 10,000 plants ha^{-1} on fertile soils and up to 20.000 plants ha^{-1} on poorer soils will result in earlier canopy closure and subsequently less weed pressure. This effect can be reinforced through the use of vigorous early branching genotypes instead of erect genotypes (Leihner, 1980). Cassava breeders will need to find a balance between yield potential and weed control as early branching genotypes generally have less yield potential than erect genotypes. For farmers with sufficient financial means, the use of pre-emergence herbicides is perhaps an option to reduce labour requirements for weed management (Melifonwu, 1994; Leihner, 2002; Nguyen et al., 2008).

To reduce the impact of soil fertility constraints in cassava production, fertilizer is perhaps the easiest, but probably also the most expensive technology. We observed strong responses to NPK fertilizer (Table 1) and cost-benefit analysis indicated that fertilizer use was profitable in the majority of fields (Fermont, unpublished). In Asia, fertilizer use is a key component of many technology packages for cassava production and has been widely adopted by farmers (Howeler, 2008). An added benefit of fertilizer use is a reduction in labour requirements for weed management due to faster canopy closure. Medium/low technologies to (partially) overcome soil fertility constraints could include adaptations of best-best options developed for African cereal systems (Odendo et al., 2006; Okalebo et al., 2006; Ojiem et al., 2007), such as (i) the combined use of inorganic and organic fertilizer; (ii) targeted micro-dosages of fertilizer; and (iii) intercropping and/or crop rotation options with dual-purpose legumes, especially in N-limited areas. Decreasing nutrient removal from cassava fields through the non-removal of stems and the return of ashes from cassava stems when used for fuel may also help to particularly reduce the impact of potassium deficiency (Fermont et al., 2008 – Chapter 3).

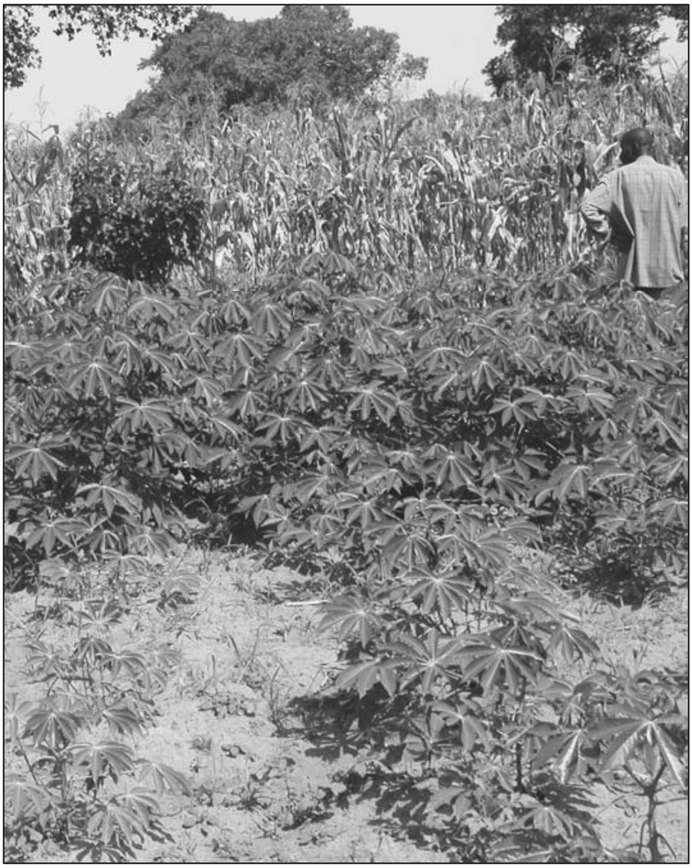
Farmers may be able to reduce the impact of drought through avoidance strategies, e.g. early planting at the onset of the rains, and improving rainfall infiltration and reducing evaporation by ensuring good soil coverage through improved weed control, mulches or conservation tillage (Stroosnijder, 2008). However, most of the above-mentioned practices require additional labour at the onset of the rainy season, a period of peak labour demand. A more practical approach perhaps is the identification and/or breeding of genotypes that are tolerant to early drought stress and subsequent introduction of these genotypes. Although cassava mosaic disease, green mites, bacterial blight and anthracnose were of limited importance in this study, new disease threats that include co-infection of mosaic geminiviruses with DNA satellites, which breaks down the known resistance to mosaic virus, and the brown streak virus (Alicai et al., 2007; Ndunguru et al., 2008) can potentially reduce cassava production substantially and thereby over-rule all other constraints. Hence, despite the findings of this study, development and dissemination of genotypes resistant to new pest and disease threats remains of paramount importance.

5. Conclusions

The comparative analysis of multi-locational on-farm and on-station experiments and farmer surveys clearly demonstrate that there is substantial ‘room to manoeuvre’ to improve cassava production in East Africa, as current cassava yields on smallholder farms are far below attainable yields in the region. The observed yield gaps are caused by a multitude of production constraints. Abiotic constraints and related crop management practices are far more important than perceived by farmers and scientists to date. Efforts to improve productivity should be geared towards combining approaches to identify and overcome the most important constraints simultaneously. This would represent a strong reappraisal of the current agenda of existing research programmes on cassava yield improvement that have tended to focus on single constraints, and particularly on specific pests and diseases (e.g. control of cassava mosaic disease, green mites and mealy bugs). This will require the development and on-farm participatory evaluation of a range of technologies geared towards integrated crop management, resting on four main pillars: (i) improved germplasm; (ii) soil fertility management; (iii) early weed control; and (iv) water capture and use efficiency. Dissemination of improved genotypes will form the back-bone of any new technology package, because the introduction of new genotypes presents the ideal entry point for the promotion of alternative crop management options.

Chapter 5

Towards understanding factors that govern fertilizer response in cassava; lessons from East Africa



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Abstract

Information on fertilizer response in cassava in Africa is scarce. We conducted a series of on-farm and on-station trials in two consecutive years to quantify yield responses of cassava to mineral fertilizer in Kenya and Uganda and to evaluate factors governing the responses. Average unfertilized yields ranged from 4.2 to 25.7 t ha^{-1} between sites and years. Mineral fertilizer use increased yields significantly, but response to fertilizer was highly variable (-0.2 to 15.3 t ha^{-1}). Average yield response per kg applied nutrient was 37, 168 and 45 and 106, 482 and 128 kg fresh yield per kg of applied N, P and K, respectively in 2004 and 2005. Fertilizer response was governed by soil fertility, rainfall and weed management, but was not influenced by genotype, pest and disease pressure and harvest age. Relative N and K yields were positively correlated to SOC and exchangeable K, while response to fertilizer decreased on more fertile soils. Still, fertilizer response varied widely on low fertility soils (e.g. on soils with < 10 g kg^{-1} SOC, responses ranged from -8.6 to 24.4 t ha^{-1}), indicating strong interactions between factors governing fertilizer response. Response to fertilizer was reduced if total rainfall <1500 mm or rainfall from 0 to 3 months after planting <400 mm. Fertilizer application promoted plant growth and resulted in a better soil coverage and reduced weed competition. Yields in fertilized fields were independent of weed management, unless growing conditions were unfavourable.

Keywords: Cost-Benefit analysis, Kenya, Rainfall, Small-holder farms, Soil fertility, Sub-Saharan Africa, Uganda, Variability, Weed management

1. Introduction

In Asia and Latin-America, mineral fertilizer use is a standard agronomic practice for farmers to increase the productivity and profitability of cassava production. In Africa, smallholder farmers use little or no fertilizer at all (an average of 9 kg ha^{-1} $year^{-1}$, compared with 73 and 135 kg ha^{-1} $year^{-1}$ used in Latin-America and Asia, respectively; Kelly, 2006). Fertilizer is rarely used on cassava (Nweke, 1994a), as there appears to be a common belief that cassava does not need fertilizer. This seems to be based on the ability of cassava to yield in areas with such low soil fertility that other crops fail.

Due to increasing population pressure, coupled with a lack of land, farming systems in large parts of Africa are intensifying. Traditional management practices (e.g. fallow, manure use) to maintain soil fertility often are no longer feasible. When farming systems in parts of East Africa intensified to such extent that natural fallowing no longer was an option, farmers expanded the acreage under cassava which is increasingly grown on poor fertility soils, as they consider cassava a crop that restores soil fertility (Fermont et al., 2008 – Chapter 3; Ebanyat et al., submitted). However to maintain productivity in these systems, the use of external inputs seems inevitable in the near future. At the same time, the growing demands for cassava in the food, fodder and industrial (starch, biofuel) markets, also increase the likelihood that farmers will adopt fertilizer to improve cassava productivity in their farms in order to profit from these developments.

The Africa Fertilizer Summit held in Nigeria in 2006 and the Soil health Initiative of the Alliance for a Green Revolution in Africa (AGRA) launched in 2007 show that there is an increasing consensus that mineral fertilizers are essential in Africa to counteract declining soil fertility and improve agricultural productivity. Although cassava produces reasonable yields on infertile soils, there is no doubt that fertilizer can increase cassava yields. Cassava is a heavy potassium feeder, but also requires nitrogen, phosphorus and meso-/micro-nutrients to produce good yields (Nguyen et al, 2002, Howeler, 2002; 2008). Nonetheless, experience with fertilizer use on cassava in Africa is extremely limited and results are elusive. Some (Arene and Oduruke, 1976; Richards, 1979) reported yield increases due to fertilizer use, others (Ogbe et al., 1993; Lema et al., 2004) observed no effect of fertilizer use, while Ofori (1973) even found a negative effect of fertilizer use on a forest soil in Ghana. Carsky and Toukourou (2005) observed an increasing response to fertilizer over time in farmers' fields in Benin. Soils in Africa are highly heterogeneous, which has strong effects on crop response to fertilizer, due to differences in soil type, historical management and resource allocation (Zingore et al., 2007) or soil fertility status (Vanlauwe et al., 2006).

We hypothesize that heterogeneity in soils within farms and between farms and research stations is partly the cause of the reported range in cassava yield responses to fertilizer.

To investigate this hypothesis, a series of on-farm and on-station trials were conducted during two consecutive years across the mid altitude zone of western Kenya and Uganda, where cassava is an important food and cash crop. Average cassava yields were 9.1 and 14.4 t ha^{-1} in 2005 in Kenya and Uganda, respectively (FAO, 2009). Environments in this region are highly heterogeneous, covering a wide range in agro ecological conditions. Our specific objectives were (i) to quantify the response of cassava to mineral N, P and K fertilizers in small-holder farmer conditions and (ii) to evaluate the role of management, abiotic and biotic factors in governing such responses.

2. Materials and Methods

2.1 Selection of study sites

Experiments were conducted in six on-farm and two on-station locations in western Kenya and central / eastern Uganda, which were chosen to represent the variation in environments and cassava-based cropping systems found in the mid-altitude zone of eastern Africa. In western Kenya these included the sub-locations of Kwang'amor (0^{o}29'N, 34^{o}14'E), Mungatsi (0^{o}27'N; 34^{o}18'E), Nambale (0^{o}28'N, 34^{o}14'E) and Ugunja (0^{o}10'N; 34^{o}18'E) in Teso, Busia, Busia and Siaya districts, respectively and the research farm of the Kenyan Agricultural Research Institute (KARI) in Alupe, Busia district (0^{o}30'N, 34^{o}08'E). In Uganda the study sites were located in the parishes of Kisiro (0^{o}67'N; 33^{o}80'E) and Minani (0^{o}80'N; 33^{o}57'E) in Iganga district and on the research farm of the National Crops Resources Research Institute (NaCRRI) (0^{o}32'N, 32^{o}37'E) in Namulonge, Wakiso district. Altitude ranged between 1100 to 1260 masl. Main soils in the region include ferric and orthic Acrisols and orthic and haplic Ferralsols, which have developed from strongly weathered granite or sedimentary parent material (KARI, 2000; Jaetzold and Schmidt, 1982). The climate in all sites is sub-humid with a bimodal rainfall distribution, such that the production of most annual crops takes place twice a year, during the long (March to June) and the short rains (September to November). Cassava is normally planted in the first two months of either the short or long rains and remains in the fields for about a year, thus receiving two peaks of rainfall during its growth cycle.

Table 1 : Overview of cassava fertilizer trials in Kenya and Uganda in 2004 and 2005

Year	Country	Sites	# trials	Plant date	Harvest date	Genotypes	Fertilizer Treatment[1]
2004	Kenya	On-station A: KARI	1	20/4/04	27/07/05	Nase 3,	T0 and
		On-station B: KARI	1	1/07/04	31/08/05	MM96/5280	T1
		On-farm: 4 villages[2]	35	5/4/04	10/03/05	MM96/4884	
	Uganda	On-station: NaCRRI	1	26/03/04	6/04/05	Nase 3,	T0 and
		On-farm: 2 villages[2]	14	15/9/04	12/10/05	TMSI92/0067	T1
						TMSI92/0057	
2005	Kenya	On-station: KARI	1	22/04/05	18/05/06	MM96/5280	T0, T1, T2,
		On-farm: 4 villages[2]	34	5/04/05	4/05/06		T3 and T4
	Uganda	On-station: NaCRRI	1	25/04/05	26/06/05	TMSI92/0067	T0, T1, T2,
		On-farm: 2 villages[2]	16	7/9/05	12/09/05		T3 and T4

[1] T0 = 0-0-0; T1 = 100-22-83; T2 = 0-22-83; T3 = 100-0-83; T4 = 100-22-0 kg ha^{-1} N-P-K

[2] Kenya: Kwang'amor, Mungatsi, Nambale and Ugunja; in Uganda: Minani and Kisiro

2.2 On-farm and on-station trials

Two sets of experiments were conducted to quantify the response of cassava to mineral N, P and K fertilizers and to identify the main factors that govern such responses (Table 1). The first set of experiments, planted in 2004 and harvested in 2005, was set up to study the response of selected genotypes, comprising three cassava genotypes with and without fertilizer. This set is labelled '2004 trials' throughout the paper. The second set of experiments, planted in 2005 and harvested in 2006, focused on the response of cassava to individual applied nutrients and consisted of the best performing genotypes in the 2004 trials with five fertilizer rates. This set is labelled '2005 trials' throughout the paper.

The 2004 trials consisted of a total of 49 on-farm trials and 3 on-station trials in Kenya and Uganda. In the on-station trials a randomized complete block design (RCBD) with four replicates was used, while in the on-farm trials a criss-cross design (Mead, 1988) was used to facilitate farmer evaluation, whereby each row was randomly assigned to a fertilizer rate and each column was planted with one genotype. Between six to ten farmers participated in each site. Each farmer was considered a single block repetition. In Kenya, cassava genotypes MM96/5280, MM95/4884 and TMS 30572 (released officially in Uganda as Nase 3) were planted, while in Uganda TMSI92/0067, TMSI92/0057 and Nase 3 were planted. Nase 3 is the most widely adopted improved genotype in Uganda and Kenya (Legg et al., 2006). The other genotypes were chosen due to good performance in on-farm selection trials. Fertilizer rates were (T0) no fertilizer added; and (T1) 100-22-83 N-P-K (i.e.100-50-100 kg ha^{-1} N-P2O5-K2O). Nitrogen fertilizer was applied in three splits: 18 kg N ha^{-1} at planting as diammonium phosphate and 41 kg N ha^{-1} at 1 and 3 months after planting (MAP) as urea. All P fertilizer was applied in the planting hole as diammonium phosphate, while K fertilizer was divided in two equal splits: 41.5 kg K ha^{-1} at 1 MAP and at 3 MAP as potassium sulphate. Top dressings were broadcast after weeding, before expected rainfall. Since genotype TMSI92/0057 succumbed to cassava brown streak disease, a new viral disease in the area, its results are not included in this paper.

The 2005 trials consisted of a total of 50 on-farm trials and 2 on-station trials in Kenya and Uganda. All trials were conducted in different fields from the 2004 trials. A complete randomized block design was used in all trials. In Kenya cassava genotype MM96/5280 was used, while in Uganda TMSI92/0067 was used. Fertilizer rates were: (T0) no fertilizer added; (T1) 100-22-83 kg ha^{-1} N-P-K; (T2) as T1 but no N, (T3) as T1 but no P, (T4) as T1 but no K. Fertilizer application was similar to the 2004 trials, except in T3 where all N was given as urea and in T2 where P was applied as triple super phosphate. Top dressings were applied, after weeding, in a hole on one side of the plant and covered with soil.

In both sets of trials, each plot was 8 x 7 m with a net harvest area of 5 x 4 m. In the on-farm trials, field selection and land preparation was done by farmers, either by hoe, oxen or tractor, depending on local practices. Experiments were planted by farmers and researchers together. The recommended planting distance of 1 x 1 m was used. Fresh cuttings of 20-25 cm were placed horizontally in a 10-20 cm deep planting hole and covered with soil. Weeding was done in the on-farm trials by farmers, according to their own judgement, while on-station trials were kept weed-free by manual weeding. Crops were harvested between 11.5-13 MAP by both farmers and researchers in the on-farm trials and between 12-15 MAP in the on-station trials by researchers.

2.3 Measurements and chemical analysis

At harvest, all plants in the net harvest area of each plot were counted and uprooted. If less than 80% (e.g. 16 plants) were present, additional representative plants from non-border rows were included to make a total of 16 plants (R. Howeler, pers. comm., 2004). Plants were split into above-ground biomass (stems and leaves), marketable and non-marketable storage roots. Storage roots were considered non-marketable if farmers considered them too small for peeling (i.e. diameter <3 cm). Total fresh weight of each component was taken and used to calculate fresh cassava yield (t ha^{-1}) and fresh aboveground biomass (t ha^{-1}) at the time of harvest. The apparent fresh harvest index (HI) at harvest was calculated, excluding the weight of leaves fallen during the growing period. A sub-sample of approximately 0.2 kg was taken from the top, middle and bottom end of five representative marketable storage roots from each plot, chopped, air-dried and subsequently oven-dried at 70 ^{o}C to constant weight, and dry matter determined. The relative fresh cassava yield in absence of N (RY_N), P (RY_P) or K (RY_K) was calculated in relation to the NPK fertilizer treatment (T1) as

$$RY_x = \frac{Fresh\ yield\ in\ treatment\ without\ x}{Fresh\ yield\ in\ NPK\ treatment} \tag{1}$$

where x stands for N, P or K. The RY_x approaches 1 when the response to applied nutrient X becomes 0.

Top soil samples (0-20 cm) were taken with an auger from 5 locations in the unfertilized plots of each field, and a composite soil sample of 1.5 kg plot^{-1} was sent to the laboratory, where they were oven-dried, passed through a 2 mm sieve and analysed for pH, available P, exchangeable K, Ca, Mg, total N, soil organic carbon and texture according to Okalebo et al. (2002). Daily rainfall data for the research stations were obtained from KARI and NaCRRI. For the on-farm sites, daily rainfall data were collected by one farmer per site by means of a simple rainfall gauge. Total rainfall during the growth cycle, rainfall from 0-3, 3-6, 6-9, 9-12, 12-15 MAP and the total number of rain days during the growth cycle were included in further analysis. Field technicians, who regularly visited the fields, scored overall weed management (WM) by farmers during the growing period on a scale from 1 (very poor) to 5 (very good).

2.4 Scoring pests and diseases

The most important cassava pests and diseases in East Africa include cassava mosaic disease, bacterial blight, green mites, anthracnose disease and mealy bugs (Legg et al., 2006; IITA, 1990). Cassava brown streak disease was first observed as a new viral disease in Uganda in 2004 (Alicai et al., 2007). Except for the Ugandan on-farm trials in 2004, the twenty plants in the harvest area of each plot were scored for incidence (yes/no) and severity on a scale of 1 to 5 (IITA, 1990) at 3, 6 and 9 MAP for all mentioned pests and diseases. An average disease severity index (*DSI*) was calculated for each recording date and each pest/disease for all unfertilized (T0) and NPK fertilized (T1) plots according to the following formula adapted from (Kim et al., 2000):

$$DSI = \left(\frac{\sum_i severity\ score - (number\ of\ \ plants\ scored)}{4 \times number\ of\ \ plants\ scored} \right) \times 100 \tag{2}$$

The *DSI* ranges from 0 for a plot with all healthy plants (score 1) to 100 for a plot where all plants received a score 5. Adjusting the procedure of Zinsou et al. (2004) to capture disease progress during the growth cycle into one number, we then determined the area under disease severity index progress curve (*AUSiPC*) for each disease in each plot as:

$$AUSiPC = \sum_i \left(\frac{DSI_i + DSI_{i-1}}{2} \right) \times \left(t_i - t_{i-1} \right) \tag{3}$$

whereby *DSIi* is the disease severity index at time *ti* with *t* corresponding to the number of months after planting. The *AUSiPC* ranges from 0 for a plot where all plants were healthy during the whole growth cycle to 750 for a plot where all plants received score 5 during the whole growth cycle.

2.5 The boundary line approach to analyse yield limitations

The boundary line approach (Webb, 1972; van Asten et al., 2003; Shatar and McBratney, 2004) was used to define boundary lines that represent the maximum (or limited) response of a dependent variable (e.g. yield) to an independent variable (e.g. rainfall) in a given environment. Boundary lines were fitted through boundary points that corresponded to the highest response of the dependent variable at each value of the independent variable, using the following model:

$$y_l = \frac{y_{\max}}{(1 + (K \times EXP(-R \times x)))} \tag{4}$$

whereby y_{max} is the observed maximum yield level, x is the independent variable and K and R are constants. The best boundary line model was obtained by minimizing the root mean squared error (RMSE) between the fitted boundary line (y_l) and the boundary points (y_p); i.e., the maximum yield values observed at each given value of the independent variable.

2.6 Partial gross margin analysis

Partial gross margins of NPK fertilizer use were calculated for the 2004 and 2005 trials. Marginal costs taken into account were purchase, transport and application costs of fertilizer. Average wholesale market prices in 2004 and 2005 were used to determine the full fertilizer package (378,200 Uganda Shillings; UgSh and 17,416 Kenya Shillings; KSh) with 1 US$ = 1818 UgSh and 80 KSh. Transport costs for fertilizer were estimated at 1 US$ per bag of 50 kg. Labour costs for fertilizer application were assumed to be similar to those of cassava planting. Prices for hired labour were used to mirror the opportunity costs of labour (CIMMYT, 1988) as farmers hired labour for agricultural activities in the study areas. Labour rates for cassava planting were obtained from a farm survey in three Ugandan and three Kenyan sites and did not vary between sites within a country. Average wholesale price for cassava chips in 2004 and 2005 (132 \$ ton^{-1} for Uganda and 150 \$ ton^{-1} for Kenya; IITA, unpublished) were adjusted to a field price of 118 \$ ton^{-1} for Uganda and 134 \$ ton^{-1} for Kenya to account for harvest and post-harvest labour costs that are proportional to yield (CIMMYT, 1988). Harvest and post-harvest labour costs expressed per ton of product harvested were measured in Uganda and took into account labour for harvesting, transport, peeling, chipping and drying and costs related to bagging and storage. The same values were used for Kenya. Marginal revenue was calculated as marginal yields times the field price of cassava. The Value/Cost Ratio (VCR) was calculated as the marginal revenue over the marginal costs. Under conditions of small-scale agriculture it is often considered that a VCR of two or more is an indication that a new production technology creates sufficient economic incentives for farmers to adopt it (Kelly, 2006), although adoption may also depend on the absolute profit margin generated by the technology.

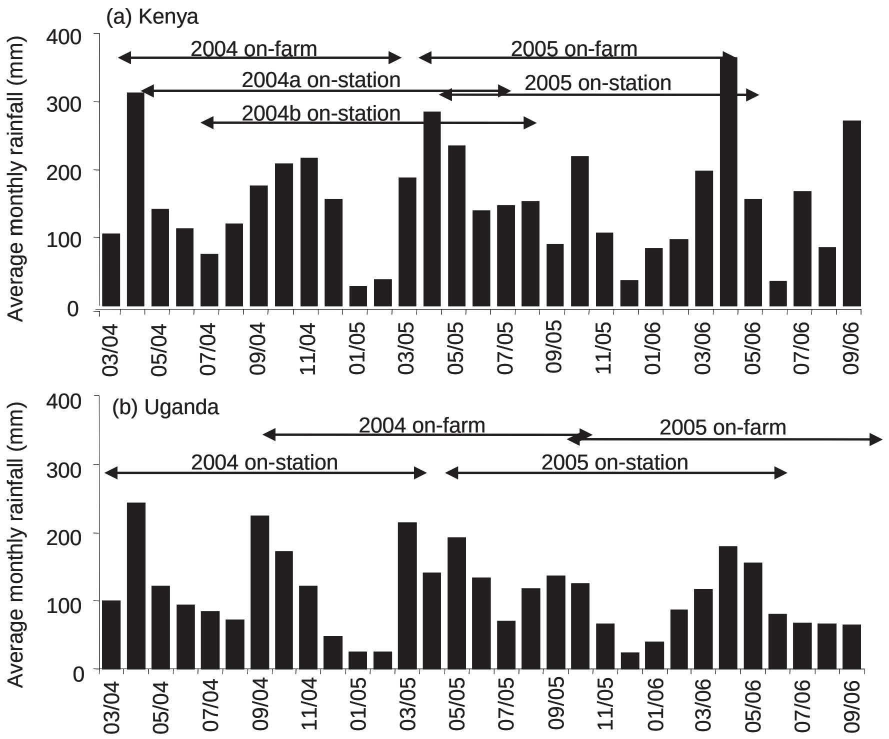
2.7 Statistical analysis

Analysis of variance was performed to test for the effect of site, season, fertilizer treatment and genotype on the biophysical variables, cassava fresh yields, yield components, plant growth variables and partial gross margins. Non-parametric tests for two or more independent samples using the Mann-Whitney U or Kruskal Wallis test, respectively, were employed if variables could not be normalised by transformation. A non-parametric test for two related samples (Wilcoxon) was used to test for the effect of fertilizer on pest and disease progression. The CROSSTAB procedure using Pearson Chi square analysis was used to test for significance of differences between years for the percentage of farmers having a VCR > 2. Statistical analyses were carried out using Genstat for Windows (version 10.2) and SPSS for Windows (version 10.0).

3. Results

3.1 Variability in abiotic and biotic factors across sites and seasons

Total rainfall during the growing seasons of the 2004 and 2005 trials ranged from 1065 mm for the 2004 trial at the NaCRRI station to 2460 mm for the 2005 trials in Nambale (Figure 1). The KARI station in Kenya received considerably less rain in 2004 and considerably more rain in 2005 than the long-term mean, while rainfall at the



(c) Total rainfall

	Kenya					Uganda		
	Kwang'amor	Mungatsi	Nambale	Ugunja	KARI	Kisiro	Minani	NaCRRI
2004	1447	1781	1830	1316	2268	1478	1771	1065
2005	2187	2377	2460	1677	1914	1270	1292	1152

Figure 1: Rainfall measured in the study sites between March 2004 and September 2006 for the 2004 and 2005 trials in Kenya and Uganda. (a) Average monthly rainfall in Kenya; (b) Average monthly rainfall in Uganda ; and (c) Total rainfall per site in 2004 and 2005. The arrows in (a) and (b) indicate the growing season (from planting to harvesting) of the on-station and on-farm trials.

NaCRRI station in Uganda was around average in both years. In the Kenyan on-farm sites, the 2005 trials received more rainfall during early (2 and 4 MAP) and late (10-11 MAP) growth stages than the 2004 trials, while they were also harvested 5 weeks later. Consequently, the 2005 Kenyan trials received between 361 and 741 mm more rainfall than the 2004 trials. The opposite was true for the Ugandan on-farm sites. The 2004 trials received more rainfall during the first 4-6 MAP, resulting in 177 to 479 mm more total rainfall than the 2005 trials. Soil texture ranged from sandy loam to sandy clay loam to clay loam (Table 2). Soil fertility was generally low, although the soils on

Table 2. Main abiotic and biotic characteristics and weed management score of the 2004 and 2005 trials in Uganda and Kenya

		Particle size (%)			pH water	SOC	Tot N	Ext. P	Exch. Bases (cmol$_+$ kg^{-1})			AUSiPC[1]				WM[2]
Location	n	Clay	Silt	Sand	(1:2.5)	(g kg^{-1})	(g kg^{-1})	(mg kg^{-1})	K	Ca	Mg	CBB	CGM	CAD	CMD	-
2004																
Kenya																
Kwang'amor	10	17	8	76	6.0	6.9	0.46	4.5	0.33	0.8	0.3	113	105	12	95	3.6
Mungatsi	7	28	18	54	5.5	11.4	1.04	5.8	0.56	1.6	0.8	76	64	1	132	4.4
Nambale	9	27	14	59	5.4	10.6	0.93	3.8	0.37	1.3	0.8	146	75	23	68	3.1
Ugunja	9	29	21	50	5.7	8.7	0.76	3.0	0.40	0.8	0.7	70	41	6	86	3.4
KARI	8	37	21	42	5.2	14.7	1.34	3.1	0.42	4.4	2.7	172	18	6	111	5
Uganda																
Kisiro	6	26	7	67	6.5	8.0	0.49	12.3	0.46	2.8	0.8					3.5
Minani	8	16	9	76	6.2	10.0	0.99	5.6	0.78	6.5	1.7					3.2
NaCRRI	4	35	11	54	6.2	20.5	2.08	7.1	1.32	11.4	5.1	58	71	1	199	5
SED[3]		2	3	3	0.2	1.0	0.24	1.7	0.19	0.9	0.3	18	15	7	34	0.3
2005																
Kenya																
Kwang'amor	7	18	11	75	5.8	7.2	0.38	8.5	0.33	1.7	0.5	119	126	10		2.9
Mungatsi	8	26	19	55	5.4	9.0	0.48	5.3	0.33	0.5	0.2	144	123	29		3.6
Nambale	9	28	15	57	5.3	8.7	0.50	3.4	0.19	0.8	0.4	140	119	2		3.2
Ugunja	10	32	23	44	5.7	7.8	0.45	2.7	0.22	0.9	0.4	125	31	1		3.6
KARI	4	40	19	41	5.1	17.1	1.52	2.3	0.35	4.9	3.4	197	46	14		5
Uganda																
Kisiro	8	14	9	67	6.3	8.5	0.88	4.6	0.32	3.4	1.5	51	3	0		3.5
Minani	8	19	8	74	6.1	9.4	1.0	2.5	0.55	3.6	1.4	53	38	0		3.4
NaCRRI	4	39	10	51	6.4	18.9	1.8	5.7	0.97	8.4	3.0	120	33	0		5
SED		8	2	5	0.1	1.2	1.00	1.3	0.12	0.8	0.3	11	17	7		0.5

[1] Average area under severity index progress curve (AUSiPC – see section 2.4) for cassava bacterial blight (CBB), cassava green mites (CGM), cassava anthracnose disease (CAD) and cassava mosaic disease (CMD). Scores for CMD are for MM96/42884 and Nase 3 only as MM96/5280 and TMSI92/0067 are resistant to CMD.

[2] Weed management (WM) ranges from 1 (very poor) to 5 (good).

[3] SED: Standard error of the differences.

Table 3: Fresh cassava yields (t ha^{-1}) of selected varieties with selected NPK fertilizer treatments (N: 100 kg ha^{-1}; P: 22 kg ha^{-1}; K: 83 kg ha^{-1}; '-' signifies no fertilizer) in the 2004 and 2005 trials in six on-farm sites and two research stations (KARI and NaCRRI) in Kenya and Uganda

Location	*n*	2004								*n*	2005				
		MM96/5280		MM96/4884		Nase 3		TMSI92/0067			MM96/5280 in Kenya and TMSI92/0067 in Uganda				
		-	NPK	-	NPK	-	NPK	-	NPK		-	PK	NK	NP	NPK
Kenya															
Kwang'amor	10	11.6	16.2	12.8	15.9	9.9	13.9			7	9.7	9.7	16.7	16.9	24.9
Mungatsi	7	14.0	16.8	12.9	13.9	10.8	15.3			8	14.8	17.3	15.9	18.0	23.6
Nambale	9	9.4	14.8	8.9	11.9	7.4	13.0			9	18.7	22.7	25.5	24.8	29.0
Ugunja	9	6.4	11.2	4.2	7.4	5.2	6.2			10	14.3	21.2	17.9	17.7	27.3
KARI	8	12.4	17.7	16.3	20.3	10.8	16.3			4	17.4	17.2	20.0	19.6	23.4
Uganda															
Kisiro	6					11.9	13.7	15.7	17.1	8	14.7	21.6	20.5	24.1	27.5
Minani	8					13.0	16.5	19.1	26.7	8	14.4	17.2	17.7	21.6	24.2
NaCRRI	4					15.5	16.5	17.0	16.8	4	25.7	28.4	25.7	25.9	26.2
				Kenya	Uganda									Kenya	Uganda
SED[1] (Variety)				0.68	1.12										
SED (Fertilizer)				0.55	1.12					SED (Fertilizer)				1.56	1.72
SED (Environment				0.89	1.45					SED (Environment)				1.79	1.49
P for the effects of:										for the effects of:					
Variety (V)				*<0.01*	*<0.001*										
NPK Fertilizer (F)				*<0.001*	*<0.01*					NPK Fertilizer (F)				*<0.001*	*<0.001*
Environment (E)				*<0.001*	*<0.01*					Environment (E)				*<0.001*	*<0.001*
V x F/V x E/F x E				*ns*	*ns / <0.05 / ns*					F x E				ns	*ns*

---

[1] SED = Standard error of the difference between means for variety, fertilizer and environment effects.

and Mg due to a higher clay content than the soils of farmer fields where trials were conducted (*P*<0.001). Experimental sites used in 2004 had higher concentrations of total N and available K than sites used in 2005 (*P*<0.05), while Kenyan soils had a lower concentration of all macro nutrients than Ugandan soils (*P*<0.01) Average soil organic carbon values ranged from 6.9 to 20.5 g kg^{-1}, while average available P and exchangeable K ranged from 2.3 to 12.3 mg kg^{-1} and 0.19 to 1.32 cmol$_{(+)}$ kg^{-1}, respectively.

Bacterial blight and green mite symptoms were observed on all genotypes and in all trials and usually increased with plant age. Bacterial blight infections and green mite infestations were more severe in Kenya than in Uganda (*P*<0.001) and bacterial blight was overall more important in 2005 than in 2004 (*P*<0.01), although the most severe infections were noted in Nambale in 2004 with 37% of the monitored plants having a severity score of 4-5 ('candle stick' stage) at 9 MAP, compared with less than 5% in all other sites. Moderate green mite infestations were observed in Nambale, Mungatsi and Kwang'amor with 20-30% of the monitored plants having a severity score of 3-4 at 6 MAP. Cassava mosaic disease was observed on genotypes that are not resistant to the virus (Nase 3 and MM96/4884), anthracnose symptoms were found only in individual fields in Kenya that were hit by severe hail storms, while mealy bugs were not observed in any of the sites.

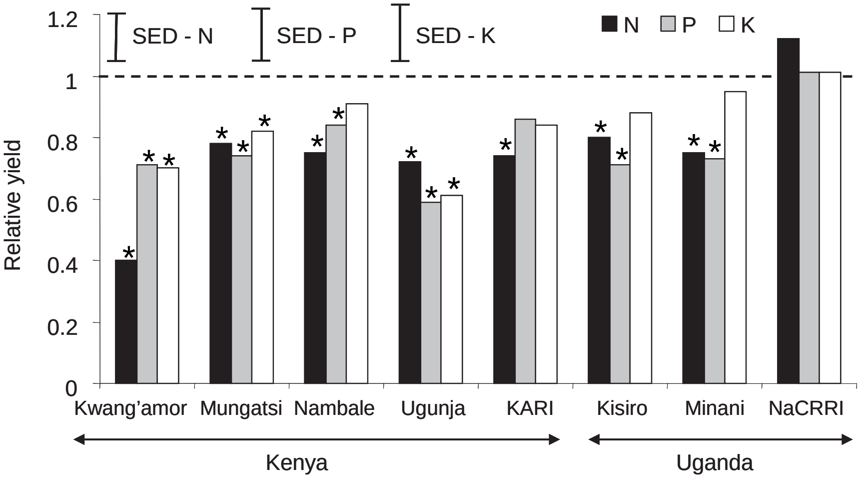


Figure 2: Relative fresh cassava yield in absence of N, P and K for the 2005 trials in 8 sites in Kenya and Uganda. SED stands for Standard Error of the Difference of the means for relative N, P and K yields. Asterisk above bars indicate that observation is significantly different from the fully fertilized control (relative yield = 1) at *P*<0.05.

3.2 Effect of fertilizer on cassava yields and yield components

In Kenya, average fresh yields of unfertilized cassava ranged from 4.2 to 16.3 t ha^{-1} in the 2004 trials and from 9.7 to 18.7 t ha^{-1} in the 2005 trials and were significantly (P<0.001) higher in the latter set of trials (Table 3). In Uganda, average yields of unfertilized cassava also tended to be higher in the 2005 trials (14.4 to 25.7 t ha^{-1}) than in the 2004 trials (11.9 to 19.1 t ha^{-1}). NPK fertilizer application (100-22-83 N-P-K) increased cassava yields in both countries and both years (P<0.01). Yield responses were much stronger in the 2005 than in the 2004 trials (P<0.001). In Kenya, average yield responses ranged from 0.9 to 5.6 t ha^{-1} in the 2004 trials and from 6.0 to 15.3 t ha^{-1} in the 2005 trials (Table 3). In Uganda, average yield responses ranged from -0.2 to 7.7 t ha^{-1} in the 2004 trials and from 0.5 to 12.9 t ha^{-1} in the 2005 trials. The average yield response per kg of applied N, P and K was 37, 168 and 45 kg, respectively in 2004 and 106, 482 and 128 kg, respectively in 2005. In both countries, yields varied between genotypes (P<0.01) and between environments (P<0.01), but yield responses to fertilizer (i.e., the relative increase with respect to control) did not differ between genotypes and environments nor did fertilized yields of the 2005 trials differ between sites.

The missing nutrient trials showed significant yield responses to applied N and P in all on-farm sites (P<0.05; Figure 2). Yield responses to applied K were significant in most Kenyan on-farm sites, but not in the Ugandan sites. Overall, yield response to applied N and P was similar, while response to applied K was smaller (P<0.05) than to applied N and P. The most limiting nutrients for cassava production were not the same

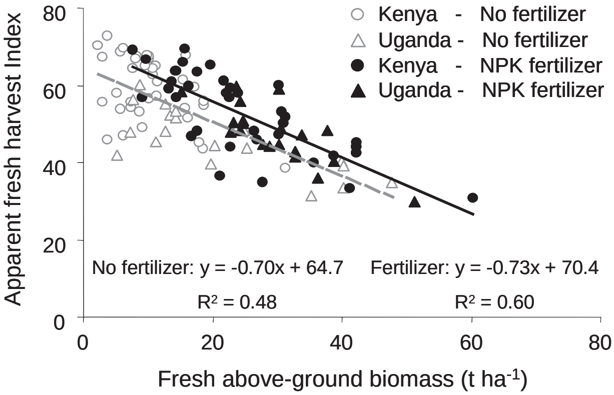


Figure 3: Relationship between fresh above-ground biomass and apparent fresh harvest index (not taking into account fallen leaves) for the unfertilized and fertilized plots in the 2005 trials in 8 sites in Kenya and Uganda.

across sites; for example, N was most limiting in Kwang'amor and KARI, P+K in Ugunja and N+P in Kisiro and Minani (Table 3; Fig. 2). NPK fertilizer significantly increased fresh above-ground biomass ($P<0.05$) and the number of storage roots per plant ($P<0.001$) in both Kenya and Uganda, but did not affect the individual weight of marketable storage roots and the dry matter content of storage roots (Table 4 and not shown). In Kenya the effect of fertilizer on yield, above-ground biomass and the number of storage roots per plant was more pronounced in 2005 than in 2004, while in

Table 4: Effect of NPK fertilizer[1] on selected yield components of MM95/5280 and I92/0067 in the 2004 and 2005 trials in 5 sites in Kenya (a) and 3 sites in Uganda (b)

		n	Yield t ha^{-1}	AG Biomass[2] t ha^{-1}	HI -	# storage roots plant^{-1} -	mark. Roots[3] g	% mark. roots %	Dry matter %
a. Kenya									
2004	0-0-0	42	10.6	11.4	49	5.4	277	65	36.9
	N-P-K	42	15.2	17.7	48	8.0	276	63	37.4
2005	0-0-0	38	14.7	10.4	59	6.0	374	66	38.6
	N-P-K	38	26.0	24.4	53	10.4	392	65	39.6
SED[4] (Fertilizer):			0.92	1.35	1.6	0.33	13	1.9	0.67
SED (Year):			0.92	1.35	1.6	0.34	13	1.9	0.67
P for the effects of:									
Fertilizer (F)			*<0.001*	*<0.001*	*<0.05*	*<0.001*	*ns*	*ns*	*ns*
Year (Y)			*<0.001*	*<0.05*	*<0.001*	*<0.001*	*<0.001*	*ns*	*<0.01*
F × Y			*<0.001*	*<0.01*	*ns*	*<0.01*	*ns*	*ns*	*ns*
b. Uganda									
2004	-	18	17.3	28.2	40	5.1	583	76	33.6
	NPK	18	20.4	34.3	40	5.9	581	74	34.2
2005	-	20	17.0	21.0	46	4.3	581	76	40.3
	NPK	20	25.9	29.4	48	6.6	640	75	42.2
SED (Fertilizer):			1.32	2.95	2.1	0.39	40	2.7	0.95
SED (Year):			1.31	2.95	2.1	0.39	40	2.7	0.95
P for the effects of:									
Fertilizer (F)			*<0.001*	*<0.05*	*ns*	*<0.001*	*ns*	*ns*	*ns*
Year (Y)			*<0.05*	*<0.05*	*<0.01*	*ns*	*ns*	*ns*	*<0.001*
F × Y			*<0.05*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*

[1] 100-22-83 kg ha^{-1} N-P-K; '-' signifies no fertilizer.

[2] AG biomass = above ground biomass (stems and leaves).

[3] mark. roots = marketable roots (diameter < 3 cm).

[4] SED = Standard error of the difference between means for fertilizer and year effects

Uganda this only held for the effect of fertilizer on yield. In Kenya, but not in Uganda, the apparent harvest index was reduced by fertilizer application (Table 4). Greater above-ground biomass was generally associated with smaller apparent harvest indices, but for a given above-ground biomass, fertilized fields had a higher apparent harvest index than unfertilized fields (Figure 3).

Table 5: Partial gross margin analysis for NPK fertilizer use[1] for the 2004 and 2005 trials in 8 sites in Kenya and Uganda

	n	Marginal yield (t ha^{-1})	Marginal costs (\$ ha^{-1})	Marginal revenue (\$ ha^{-1})	VCR[2] -	Fields with VCR>2 %
2004						
Kenya						
Kwang'amor	28	3.9	266	520	2.0	53
Mungatsi	21	2.8	266	374	1.4	43
Nambale	27	4.7	266	626	2.4	41
Ugunja	24	3.0	266	406	1.5	38
KARI	24	4.9	266	656	2.5	63
Uganda						
Minani	12	5.3	251	620	2.5	50
Kisiro	10	1.6	251	184	0.7	30
NaCRRI	8	0.4	251	43	0.2	13
Overall mean	154	3.7	363	483	1.8	45
2005						
Kenya						
Kwang'amor	7	15.3	266	2042	7.7	100
Mungatsi	7	8.9	266	1191	4.5	86
Nambale	7	10.3	266	1379	5.2	71
Ugunja	9	14.0	266	1877	7.0	100
KARI	4	6.0	266	804	3.0	75
Uganda						
Minani	7	9.7	251	1139	4.5	71
Kisiro	7	12.9	251	1519	6.1	100
NaCRRI	4	0.5	251	57	0.2	25
Overall mean	52	10.6	261	1370	5.2	83
P for the effects of:						
Environment (E)	-	*<0.001*	-	*<0.001*	*<0.001*	*ns*[3]
Year (Y)	-	*<0.001*	-	*<0.001*	*<0.001*	*<0.001*
E × Y	-	*<0.001*	-	*<0.001*	*<0.001*	-

[1] 100-22-83 kg ha^{-1} N-P-K

[2] Value Cost Ratio

[3] Chi-square statistics

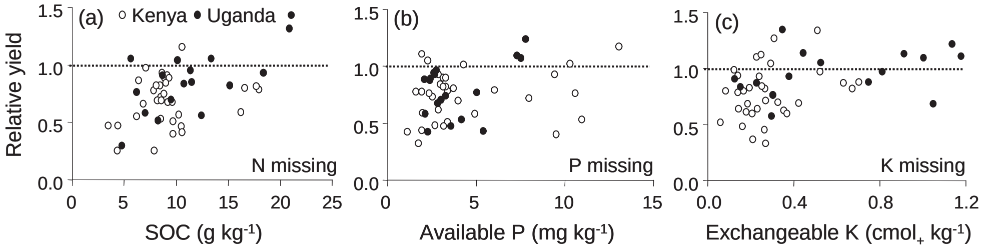


Figure 4: Relative cassava yields from the 2005 trials in Kenya and Uganda without N, P and K in relation to (a) SOC; (b) available P; and (c) exchangeable K, respectively. Relative yields are calculated as missing N, P or K yields over yields with full nutrient (NPK) application (100-22-83 kg ha^{-1} N-P-K). The dashed line indicates the control yield (no response to applied N, P or K).

3.3 Cost-benefits of fertilizer use

A partial gross margin analysis showed no difference in the benefits of NPK fertilizer use between genotypes or countries (data not shown), but fertilizer use was more profitable in the 2005 trials than in the 2004 trials (P<0.001; Table 5). In 2005, the average marginal revenue was 1370 US$ ha^{-1} and the average Value Cost Ratio (VCR) was 5.2, while figures for 2004 were 483 US$ ha^{-1} and 1.8. Overall, 45% of the fields in the 2004 trials had a VCR > 2 compared with 83% of the fields in the 2005 trials (P<0.001). Profitability differed between sites (P<0.001). In the Kenyan on-farm sites, NPK application resulted in VCR's larger than 2 (P<0.001), while in the Ugandan on-farm sites NP and NPK application resulted in VCR's larger than 2 (P<0.05), but adding K to the NP package did not give economic benefits (data not shown).

3.4 Factors that influence response to fertilizer

In the 2005 trials, RY_N and RY_K were positively related to SOC (r = 0.51, P<0.001) and exchangeable K (r = 0.40; P<0.01), respectively, while RY_P was weakly associated (r = 0.25) with available P (Figure 4a-c). Yield responses of cassava to NPK fertilizer were negatively associated with SOC, total N, available P, exchangeable K and the sum of bases (Figure 5). These relationships were weak (r = -0.17 to -0.29), but significant (P<0.05), and were stronger for the 2005 data (r = -0.52 to -0.61; P<0.001) than for the 2004 data (r = -0.05 to -0.11), except for available P. Soil pH and texture were not associated with fertilizer response. Even on soils with low nutrient levels, responses to fertilizer varied strongly (i.e. on soils with a SOC content of < 10 g kg^{-1}, responses ranged from -8.6 to 24.4 t ha^{-1}). Considering a VCR of 2 (which translates into a yield increase of 4.0 t ha) as a minimum requirement for fertilizer adoption, responses to fertilizer are likely to be too small to stimulate adoption if SOC > 20 g kg^{-1}; available P > 13 mg kg^{-1}; exchangeable K > 1.0 cmol kg^{-1} and Ca > 10 cmol kg^{-1} (Figure 5a-d).

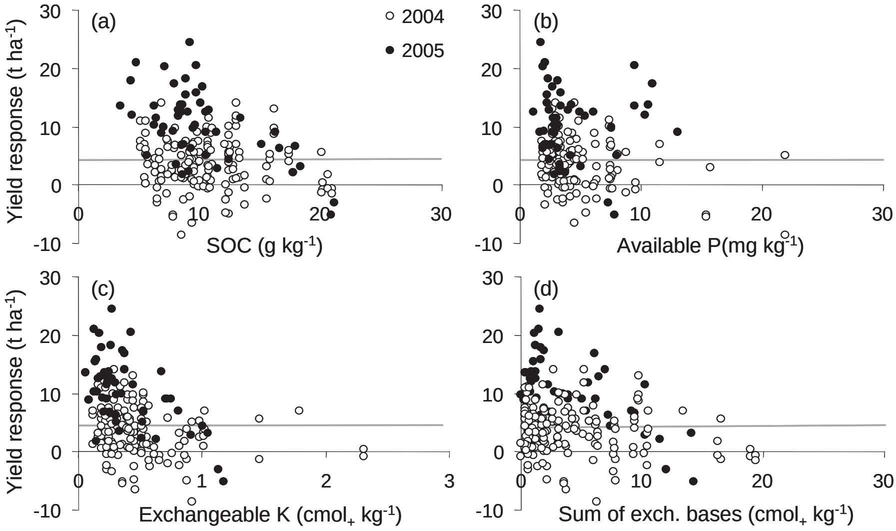


Figure 5: Fresh yield response to NPK fertilizer (100-22-83 kg ha^{-1} N-P-K) for the 2004 and 2005 trials in 8 sites in Kenya and Uganda in relation to (a) SOC; (b) available P; (c) exchangeable K; and (d) sum of exchangeable bases (K, Ca, Mg) in the topsoil (0-20 cm). The solid lines indicate a VCR of 2 (i.e. yield response of 4 t ha^{-1}).

Across years, yield response to NPK fertilizer was best correlated to total rainfall and rainfall during the first three months (r = 0.31; *P*<0.01 and 0.18; *P*<0.05, respectively). Although correlations were weak, there was a clear indication that larger maximum yield responses to NPK fertilizer occurred with higher rainfall in both years (Figure 6a and b), when total rainfall > 1500 mm or rainfall from 0-3 MAP > 400 mm. Similar trends were observed for the response in above-ground biomass and the change in the number of roots per plant due to NPK fertilizer application (Figure 6 c-f). No clear trends were observed across years for the apparent fresh harvest index, individual storage root weight and the dry matter content of storage roots and rainfall.

Overall, better weed management was associated (r = 0.34; *P*<0.001) with higher cassava yields in unfertilized plots up to a weed management score of 3.5 (Figure 7a). In fertilized plots, though, no relation was found between weed management and yields (Figure 7b). A different picture was observed in the Kenya 2004 trials. In these trials, better weed management was strongly associated with higher yields in both the unfertilized and fertilized plots (r = 0.46; *P*<0.001 in both cases) up to the highest weed management score (5). In the unfertilized plots of the Kenyan trials, plant width of MM96/5280 at 3 MAP was similar in both trial years, but at 6 MAP plants were 19% wider in 2005 than in 2004 (*P*<0.001; Figure 8). In the fertilized plots of the same

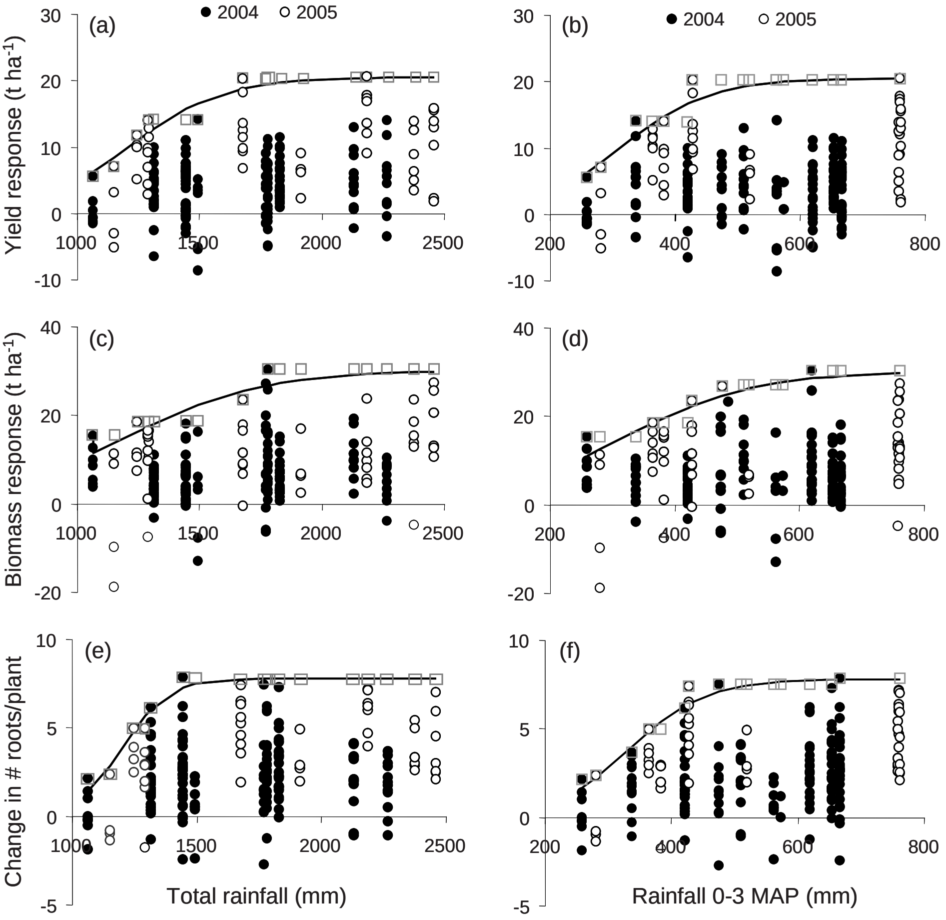


Figure 6: Effect of rainfall on response of yield, above-ground biomass and number of storage roots per plant to NPK fertilizer (100-22-83 kg ha-1 N-P-K). Fresh cassava yield response (a, b), fresh above-ground biomass response (c,d) and change in number of storage roots per plant (e,f) in the 2004 and 2005 trials in Kenya and Uganda against total rainfall (a,c,e) and rainfall during the first three months after planting (b,d,f). Lines indicate boundary lines, squares indicate boundary points (see text for further explanation).

trials, plants were already 21 % wider at 3 MAP (*P*<0.001) and 23% wider (*P*<0.001)at 6 MAP in 2005 than in 2004. In 2004, fertilizer use increased plant width of MM96/5280 by 14% at 3 MAP and by 28% at 6 MAP (*P*<0.001), while in 2005 fertilizer used increased plant width by 33 and 43% at 3 and 6 MAP, respectively (*P*<0.001). Full ground cover was thus reached earlier, contributing to more effective weed suppression through light competition, in the fertilized plots than in the unfertilized plots and in 2005 than in 2004.

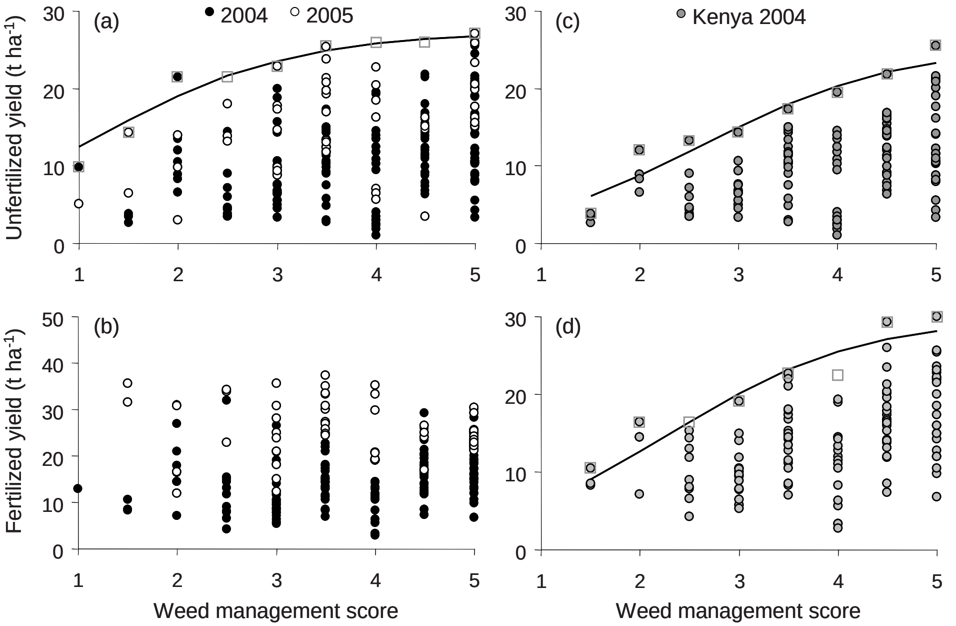


Figure 7: Effects of weed management on fresh cassava yield in unfertilized treatments (a, c) and yield with NPK fertilizer (100-22-83 kg ha^{-1} N-P-K) (b, d) for the 2004 and 2005 trials in Kenya and Uganda (a,b) and for the 2004 Kenyan trials separately (c,d). Farmer weed management during the growing cycle was scored from very poor (1) to very good (5). Lines indicate boundary lines, squares indicate boundary points (see text for further explanation).

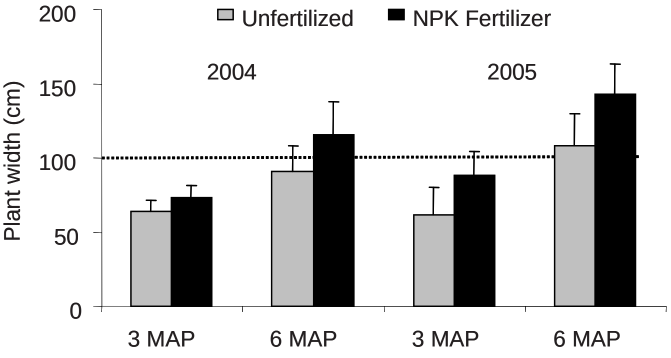


Figure 8: Effect of NPK fertilizer (100-22-83 N-P-K) on average plant width of MM96/5280 in the 2004 and 2005 Kenyan on-farm trials at 3 and 6 months after planting. Plant width was measured on the twenty plants in the net harvest area. As plant spacing was 1 x 1 m (10,000 plants ha-1), width corresponds directly to % soil cover and the dashed line indicates full ground cover.

3.5 Factors that did not influence response to fertilizer

Although yields varied significantly (*P*<0.001) between genotypes, the yield response to NPK fertilizer was similar for the four genotypes used in the 2004 trials (Table 3). Similar results were found for the aboveground biomass, number of storage roots per plant, individual weight of marketable storage roots and dry matter content of the storage roots (data not shown).

No effects of pest and disease pressure on fertilizer response were seen. Average yield response to fertilizer in the 25% of the fields that were least affected by bacterial blight, green mites and cassava mosaic disease was similar to average yield response to fertilizer in the 25% most affected fields by these pests and diseases. No analysis was done for anthracnose as >95% of the fields had low severity scores (*AUSiPC* < 50). NPK fertilizer use decreased green mites on all genotypes (*P*<0.01), but increased cassava mosaic disease severity (*P*<0.01) on genotypes that are susceptible to this virus, i.e. Nase 3 and MM96/4884, slightly increased anthracnose on MM96/5280 and Nase 3 (*P*<0.05) and slightly increased bacterial blight (*P*<0.05), except on I92/0067 (Figure 9a-d). Although harvesting at an older age was weakly associated with higher yields in both years (r = 0.25 and 0.22 for 2004 and 2005, respectively), no effects of harvest age on fertilizer response were found.

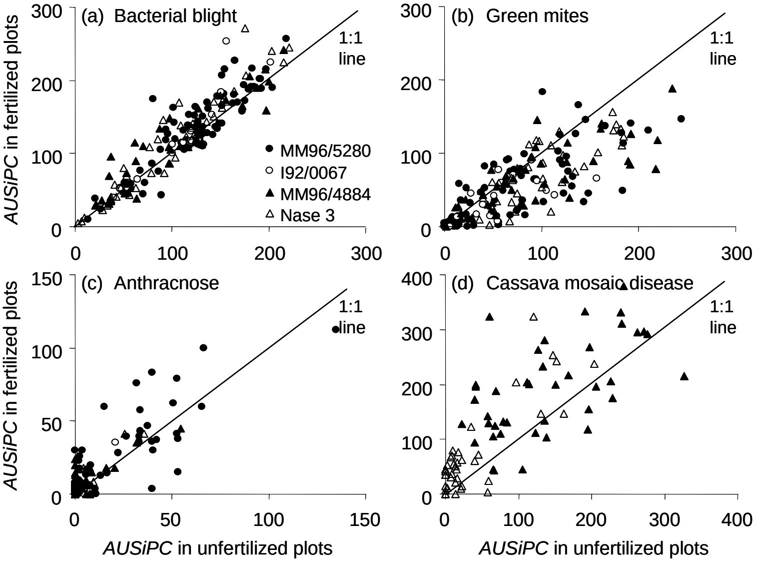


Figure 9: Effect of NPK fertilizer (100-22-83 N-P-K) on (a) bacterial blight; (b) green mites; (c) anthracnose disease; and (d) cassava mosaic disease for four genotypes in the 2004 and 2005 trials in Kenya and Uganda. Pest and disease pressure in unfertilized and fertilized plots is expressed as Area Under Severity index Progress curve (AUSiPC). See text for more details.

4. Discussion

NPK fertilizer application resulted in strong increases in cassava yield in the two years of the study. Response to fertilizer was highly variable between years and sites and was affected by soil fertility, rainfall and weed management. Fertilizer response in our trials was not influenced by genotype choice, pest and disease pressure and harvest age. As nutrient demands did not vary between the genotypes we used in 2004, we subsequently focused on identifying the main nutrients limiting cassava production in 2005. Cassava yields in farmers' fields in Kenya and Uganda were limited by both N and P, while K was only limiting production in Kenya.

4.1 Variability in unfertilized cassava yields

Unfertilized cassava yields varied strongly between sites and years (Table 3). Yields were much lower in 2004 than in 2005, indicating generally less favourable growing conditions for cassava during the first set of trials. Lower yields in the 2004 Kenya trials can partially be explained by the early harvest at 11 MAP and by the relatively low amounts of rainfall received during 2 to 4 months after planting (Figure 1) as a water deficit during 1 to 5 months after planting may reduce storage root yields by up to 32-60% (Alves, 2002). Unfertilized cassava yields in the trials were much higher than farmer estimates of average cassava yields in the same sites in Kenya (7.0 t ha^{-1}) and Uganda (11.2 t ha^{-1}) (Fermont et al., 2008 – Chapter 3). They were also generally, but not always, higher than the average yields reported by FAO (2009) for Kenya (9.1 t ha^{-1}) and Uganda (14.4 t ha^{-1}) in 2005. The use of improved genotypes, that are resistant to cassava mosaic disease, sole cropping and timely planting at the start of the growing season will have contributed to the higher yields obtained in the trials.

4.2 Variability in fertilizer response

NPK fertilizer application increased cassava yields significantly in both years (cf. Table 3). The response to NPK fertilizer of MM96/5280 and TMSI92/0067, genotypes that were used in both sets of trials, was much stronger in the 2005 than in the 2004 trials (Table 4), when rainfall distribution was less favourable. Total N and exchangeable K contents in the soils of the study sites were higher for the 2004 than for the 2005 trials (Table 2). This likely reduced the overall response to applied N and K (Figure 4) in 2004. The use efficiency of N was perhaps also lower in 2004, when fertilizer top dressings were applied as a surface application in contrast to 2005 when top dressings were incorporated in the soil. Surface application of fertilizer may result in N being more prone to volatilization losses (Mahli et al., 1996). Even on infertile soils, with SOC, P and/or K below the critical ranges for cassava proposed by Howeler (2002), response to fertilizer was extremely variable (Figure 4 and 5). This may be due to nutrient limitations other than N, P or K, variation in efficiency of mycorrhizal associations between fields (Howeler, 2002), and/or interactions between multiple constraints.

Yield increases due to fertilizer application were the result of an increased sink capacity (i.e. increased number of storage roots per plant), an increased source supply (i.e. increased above-ground biomass) and a slightly higher dry matter partitioning to the roots at a given above-ground biomass (Figure 3). An increase in the number of storage roots per plant in response to fertilizer application has also been observed by Kasele (1980) and Pellet and El-Sharkawy (1993). Cassava yield components that are of interest for commercial cassava producers (dry matter, average root weight, % marketable roots) were not affected by fertilizer use. Root starch content may decrease with N fertilization and increase with K fertilization (Obigbesan and Matuluka, 1977; Howeler, 1998; 2002).

4.3 Nutrient limitations

Zinc deficiency symptoms were observed on cassava leaves during the first 3 to 4 MAP in three quarters of the fields in the Ugandan site with the highest sand content (Minani). High P availability through fertilizer application can induce Zn deficiencies, most likely through precipitation of $ZnPO_4$ (Lozano et al., 1981; Howeler, pers. comm., 2006). In serious cases, plant vigour in fertilized plots was strongly retarded, especially during early growth and resulted in negative responses to applied fertilizer.

Major nutrient limitations to cassava production varied between sites in Uganda and Kenya (Figure 2). In western Kenya the combined application of NPK gave highest returns to investment, while in Uganda application of K was not economic (Table 5). Howeler and Cadavid (1990) also found that limitations to N, P and K varied between sites in Colombia, but pointed out that K became the limiting element when cassava was grown continuously in the same field. Similar conclusions were drawn for Benin by Carsky and Toukourou (2005). In our study, the Kenyan soils had lower amounts of soil nutrients than the Ugandan soils. Soils in western Kenya are generally considered as degraded as a consequence of long-term cultivation with no or little carbon and nutrient inputs (Tittonell, 2008a).

Responses, expressed as kg fresh cassava per kg nutrient applied, were larger than those found on low fertility soils in Benin using an N:P:K fertilizer application of

60:16:138 (23, 88 and 10 kg cassava per kg N, P and K applied, respectively; calculated from Carsky and Toukourou (2005)), and similar to those found in 22 sites across Colombia using an N:P:K fertilizer application of 100:50:100 (92, 184 and 92 kg cassava per kg N, P and K applied, respectively; calculated from Howeler and Cadavid (1990)). Based on empirical evidence, critical soil nutrient contents for cassava were estimated to range between 4-8 mg kg^{-1} for available P (Bray I), 0.08-0.18 cmol$_+$ kg^{-1} for exchangeable K (NH$_4$-acetate) and around 3.1 % for soil organic matter (or 18 g kg^{-1} SOC) for cassava in Asia, Latin America and Nigeria (Howeler, 2002). Carbon contents in the majority of the soils in our study were below 18 g kg^{-1}, and significant responses to applied N up to this critical value were observed (cf. Figure 2, 4 and 5). Although approximately half of the soils in our study had available P contents below the critical range indicated above, we observed significant responses to applied P in soils with somewhat greater P availability (Figure 4) and did not observe better responses in soils with less P available. Approximately two thirds of the soils in our study had exchangeable K values above the critical K range of reference, but response to K was observed in soils with up to 0.4 cmol$_+$ K kg^{-1} (cf. Figure 4). These results question the validity of the critical thresholds referred to outside the conditions (of soil, climate and farming systems) from which they were derived.

4.4 Water stress

The observed variability in fertilizer response was not only related to differences in native nutrient supply but was also due to differences in water stress during early plant growth. In case rainfall during the first 3 MAP was limited, both the increase in source (i.e. above-ground biomass) and sink capacity (i.e. number of storage roots per plant) due to fertilizer were less than if rainfall during initial growth was sufficient (Figure 6d and f). This translated in reduced yield responses to fertilizer (Figure 6b). Water stress during early growth (1-5 months) is known to reduce the number of storage roots per plant and has severe implications for root yield as this period is critical for storage root initiation (Connor et al., 1981; Duque et al., 2008). Seasonal water stress after 3 to 4 MAP did not affect fertilizer response (De Tafur et al., 1997b). Cassava exhibits strong defence mechanisms against prolonged seasonal droughts, which include, amongst others, partial stomatal closure, ability to maintain reasonable net photosynthetic rates, leaf area reduction, leaf folding and extraction of water from deeper soil layers (De Tafur et al., 1997b; Alves, 2002; El-Sharkawy, 2004; El-Sharkawy, 2007). In addition the crop has the ability to recover from a seasonal drought period and compensate for its adverse effects through an increase in leaf canopy area and by higher photosynthetic rates in the newly developed leaves. Thus, water stress before 3 to 4 MAP reduces the response to fertilizer as it limits the formation of additional sink (i.e.

storage roots) and source (i.e. above-ground biomass) capacity, while seasonal water stress after 3 to 4 months does not affect fertilizer response as the source capacity is able to quickly recover from the experienced stress and can fulfil the carbohydrate demand of the sink.

4.5 Weed competition

As expected, weed management had a positive effect on the yields of unfertilized cassava fields (Fig 7a) and was more important when plant vigour in early growth stages is poor (Figure 7c; Figure 8). The slow initial growth of cassava renders the crop particularly vulnerable to weed competition in the first three months after planting and uncontrolled weed growth may reduce yields by 50-65% (Melifonwu, 1994; Doll et al., 1982, quoted in Leihner, 2002). Once complete ground cover is reached, cassava shades out weeds (Melifonwu, 1994). Plants that received fertilizer grew faster, enabling the crop to reach complete ground cover earlier (Figure 8; Pellet and El-Sharkawy, 1997). Consequently, weeds were shaded out earlier in fertilized plots and weed management in fertilized cassava fields only paid off when plant development in early growth stages was slow (Figure 7b and d). Considering that in East Africa farmers weed cassava fields on average 4.5 times and spend 60% of all labour used on cassava on weeding (Fermont, unpublished), fertilizer use has a considerable potential to reduce labour requirements of cassava. This potential reduction in labour for weeding through the introduction of fertilizer was not taken into account in the economic analysis (Table 5). With fertilizer use, the canopy closes within approximately 3 MAP (Fig 8) and the number op weed operations could possibly be reduced from 4.5 to 2. This could potentially improve the VCR by approximately 26% and translate into a reduction of the economic threshold for fertilizer use from a yield response of 4 t ha^{-1} to 3 t ha^{-1}.

4.6 Effect of fertilizer on pests and diseases

The use of balanced NPK fertilizer has been recommended for the control of pests and diseases, in particular for bacterial blight, as it encourages plant vigour (Figure 8) and thus reduces the effect of early attacks in the rainy season when plants are still vulnerable (Persley et al., 1976). The effect of fertilizer on pest and diseases in our trials was variable and apparently depended on local conditions. Overall, fertilizer decreased green mite pressure on all genotypes, but increased cassava mosaic virus on susceptible genotypes and slightly increased bacterial blight and anthracnose pressure (Fig 9a-d). Previous reports on the effect of fertilizer on bacterial blight and mosaic disease were contradictory. Some authors (Obigbesan and Matuluka, 1977; Mollard,

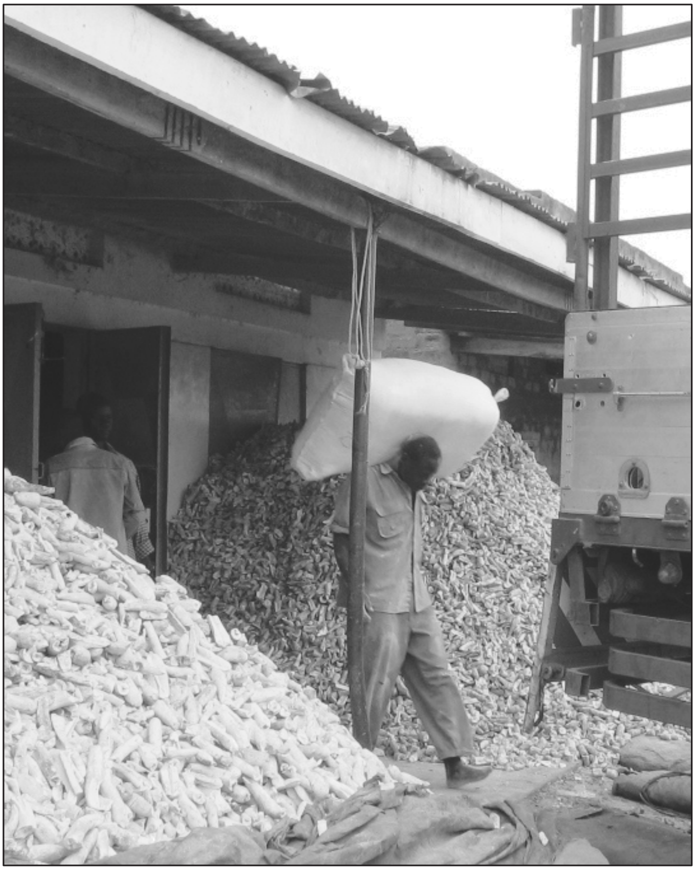
1987) reporting an increase, others (Sseruwagi et al., 2003; Zinsou et al., 2004) reporting no effect of fertilizer, while Adeniji and Obigbesan (1976) and Odurukwe and Arene (1980) found a decrease due to fertilizer application. Nonetheless, changes in pest and disease pressure due to fertilizer were small in our trials and did not affect the yield response of cassava to fertilizer use.

5. Conclusions

The response of cassava to fertilizer in Kenya and Uganda was governed by soil fertility conditions, rainfall during initial growth stages and weed management in case of slow initial plant growth. The high variability in fertilizer response, even on infertile soils, is an indication that interactions between these factors are important and should be considered when developing fertilizer recommendations for cassava. Although profitability of fertilizer use varied strongly between sites and years, the high returns to investment in 2005 (90% of the fields had a VCR > 2) shows that there is a huge scope to use fertilizer to increase cassava productivity and profitability on smallholder farms in Africa. This is so even with the current high fertilizer and relatively low cassava prices. Fertilizer use did not negatively affect cassava properties that are of interest in commercial cassava production (e.g. dry matter content, root weight, percentage of marketable roots) nor did it considerably change pest and disease pressures. Various practices may improve the profitability of fertilizer. They include (i) reducing the risk of water stress during the first 3-4 MAP through planting at the start of the rains and promotion of management practices that improve infiltration of rainwater and/or reduce evaporation from the soil surface; (ii) proper weed management in case of slow plant development; (iii) resolving possible micro-nutrient deficiencies (e.g. Zn); and (iv) determining the economic optimal rate of NPK fertilizer. The expected development and increases in prices of food, feed and especially industrial markets for ethanol and starch in Africa will strongly increase the demand for cassava and will require farmers to adopt technology packages that improve both productivity and profitability of cassava production. It is without doubt that fertilizer should be a key component of such packages in Africa, as it is currently in Asia and Latin America.

Chapter 6

Exploring the effect of management on sustainability indicators in cassava-maize based systems



Abstract

We present an exploratory study to assess the potential impact of different management options on sustainability indicators in cassava-maize based farming systems in western Kenya. We combined the SOC (Soil Organic Carbon) module of the FIELD model with boundary line functions describing yield and biomass versus SOC at three Management regimes. Though the approach is simple and does not take into account other production constraints, it brings out interesting themes that will be worthwhile to explore using more detailed models. Our simulations suggest that in addition to producing larger yields, cassava may also have a small positive impact on SOC development (ca. +6% in 10 years) and on nitrogen recycling, whereas SOC levels under maize may decline (ca. -8% in 10 years), if planted on infertile soils (SOC = 5 g kg^{-1}). This may explain why farmers increased cassava cultivation when soil fertility declined and why farmers consider cassava a ‘soil fertility regenerator’. Cassava genotypes that were widely adopted to control the cassava mosaic disease pandemic have similar yields, biomass production, dry matter and nutrient concentrations as popular landraces. Their introduction did therefore not have an impact on farming system sustainability. Recently developed genotypes combine disease resistance with a higher yield potential, and produce more biomass. Their introduction will improve farm productivity and increase nutrient removal, but may simultaneously have a positive impact on SOC content, and also on nutrient availability for the subsequent crop due to increased nutrient recycling through crop residues. Similarly, improving crop management will have positive effects on the short-medium term, but may negatively influence system sustainability on the long term through nutrient removal. Management options to improve the nutrient balance include fertilizer use and improving cassava stem management. Farmers return ca. 20% of the stems to the field after harvest, using the remainder as planting material and fuel. If farmers adopt recently developed genotypes, they can return larger proportions of the stems, without compromising on other uses, and partially compensate for increased nutrient removal through larger yields. Our simulations suggest that labour can best be targeted to all crops on more fertile fields and fertilizer to maize and subsequently recent developed cassava genotypes on more infertile fields for the largest gains in yield and SOC. Nutrient redistribution from deeper soil layers to the topsoil through crop residues may be important in maintaining nutrient availability in the topsoil. Quantifying this will improve our understanding of the potential positive contributions cassava can make to maintaining system productivity.

Keywords: Boundary line functions, Genotypes, Management, Nutrient recycling, Modelling, Smallholder farms, Soil organic carbon, Sub-Saharan Africa

1. Introduction

The studied farming systems in East Africa have undergone three major interrelated changes during the past few decades: i) increasing land pressure has resulted in continuous cultivation systems, with virtually no fallow; ii) soil fertility has declined; and iii) the importance of cassava cultivation has increased substantially (Chapter 3). Besides, cassava production has been seriously affected by the cassava mosaic disease (CMD) pandemic in the past fifteen years and is now under threat from the rapidly spreading cassava brown streak disease (CBSD) epidemic (Legg et al., 2006).

At present, cassava and maize account for 58 and 82% of the annually cropped acreage of the studied systems in Uganda and western Kenya, respectively. The evolution of these systems, in terms of productivity and soil fertility, thus strongly relies on cassava genotypes, crop management, integrated pest management (IPM) and integrated soil fertility management (ISFM) practices used in cassava and maize fields. Current crop management is below optimal, with late planting in relation to the rains and poor weed management (Chapter 2 and 4). Farmers have widely adopted an initial set of improved cassava genotypes that were released about ten years ago to control the CMD pandemic and includes Nase 3 (TMS 30572) (Legg et al., 2006). Recently developed genotypes combine virus resistance with higher productivity (Ntawuruhunga, pers. comm.). Management of crop residues varies between the two crops with approximately 20, 100 and 76 % of cassava stems, cassava leaves at maize stover, respectively, returned to the field after harvesting (Tittonell, 2003; Chapter 3). Like in large areas of Africa, little manure and fertilizer is used, though more is used with maize in western Kenya than in Uganda (Kelly, 2006; Chapter 2). Nonetheless, there is an increasing consensus among African leaders that mineral fertilizers are essential in Africa to counteract declining soil fertility and improve agricultural productivity. Both cassava and maize respond well to fertilizer use in East Africa (Vanlauwe et al., 2006; Tittonell et al., 2008; Chapter 5).

A sustainable system is often defined as a system that meets the needs of the present without compromising the ability to meet future needs (Pearce et al., 1989). Several indicators are used to evaluate the sustainability of farming systems. These include nutrient balances at field and farm level, crop productivity, soil quality parameters (with an emphasis on soil organic carbon (SOC)), income and labour productivity (Stoorvogel and Smaling, 1990; O'Callaghan and Wyseure, 1995; Tittonell et al., 2007b). The objective of this study is to explore the potential impact of management changes in cassava-maize based farming systems on the short to medium term evolution of soil quality and productivity indicators. Specific research questions focus on the impact of observed and possible future management changes on these indicators and include the impact of: i) increasing cassava cultivation; ii) adoption of higher yielding cassava genotypes; iii) adoption of improved crop management and; iv) adoption of fertilizer use. We further explore the impact of changes in cassava residue management to improve system sustainability. This study focuses on western Kenya because of i) the importance of cassava and maize in this area and; ii) the relatively poor soil fertility, which is common with continuous cropping in areas with high land pressure.

2. Materials and methods

2.1 Cassava trials

To evaluate the yield, above ground biomass and nutrient concentrations of selected cassava landraces versus early released (ER) and recent developed (RD) improved genotypes two sets of trials were used. The first set was installed at the research stations of the Kenyan Agricultural Research Institute (KARI) in Alupe, Busia district in western Kenya (0^o30’N; 34^o08’E) and at the Ugandan National Crops Resources Research Institute (NaCRRI) in Namulonge, Wakiso district in central Uganda (0^o32’N; 32^o37’E). Trials were installed in 2003 and 2004 in Uganda and in 2003 and 2005 in Kenya and included three landraces, one ER genotype and two RD genotypes. Selected landraces included some of the most popular landraces in Uganda (Bao, Nyaraboke and Njule) and Kenya (Matuja, Mwitamigera and Gachaga). In Kenya, Mwitamigera and Gachaga broke down due to severe CMD infections in 2004 and trials were repeated in 2005 with two different CMD tolerant landraces (X-Julia and Fumba Chai). Nase 3 represented the ER in both countries, while the RD genotypes were represented by TME 204 and MH95/0414 (released as Nase 12) in Uganda and MM96/5280 and MM96/4884 in Kenya. Each trial was installed with four repetitions, a net harvest area of 4 m x 5 m, two border rows per plot and a plant spacing of 1 m x 1 m. Weeding was done manually as required. Litterfall was collected from litterfall trays at a weekly basis in selected plots from 5 to 15 MAP. Composite samples were made per genotype for three periods (5-9, 9-12 and 12-15 MAP) and analysed for N, P and K. Trials were harvested between 12 and 15 months after planting (MAP) and fresh yield and fresh above ground biomass were determined. Sub-samples of roots, stems and leaves were taken from each plot and analysed for dry matter content. They were then recombined for each genotype into one composite sample for roots, stem and leaves per trial and analysed for N, P and K using standard methods (Okalebo et al., 2002).

A second set of trials was installed to evaluate the performance of Nase 3 versus MM96/5280 and I92/0067 in Kenya and Uganda, respectively, with and without 100-22-83 kg ha^{-1} N-P-K fertilizer in the heterogeneous conditions of farmer's fields. See Chapters 4 and 5 for more details.

2.2 Model description

To explore the short to medium term consequences of several management options on crop productivity and soil quality indicators, we used a modeling approach. Several independent cassava models or cassava modules within a larger modeling framework (e.g. DSSAT) exist, however, none of them are calibrated for African conditions and genotypes (Boerboom, 1978; Cock et al., 1979; Matthews and Hunt, 1994; Singh et al., 1998). Work is ongoing to develop a cassava crop model within FIELD, the crop and soil sub-model of FARMSIM, a bio-economic model developed to analyze trade-offs around farming systems and environments in Africa (Tittonell et al., 2007a; 2008b). The FIELD model is based on the principles of production ecology and defines yields in four steps: potential yield, water limited yield, N, P and K limited yield and yield reduced due to weed competition. Owing to the lack of a functional cassava model yet, we resorted to combining the SOC module of field with boundary line functions describing yield and biomass production versus SOC as observed in farmer fields in western Kenya. Jones (1972) and Foster (1981) suggested that SOC can be used as an indicator for soil fertility in East Africa as it is closely linked to available N and P. The boundary line functions may therefore be interpreted as an approximation of nutrient limited yields, whereby observations beneath the boundary lines represent actual yields limited by other production constraints.

2.2.1 Soil organic matter model

The SOC module of FIELD follows the conceptual model of SOC stabilisation of Six et al. (2002). This concept considers three functional pools of organic C: i) a fresh C pool, which consists of newly added C in the form of crop residues and other organic amendments; ii) an active C pool of decomposing organic matter that is not yet 'protected'; iii) a stable C pool that represents the older physically and chemically stabilised organic matter (see Figure 1). The pools are assumed to decompose according to first-order kinetics, whereby each pool has a specific decomposition rate (kR, kA, kS and kI) and a constant turnover fraction (eA, eH and eS) that (re)enters the (next) pool. Thus the change in the stable C pool over time is defined as:

$$dCS/dt = CA \times kA \times eH - CS \times kS + CS \times kS \times eS \qquad (1)$$

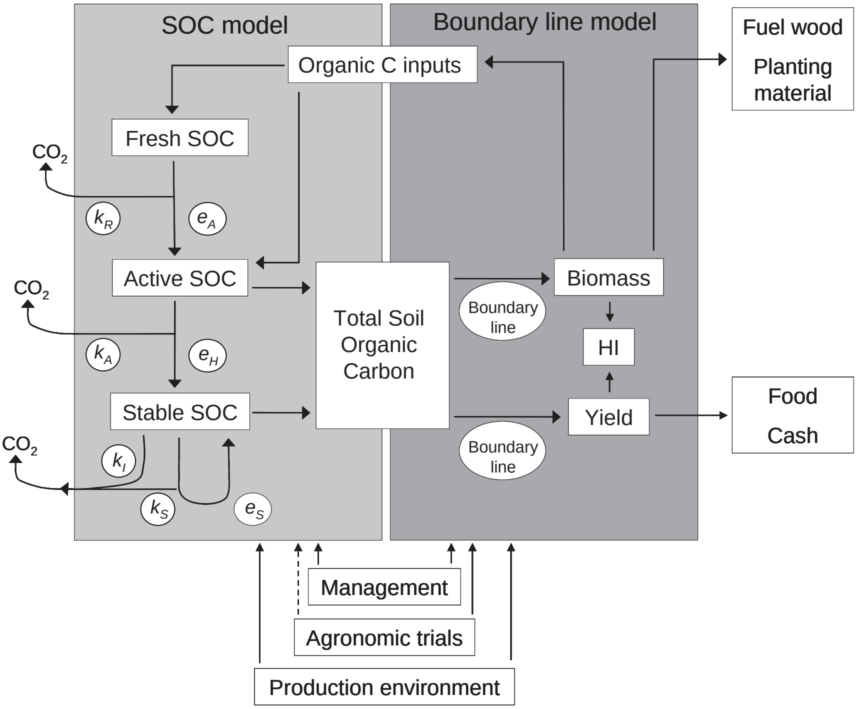


Figure 1: Schematic overview of the combined SOC and Boundary line models. Soil organic carbon in the soil is divided into three pools (fresh, active, and stable). The pools decompose according to a constant rate (*kR*, *kA*, *k*S and *kI*) and have a constant turnover fraction (*eA*, *eH* and *eS*) that (re)enters the (next) pool. The active and stable pools add up to the total soil organic carbon amount in the soil. Boundary line functions are used to calculate yield and biomass and the organic C input into the soil.

whereby *CS* and *CA*, *kA* and *kS*, and *eH* and *eS* are the amounts of C, the decomposition rates and the turnover fractions of the stable (S) and active (A) pools, respectively. The minimum content of SOC observed in the top soil (0-20 cm) of the cassava data set (3.5 g kg^{-1}) was taken as the initial size of the inert C pool. A constant bulk density was used to convert the total SOC as expressed in kg in the top 20 cm of the soil to SOC contents as expressed in g kg^{-1}. This was used as an input variable in the boundary line functions (see below) to calculate expected cassava and maize yield, stover and/or above ground biomass production for each time step. The SOC model, which was developed for maize, uses a seasonal time step. For cassava the model was adjusted to accommodate the crop's annual growth cycle and the production of litterfall. For maize the newly added C into the next time step is defined as:

$$C_{maize} = C_{stover} + C_{maize\ root} \qquad (2)$$

whereby C_{stover} and $C_{\text{maize root}}$ are the amounts of C added through maize stover and root residues. For cassava the newly added C into the next time step is defined as:

$$C_{cassava\text{-}1} = C_{litterfall\text{-}1} \tag{3}$$

$$C_{cassava\text{-}2} = C_{leaf} + C_{stem} + C_{cassava\ root} + C_{litterfall\text{-}2} \tag{4}$$

whereby $C_{litterfall\text{-}1,}$ C_{leaf}, C_{Stem}, $C_{cassava\ root}$ and $C_{litterfall\text{-}2}$ are the amounts of C added through cassava litterfall in the first season and the amounts of C added through cassava leaves, stems, fine roots and litterfall in the second season, respectively. For maize, C_{stover} and $C_{maize\ root}$ are defined as:

$$C_{stover} = Stover \times F_{retained} \times \mathrm{C}_{\%\mathrm{stover}} \tag{5}$$

$$C_{maize\ root} = Stover \times F_{root} \times C\%_{maize\ root} \tag{6}$$

whereby *Stover* is the produced stover in the previous time step, $F_{retained}$ is the fraction of biomass retained in the field after harvesting, F_{root} is the ratio of root residues to stover and $C\%_{stover}$ and $C\%_{maize\ root}$ are the C contents of stover and root residues, respectively. Similarly, C_{leaf}, C_{stem}, and $C_{cassava\ root}$ are determined for cassava, based on above ground biomass production, fraction of leaves and stems retained in the field after harvest, the stem/leaf ratio at harvest and the C contents of leaves, stems and roots. We assumed that 20% of the maize stover and 50% of the cassava stems directly entered the stable C pool. Maize stover retention in the field after harvest was taken as 76% as determined by Tittonell (2003) for a site in western Kenya that has a comparable farming system to the ones found in our study area. Retention fractions for cassava leaves and stems were observed in the field as 100 and 20% (with the remained used as planting material or fuel wood), respectively. C content of various maize and cassava parts was assumed to be 45%. Cassava litterfall was estimated at 27% of total dry matter production, e.g. roots + above ground biomass (Carsky and Toukourou, 2003), whereby one third is produced during the first and two thirds during the second half of the growth cycle (based on Carsky and Toukourou, 2003).

2.2.2 Definition of boundary lines

We used agronomic data for maize and cassava to develop boundary line functions describing the yield and biomass production under non-fertilized and fertilized conditions versus SOC, following the approach outlined in Chapter 4. Boundary line functions for cassava were based on the second set of on-farm cassava trials in western Kenya described above and in Chapter 4 and 5. Boundary lines for maize were based

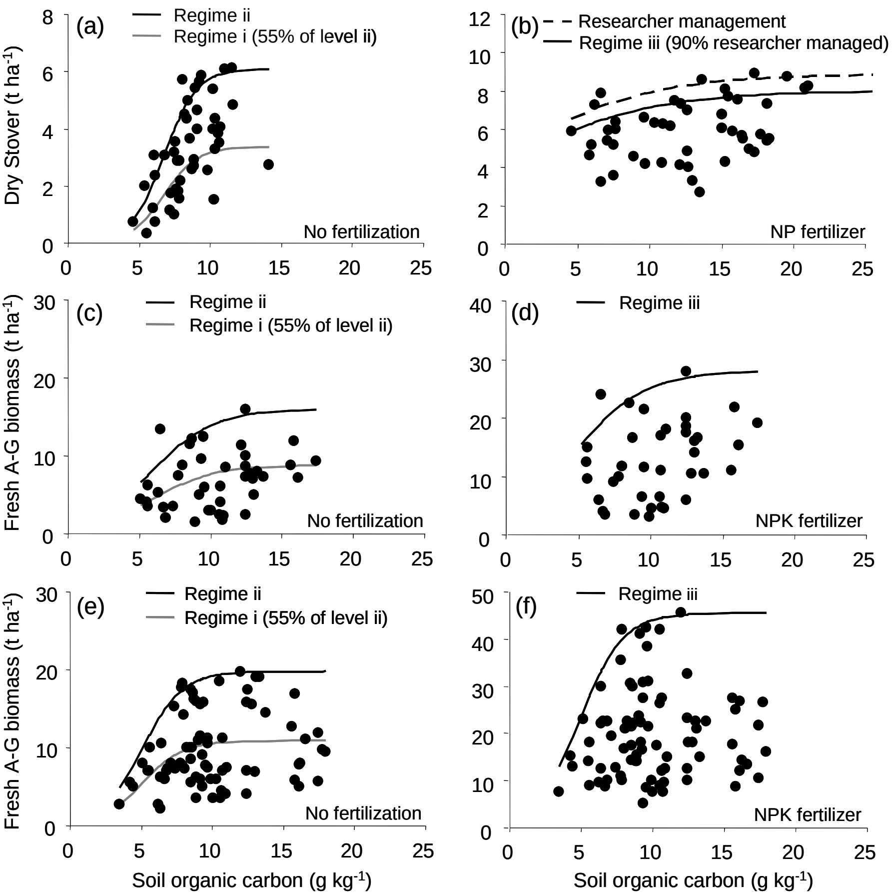


Figure 2: Boundary line functions describing the relation between soil organic carbon and dry maize stover (a, b) and between soil organic carbon and fresh above ground biomass of early released (ER) (c,d) and recently developed cassava genotypes (e,f) for management regimes i (farmer management) and ii (optimal crop management) (a,c,e) and management regime iii (optimal crop management + NPK fertilizer)(b,d,f). See text for more details.

on two data sets from western Kenya. Unfertilized maize data were obtained from a field study in 2002 of 48 farmer fields in Aduleka, a village in Teso district that is very closely located to Kwang'amor (Tittonell, 2003). Fertilized maize data were obtained from researcher-managed agronomic trials in 2003 on 52 farmer fields in three sites in western Kenya, which included Aduleka (Vanlauwe et al., 2006), whereby maize (HB 513) was grown with NP fertilization (100-100-0 kg ha^{-1} N-P-K) as no response was observed for K. Soil conditions in the cassava and maize data sets were comparable.

The obtained boundary line functions describe the relation between SOC versus yield and biomass production for management regimes ii and iii (See section 2.2.4), e.g.

unfertilized and fertilized production with optimal farmer management (and no other limitations). To account for the researcher management of the fertilized maize trials, the boundary lines for fertilized maize were adjusted downward by 10%. Boundary line functions for management regime i (current farmer management, see below) were defined as a fraction of the unfertilized boundary line functions. The reduction factors for Nase 3 and maize were based on the average SOC content in the cassava trials (8.9 g kg^{-1}) and average cassava and maize yields (6.8 and 1.1 t ha^{-1}) as observed in independent farm surveys in the area (Chapter 2 and 3). Reduction factors for stover/above ground biomass were considered similar to those of yield and the reduction factors for MM96/5280 were considered similar to those of Nase 3. Figure 2 shows the boundary line functions for maize stover and above ground biomass production of ER and RD cassava genotypes.

2.2.3 Model calibration, sensitivity analysis and assumptions

The soil organic matter model was parameterised using long-term chronosequence data for Machanga, western Kenya which has soils and climate similar to our study area (Tittonell et al., 2008b). Simulated yield and stover/above ground biomass were used to determine harvest indices and relations between yield and harvest index. In case simulated relationships differed from those observed in the agronomic trials, boundary lines were slightly adjusted until the model outcomes showed similar patterns as the field observations. A sensitivity analysis of the SOC model showed that changes of 50% in input variables caused a relative small change of 2-12% in SOC and yield over a period of 50 years, except for changes in % DM roots which caused larger changes in cassava yield. We assumed that SOC development is not affected by erosion as most fields in our study areas are situated on flat to slightly sloping land that showed no to limited signs of water and wind erosion.

2.2.4 Scenarios analysed

Crops

As indicated above, this study focuses on cassava and maize, the two major staple food crops in the studied farming systems of western Kenya. For cassava we included two distinctly different groups of genotypes (see Section 3.1): landraces + ER genotypes versus RD genotypes. The first group is represented by Nase 3 which has been widely adopted by farmers (Legg et al., 2006), while the second group was represented by MM96/5280, an average yielding genotype among the recently-developed introductions in western Kenya (Ntawuruhunga et al., 2004).

Management regimes

The model was run for three regimes of increasing management intensity: i) current farmer practice; ii) optimal crop management and iii) optimal crop management + NP(K) fertilizer.

Soil fertility status

The model was run for two contrasting soil types: an infertile soil with an initial SOC content of 5 g kg^{-1} and a medium fertile soil with an initial SOC content of 15 g kg^{-1}. Initial SOC contents of the medium fertile and low fertile soil are based on the minimum and maximum SOC values observed in the cassava data sets.

Cassava stem management

Farmers currently return 20% of the cassava stems after harvest to the field, while they use the remaining 80% as planting material and fuel wood (Fermont et al., 2008). To explore the effect of returning a larger proportion of cassava stems to the field, the model was run for the RD genotype with 20, 50 and 75% of the stems returned.

2.2.5 Calculation of partial nutrient balances

Partial nutrient balances (kg ha^{-1} yr^{-1}) were calculated at field level for each combination of crop/genotype group × soil type × management regimes on the basis of removal of harvest products (OUT1), removal of crop residues (OUT2) and fertilizer (IN1). OUT1 and OUT2 were calculated by multiplying the respective quantities of dry matter with average N, P and K concentrations of maize grain, maize stover, cassava roots, stems and leaves. IN1 for management regime iii was taken as the fertilizer rates used in the agronomic trials. To account for the amount of nutrients returned to the soil in the form of crop residues retained in the field after harvest, the 'recycled amounts' of N, P and K were calculated by multiplying the respective quantities of dry matter with average N, P and K concentrations of stover, stem, leaf and litterfall material. Partial nutrient balances and amounts of recycled nutrients were calculated on an annual basis for a period of 10 years and the average annual nutrient balance and nutrient recycling rates were calculated.

For each combination of crop/genotype × soil type × management regime the average annual C input into the soil through crop residues and the average annual change in soil C was calculated for a period of 10 years.

3. Results and discussion

3.1 Trials

Cassava landraces and the ER genotype performed similarly in terms of root and above ground biomass production and dry matter concentrations in root, stems and leaves, except for above ground biomass in the KARI station. RD genotypes produced significantly (*P*<0.05) more yield than landraces and ER genotypes in both on-station and on-farm locations (Table 1). They also produced more above ground biomass, though not always significant, and generally had higher root dry matter contents (P<0.05). Nutrient concentrations in the roots, stems and leaves generally did not vary between genotype groups or sites, though landraces in Uganda contained significantly (*P*<0.05) more N and P in the roots than ER and RD genotypes and cassava stems contained significantly (*P*<0.001) more P in Uganda than in Kenya (Table 2). The latter may be related to more available P in the soil at the NaCRRI station in Uganda than at the KARI station in Kenya (Chapter 4). Litterfall contained on average 2.48% of N, 0.17% of P and 1.36% of K and nutrient concentrations did not vary between genotype groups. Litterfall contained significantly (*P*<0.01) more K in Kenya than in Uganda, though exchangeable K contents were smaller in Kenya than in Uganda (Chapter 4). Overall, nutrient concentrations were in the same range as observed by Howeler (1985, quoted in Howeler (2002)) in Colombia, except for root and leaf N and litterfall K which were larger and stem P which was smaller in our trials.

Table 1: Averages and standard deviations for fresh cassava yield (t ha^{-1}), fresh above ground biomass (t ha^{-1}) and dry matter content (%) of roots, stems and leaves by genotype group for two sets of trials in Kenya and Uganda

	Yield		Above ground biomass		Dry matter content			
					Roots		Stem	Leaves
	Station [1]	Farmer [2]	Station	Farmer	Station	Farmer	Station	Farmer
Kenya								
Landraces	8.4 ± 3.7	-	10.2 ± 4.3	-	31 ± 3	-	25 ± 4	20 ± 5
ER genotypes	10.8 ± 4.3	8.8 ± 4.7	6.7 ± 3.0	6.9 ± 3.6	27 ± 2	36 ± 4	26 ± 3	23 ± 2
RD genotypes	12.4 ± 6.3	12.4 ± 5.7	12.6 ± 4.5	10.9 ± 6.4	34 ± 2	38 ± 5	28 ± 7	20 ± 4
means	*10.1 ± 5.0*	*11.1 ± 5.7*	*10.4 ± 4.6*	*9.5 ± 5.9*	*31 ± 3*	*37 ± 5*	*26 ± 5*	*21 ± 5*
P	*<0.05*	*<0.001*	*<0.01*	*<0.001*	*<0.001*	*<0.05*	*ns*	*ns*
Uganda								
Landraces	11.3 ± 6.6	-	14.7 ± 9.7	-	35 ± 3	-	28 ± 5	28 ± 2
ER genotypes	8.5 ± 8.6	13.3 ± 3.9	13.6 ±15.2	17.4 ± 8.6	35 ± 1	35 ± 5	29 ± 4	30 ± 0
RD genotypes	17.1 ± 8..0	17.8 ± 4.9	23.6 ± 11.9	24.5 ± 12.6	38 ± 2	36 ± 5	32 ± 3	28 ± 2
means	*12.8 ± 7.9*	*16.2 ± 5.0*	*17.5 ± 12.0*	*22.4 ± 11.9*	*36 ± 3*	*36 ± 5*	*30 ± 4*	*29 ± 2*
P	*<0.05*	*<0.01*	*<0.05*	*<0.05*	*<0.001*	*ns*	*0.05*	*0.05*

[1] On-station trials were installed in 2003 and 2004 in Uganda and in 2003 and 2005 in Kenya with 3 landraces, 1 early released (ER) genotypes and 2 recent developed (RD) genotypes and four repetitions per trial. For details on cassava genotypes used, see footnotes in Table 2. n = 96.

[2] Trials were installed in 2004 and 2005 in mainly on-farm field and a few on-station fields in Uganda and Kenya with 1 early released (ER) genotype (2004) and 1 recent developed (RD) genotype (2004 and 2005) per trial. Each farmer was considered a repetition. More details are given in Chapter 4 and 5. n = 162.

Table 2: Averages and standard deviations for N, P and K concentrations (%) in cassava roots, stems and leaves by site and genotype group for the on-station trials in Uganda (NaCRRI) and Kenya (KARI)

Site	n	Roots			Stems			Leaves		
Genotype group		N	P	K	N	P	K	N	P	K
KARI										
Landrace[1]	16	0.68 ± 0.16	0.07 ± 0.01	0.87 ± 0.10	1.04 ± 0.24	0.08 ± 0.03	1.07 ± 0.38	4.60 ± 0.75	0.30 ± 0.07	1.64 ± 0.26
ER genotype[2]	6	0.73 ± 0.11	0.09 ± 0.01	0.83 ± 0.09	1.06 ± 0.22	0.07 ± 0.02	1.03 ± 0.32	4.53 ± 0.89	0.24 ± 0.04	136 ± 0.25
RD genotype[3]	10	0.54 ± 0.09	0.09 ± 0.01	0.68 ± 0.12	1.07 ± 0.17	0.09 ± 0.01	1.35 ± 0.30	4.63 ± 0.71	0.29 ± 0.07	1.67 ± 0.34
Means	*32*	*0.65 ± 0.15*	*0.08 ± 0.01*	*0.82 ± 0.11*	*1.06 ± 0.21*	*0.08 ± 0.02*	*1.14 ± 0.36*	*4.60 ± 0.74*	*0.29 ± 0.07*	*1.60 ± 0.29*
P		*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	ns
NaCRRI										
Landrace[4]	16	0.80 ± 0.23	0.11 ± 0.03	0.86 ± 0.19	1.08 ± 0.20	0.16 ± 0.05	1.32 ± 0.47	4.31 ± 0.80	0.30 ± 0.06	1.31 ± 0.35
ER genotype[2]	4	0.63 ± 0.10	0.09 ± 0.01	0.53 ± 0.12	1.06 ± 0.16	0.10 ± 0.02	0.91 ± 0.21	4.95 ± 0.69	0.29 ± 0.05	1.06 ± 0.13
RD genotype[5]	12	0.57 ± 0.07	0.09 ± 0.03	0.66 ± 0.13	1.10 ± 0.33	0.17 ± 0.05	1.01 ± 0.43	4.45 ± 1.14	0.31 ± 0.07	1.29 ± 0.37
Means	*32*	*0.70 ± 0.20*	*0.10 ± 0.03*	*0.74 ± 0.20*	*1.10 ± 0.26*	*0.16 ± 0.05*	*1.15 ± 0.46*	*4.45 ± 0.93*	*0.30 ± 0.06*	*1.27 ± 0.34*
P		*< 0.05*	*ns*	*< 0.01*	*ns*	*< 0.05*	*ns*	*ns*	*ns*	*ns*
Overall means	*64*	*0.68 ± 0.18*	*0.09 ± 0.02*	*0.75 ± 0.19*	*1.04 ± 0.24*	*0.12 ± 0.05*	*1.15 ± 0.42*	*4.60 ± 0.75*	*0.30 ± 0.07*	*1.38 ± 0.3*
P (sites)		*ns*	*ns*	*ns*	*ns*	*0.001*	*ns*	*ns*	*ns*	*0.01*

[1] Landraces in Kenya are represented by Matuja, Gachaga and Mwitamigera in the 2003 trials and Matuja, X-Julia and Fumba Chai in the 2005 trials.

[2] Early released (ER) genotypes in Kenya and Uganda are represented by Nase 3 (TMS 30572).

[3] Recent developed (RD) genotypes in Kenya are represented by MM96/5280 and MM96/4884.

[4] Landraces in Uganda are represented by Bao, Nyaraboke and Njule.

[5] Recent developed (RD) genotypes in Uganda are represented by Nase 12 and TME 204.

3.2 The effect of management on sustainability indicators of cassava-maize systems

3.2.1 Increasing cassava cultivation (Management Regime i)

Our simulations indicate that, under current farmer management and using cassava landraces, cassava cultivation on low fertility soils (5 g kg^{-1} SOC) may result in slightly improving SOC contents (ca. 6% in 10 years), whereas maize cultivation may result in gradually declining SOC contents (ca. 8% in 10 years; Figure 3a). Cassava landraces produce more biomass than maize on infertile soils (Figure 2a and c), which translates into roughly two times larger annual C inputs for cassava (Table 3). It also translates into approximately four times more nitrogen recycling than for maize (Table 3). These results are in line with farmer perceptions in both East and West Africa that cassava regenerates soil fertility and has a positive effect on the subsequent crop (Carsky and Toukourou, 2003; Obiero, 2004; Adjei-Nsiah et al., 2007) and suggest that the effect of cassava cultivation on low fertility soils goes beyond increasing easily accessible nutrients for the next crop as anticipated earlier in Chapter 3. Taking into account as well the roughly five times larger yields for cassava landraces than for maize on infertile soils (Figure 3b), the substantial increase in cassava cultivation that has been observed in high land pressure areas in East Africa is a logical move, both in terms of maintaining soil fertility and in terms of maintaining crop productivity in infertile parts of the farm. On more fertile soils (15 g kg^{-1} SOC) yield levels of cassava landraces and maize under farmer management are similar (ca. 2.5 t ha^{-1} year^{-1} dry matter yield), and our simulations suggest that cassava cultivation on these soils may have a more negative effect on SOC contents than maize cultivation (Figure 3a and b).

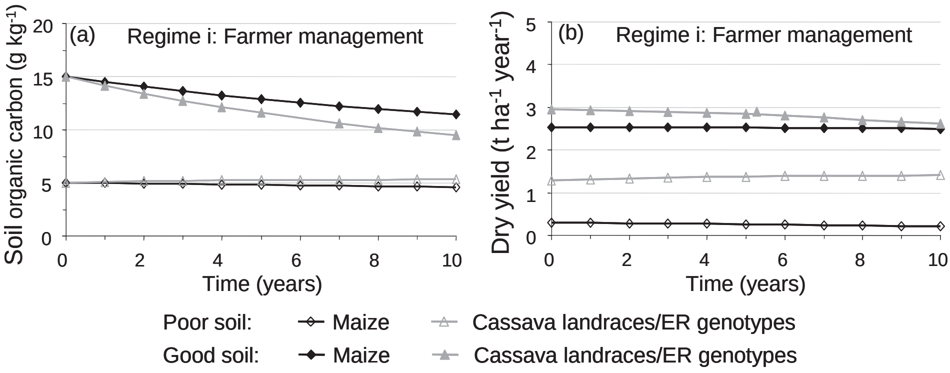


Figure 3: Changes in soil organic carbon and annual dry matter yield over a 10 year period for maize and cassava landraces/early released (ER) genotypes planted on an initially infertile soil (5 g kg^{-1} SOC) and a more fertile soil (15 g kg^{-1} SOC) under Management regime i (farmer management).

Table 3: Average annual C budget, partial nutrient balances and nutrient recycling for N, P and K (kg ha^{-1} yr^{-1}) for a 10 year period for maize and two cassava genotype groups grown on an initially infertile (SOC = 5 g kg^{-1}) and a more fertile (SOC = 15 g kg^{-1}) soil under three Management regimes

Management regime		Annual C budget		Annual partial nutrient balance			Annual nutrient recycling		
Soil fertility status	Crop/ Genotype group	C input	Change in soil C	N	P	K	N	P	K
Regime i: Farmer management									
Infertile	Maize	581	-104	-5	-1	-7	6	1	18
	Cassava landrace/ER	1401	87	-17	-2	-19	26	2	13
	Cassava RD	2120	296	-33	-4	-36	46	3	24
Fertile	Maize	3522	-966	-46	-7	-47	36	6	112
	Cassava Landrace/ER	2005	-1538	-37	-5	-40	55	4	29
	Cassava RD	2752	-1332	-54	-7	-58	75	5	40
Regime ii: Optimal crop management									
Infertile	Maize	1546	232	-16	-2	-19	15	3	48
	Cassava landrace/ER	2007	265	-39	-5	-43	56	4	29
	Cassava RD	3331	689	-80	-10	-87	106	8	57
Fertile	Maize	6463	-48	-83	-13	-86	65	11	204
	Cassava landrace/ER	3128	-1208	-76	-9	-83	110	8	57
	Cassava RD	4268	-893	-109	-14	-119	149	11	79
Regime iii: Optimal crop management + NP(K) fertilizer									
Infertile	Maize	7332	2096	-31	80	-110	74	13	232
	Cassava landrace/ER	3185	681	16	12	-8	131	9	68
	Cassava RD	5991	1609	-63	2	-95	237	17	125
Fertile	Maize	8184	497	-51	77	-124	82	14	259
	Cassava landrace/ER	4318	-822	-9	9	-36	171	12	88
	Cassava RD	7050	-1	-93	-1	-127	285	20	151

Both crops do not produce sufficient C inputs into the soil under farmer management to maintain the relatively high initial SOC contents, but maize produces more biomass than cassava landraces due to its bi-annual production and relative good growth on more fertile soils (Figure 2a and c, Table 3). Nonetheless, annual nitrogen recycling rates under cassava are still almost double those of maize (Table 3), which may explain why farmers also maintain high cassava cultivation intensities on more fertile soils (Chapter 3).

Annual nutrient balances for all fields were negative, more so for the medium fertile than for the infertile fields (Table 4). Farmers in western Kenya currently use some fertilizer and manure, which they often target to maize fields (Chapter 2). This may offset nutrient removal in fields with poor fertility and have a positive impact on yields and SOC contents in maize fields.

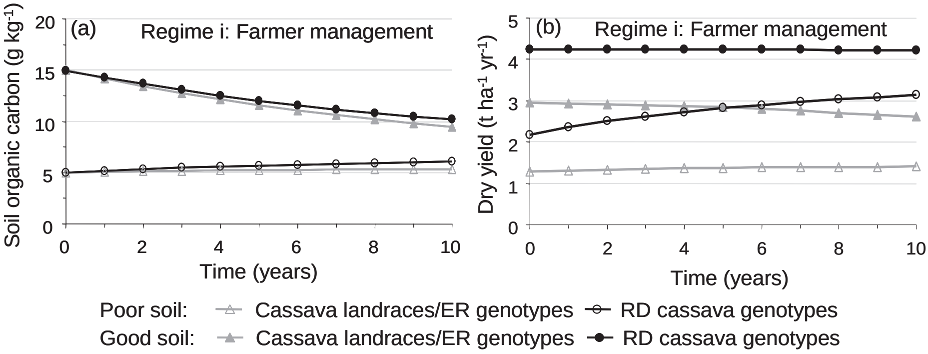


Figure 4: Changes in soil organic carbon and annual dry matter yield over a 10 year period for cassava landraces/early released (ER) genotypes and recently released (RD) genotypes planted on an initially infertile soil (5 g kg^{-1} SOC) and a more fertile soil (15 g kg^{-1} SOC) under Management regime i (farmer management).

Table 4: The absolute and relative average effect of adoption of RD cassava genotypes[1] on cassava yield (t ha^{-1}), SOC (g kg^{-1}) in the topsoil (0-20 cm), partial N balance (kg ha^{-1} yr^{-1}) and N recycling (kg ha^{-1} yr^{-1}) over a period of 10 years on an initially infertile (SOC = 5 g kg^{-1}) and a more fertile (SOC = 15 g kg^{-1}) soil

	Infertile soil				More fertile soil			
	yield	SOC	partial N balance	N recycled	yield	SOC	partial N balance	N recycled
Absolute change	+ 1.4	+ 0.4	- 16	+ 20	+ 1.4	+ 0.4	- 17	+ 20
Relative change	+ 102	+ 8	- 91	+ 78	+ 51	+ 3	- 45	+ 36

[1] Replacement of cassava landraces/early released (ER) genotypes by recent developed (RD) genotypes

3.2.2. Adoption of improved cassava genotypes (Management Regime i)

Nase 3, the most widely adopted ER genotype, did not differ from popular cassava landraces in terms of yield, biomass production, dry matter and nutrient contents. The wide-scale adoption of this genotype (Legg et al., 2006) will therefore not have had an impact on the evaluated sustainability indicators.

In contrast, RD genotypes had significantly higher yields and dry matter contents and more biomass production than cassava landraces and ER genotypes (Table 1; Figure 2c and e; Figure 4b). Obiero (2004) and Ntawuruhunga et al. (2006) reported similar yield advantages of RD genotypes. The replacement of landraces/ER genotypes with RD genotypes under current farmer management may therefore have contradictory effects on soil fertility in the longer term. On the one hand, roughly double the amount of nutrients will be removed through harvest products (Table 3). On the other hand, the additional above ground biomass considerably increases the amount of recycled nutrients available to the subsequent crop and C inputs (ca. + 700 kg ha^{-1} yr^{-1}) into the soil (Table 3). Consequently, our simulations indicate that the adoption of RD genotypes may have a positive impact on SOC contents of both infertile soils (+ ca. 15% over a 10 year period) and medium fertile soils (ca. 10% less decline over a 10 year period) (Figure 4a).

Over a period of 10 years, there is little difference between adopting RD genotypes on infertile or more fertile soils (Table 5). The simulated positive impact on SOC contents and the increased recycling of nutrients through larger biomass return can be expected to have a positive effect on other crops in the rotation.

3.2.3 Adoption of improved crop management (Management Regime ii)

Our simulations suggest that adoption of improved crop management practices (timely planting, correct plant densities, timely weeding) will increase crop yields considerably and may have a positive effect on SOC development over time (Figure 5a and b). Labour is often the most limiting resource for smallholder farmers (Barrett et al., 2002). In case of labour limitations, farmers can best invest this scare resource in the optimalisation of crop management on their most fertile fields, as our simulations indicate that this may result in the largest absolute gains in yield, SOC and nutrient recycling for both crops and both cassava genotypes groups (Table 5). In this case, targeting labour to cassava fields may give the largest gains in yield and nutrient recycling, while targeting labour to maize fields may give the largest gain in SOC. Van Asten et al. (2009) found for rainfed rice production on acid-sulphate soils in Senegal that even though improved rice cultivars and fertilizer gave larger gains in yields and profitability on non-acidic soils than on acidic soils, farmers gave

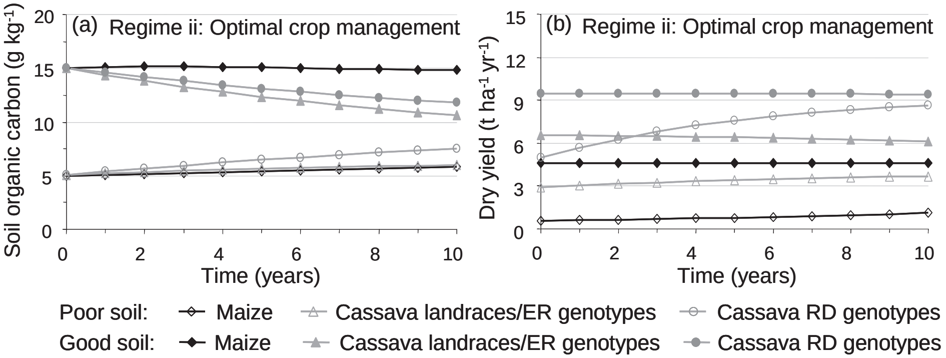


Figure 5: Changes in soil organic carbon and annual dry matter yield over a 10 year period for maize, cassava landraces/early released (ER) genotypes and recently released (RD) genotypes planted on an initially infertile soil (5 g kg^{-1} SOC) and a more fertile soil (15 g kg^{-1} SOC) under Management regime ii (Optimal crop management).

Table 5: The absolute and relative effect of adoption of optimal crop management[1] on yield (t ha^{-1}), SOC (g kg^{-1}) in the top soil (0-20 cm), partial N balance (kg ha^{-1} yr^{-1}) and recycled N (kg ha^{-1} yr^{-1}) for maize and two cassava genotype groups over a period of 10 years on an initially infertile (SOC = 5 g kg^{-1}) and a more fertile (SOC = 15 g kg^{-1}) soil

		Infertile soil				More fertile soil			
		yield	SOC	partial N balance	N recycled	yield	SOC	partial N balance	N recycled
Maize	Absolute change	+ 0.5	+ 0.6	- 10	+ 10	+ 2.1	+ 2.0	- 38	+ 29
	Relative change	+ 212	+ 12	- 197	+ 2	+ 83	+ 15	- 83	+ 83
Cassava - landrace/ER[2]	Absolute change	+ 2.0	+ 0.4	- 22	+ 30	+ 3.6	+ 0.7	- 39	+ 55
	Relative change	+ 146	+ 7	- 126	+ 118	+ 127	+ 6	- 107	+ 99
Cassava – RD[3]	Absolute change	+ 4.5	+ 0.8	- 47	+ 61	+ 5.2	+ 1.0	- 56	+ 74
	Relative change	+ 164	+ 14	- 141	+ 133	+ 123	+ 8	- 104	+ 98

[1] Change from current farmer management (regime i) to optimal crop management (regime ii)

[2] Cassava landraces and early released (ER) genotypes are represented by Nase 3

[3] Recent developed cassava (RD) genotypes are represented by MM96/5280

Table 6: The absolute and relative effect of adoption of fertilizer use[1] on yield (t ha^{-1}), SOC (g kg^{-1}) in the top soil (0-20 cm), partial N balance (kg ha-1 yr-1) and recycled N (kg ha-1 yr-1) for maize and two cassava genotype groups over a period of 10 years on an initially low (SOC = 5 g kg-1) and more fertile (SOC = 15 g kg-1) soil

		Infertile soil				More fertile soil			
		yield	SOC	partial N balance	N recycled	yield	SOC	partial N balance	N recycled
Maize	Absolute change	+ 7.1	+ 3.9	- 15	+ 58	+ 4.6	+ 1.2	+ 32	+ 18
	Relative change	+ 891	+ 73	- 96	+ 379	+ 101	+ 8	+ 38	+ 27
Cassava - landrace/ER[2]	Absolute change	+ 1.9	+ 0.8	+ 55	+ 75	+ 1.1	+ 0.8	+ 67	+ 61
	Relative change	+ 56	+ 14	+ 141	+ 135	+ 18	+ 7	+ 88	+ 55
Cassava – RD[3]	Absolute change	+ 4.5	+ 1.8	+ 17	+ 131	+ 3.7	+ 1.9	+ 16	+ 136
	Relative change	+ 62	+ 28	+ 21	+ 123	+ 39	+ 14	+ 15	+ 92

[1] Change from optimal crop management (regime ii) to optimal crop management +NP(K) fertilizer (regime iii).

[2] Cassava landraces and early released (ER) genotypes are represented by Nase 3

[3] Recent developed cassava (RD) genotypes are represented by MM96/5280

preference to using inputs on the most acidic fields as they reasoned that 'sick soils need to be cured'. East African farmers may also prefer improving crop yields and soil fertility of their poorest fields. In this case, farmers can best target labour to RD genotypes as our simulations indicate this may result in similar SOC gains as targeting labour to maize but in much better yield gains (Table 5).

For both crops and genotypes and both soil types, the adoption of improved crop management practices may roughly double to triple annual nutrient removal rates (Table 3).

3.2.4 Adoption of fertilizer use (Management Regime iii)

Adoption of fertilizer use will increase cassava and maize yields considerably (Figure 3 and Figure 6a; Chapter 4 and 5) and will also increase biomass production (Figure 2b,d and f). Our simulations indicate that under optimal crop management C inputs into the soil may increase by roughly +1000 kg ha^{-1} yr^{-1} for ER genotypes on both soil types to +6000 kg ha^{-1} yr^{-1} for maize on infertile soils (Table 3). This is likely to have a considerable effect on SOC development over time (Figure 6b). Our simulations indicate that, in terms of SOC and yield gains, fertilizer use may best be targeted to maize on infertile soils, followed by RD cassava genotypes on infertile soils, maize on more fertile soils and RD genotypes on more fertile soils (Table 6). Targeting fertilizer to ER cassava genotypes on both soil types seems to result in lowest gains over a period of 10 years due to a less above ground biomass production and a lower yield potential. These findings are in line with findings in Chapter 5 and from Vanlauwe et al. (2006), whose datasets were used for this modelling approach. They observed

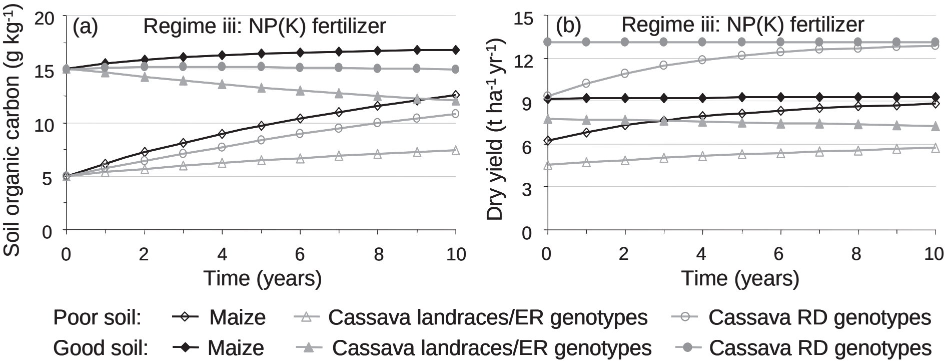


Figure 6: Changes in soil organic carbon and annual dry matter yield over a 10 year period for maize, cassava landraces/early released (ER) genotypes and recently released (RD) genotypes planted on an initially infertile soil (5 g kg^{-1} SOC) and a more fertile soil (15 g kg^{-1} SOC) under management regime iii (Optimal crop management + NP(K) fertilizer).

increasing responses for maize to N and sometimes P with distance to the homestead and/or increasing responses for cassava and maize to applied NPK with declining soil fertility variables. Our simulations are, however, in contrast to findings of Zingore et al. (2007) who reported that maize in home fields in Zimbabwe responded much better to inorganic fertilizer application than maize in outfields, particular in case of sandy soils. The latter required substantial manure application for several seasons to restore soil fertility before a fertilizer response was observed. Results from Tittonell et al. (2008) using the FIELD model for maize in western Kenya indicate that also in Kenya outfields may be less responsive to fertilizer use than home fields in some cases. Fields with a low SOC content may respond very differently to fertilizer use, depending on a range of soil qualities. Due to their heavier texture, low SOC fields in western Kenya likely had better (micro) nutrient supplies and better water availability than outfields in Zimbabwe.

3.3 Improving sustainability of cassava-maize based farming systems

Partial nutrient balances in most management × crop/genotype × soil type combinations were negative, whereby nutrient balances for RD cassava genotypes were generally more negative than for maize (Table 3). Depending on nutrient stocks and ISFM practices, the productivity of cassava-maize based farming systems will therefore, sooner or later, be affected by nutrient limitations. The adoption of RD cassava genotypes and improved crop management may accelerate this process due to higher nutrient removal rates (Table 3). Nutrient removal in cassava fields can be partially offset by returning a larger proportion of the stems to the field after harvesting. Our simulations indicate that the increased nutrient removal due to adoption of RD genotypes may be partially (30-100%) compensated by simultaneously increasing the proportion of stems returned to the field after harvesting from 20 to 75%, regardless of management regime (data not shown). Farmers currently use an estimated 0.7 and 1.5 t ha^{-1} stem material for planting material and fuel wood (estimation based on 80% stem removal from fields with cassava landraces with farmer management). RD genotypes produce more above ground biomass (and thus more stems) than cassava landraces, especially under Management Regime ii and iii (Figure 2b and c). Consequently our simulations indicate that farmers may return 50% of stems at Management Regime i and even 75% of stems at Management Regime ii and iii, without compromising the amounts of stem used for fuel and planting material (data not shown). Increasing stem return for RD genotypes planted on infertile soils from 20 to 75% may improve annual C input by roughly 400 kg ha^{-1} yr^{-1} for Management Regime i and by roughly 2000 kg ha^{-1} yr^{-1} for Management Regime iii, according to our simulations (data not shown). Over a 10 year period this may result in

SOC gains of 10 and 35%, respectively (data not shown). These findings are in line with results from Howeler (2000), who showed that incorporating plant tops at harvest time slowed down the yield decline over time in field experiments in Thailand. Improving stem management thus may contribute to maintaining or even improving farming system sustainability. Improving stem management may be easier to adopt than other ISFM options in cassava-maize based systems in western Kenya as manure availability is generally limited (2-2.5 cows per household), little fertilizer is used (< 100 kg per farm per year), and legumes are not widely grown (Chapter 2 and 3). Nonetheless, its benefits and practicality needs to be tested in the field. Potential problems may include the advantageous sprouting of thicker, woodier stem parts, the hindrance of field operations and labour shortages.

3.4 Considerations on the approach

The model used in this paper provides us with some critical insights in some of the interactive processes that influence the sustainability of cassava-maize based farming systems in western Kenya due to changes in crop and land management. It is a simple, robust model that helps to improve understanding of important crop × soil × management interactions, but predictions of future yields and soil quality should be interpreted with care. An important weakness in our model is that it considers SOC and management as the only yield determining factors, whereas in reality yields are determined by a much wider array of production factors (e.g. nutrients, climate, pest and diseases). Boundary lines used in our model were based on data from either one or two growing cycles and are only representative for the growing conditions during these periods. Cassava production in the 2004 and 2005 trials, even with fertilizer, was only half of the maximum yield observed for cassava in western Kenya (Chapter 4). Thus, it can be assumed that the boundary lines for cassava (Figure 2) are indirectly affected by other production constraints or interactions between constraints. Fertilized maize production in the data set used in this paper was close to maximum maize yields observed in western Kenya (5-7 t ha^{-1}; FURP, 1994). Hence, it can be expected that the boundary lines for maize are less affected by other production constraints than those of cassava. The lack of especially water and nutrient limitations in our model results in likely overestimations of crop and stover/biomass productivity and consequently in likely overestimations of SOC development over time. As a result of the boundary line functions used, overestimations will be likely larger for maize than for cassava. Overestimation will furthermore be likely larger at higher management intensities (Regimes ii and iii) because nutrient and water demands generally increase with larger yields and the model did not take into account any feedback loops due to depletion of P and K stocks in the soil.

The build up of SOC over time in several of the analysed scenarios implies a build-up of nutrients over time, whereas increasing yields (related to increasing SOC) result simultaneous in larger nutrient removal rates. This apparent contradiction may be explained by the uptake of nutrients from deeper soil layers and the subsequent addition of these nutrients to the top soil through the return of crop residues after harvesting. Rooting systems of maize and cassava may extend up to 1 to 1.5 m. and up to 2 m., respectively. Through its mycorrhizal association cassava can also extract nutrients from a larger soil volume (Howeler et al., 1987). Returning crop residues will make part of these nutrients available to subsequent crops in the rotation. With nutrient recycling being in the same order of magnitude as nutrient removal (Table 4), this mechanism may be important in postponing the development of nutrient limitations. Maize grown in rotation with cassava may benefit from the large amounts of N recycled through cassava crop residues, while cassava in its turn may benefit from the large amounts of K recycled through maize crop residues. On an annual basis, soil tillage is less in cassava than in maize fields and soil coverage is likely better, resulting in less aeration and lower soil temperatures and consequently in slower SOC decomposition rates. Except for crop rotations and the effect of nutrient recycling on subsequent crop yields, the other aspects discussed above (nutrient pump, mycorrhiza, soil temperature and tillage) are normally not included in farm models. Thus the positive effects of cassava on system sustainability will be generally under estimated in modelling exercises, though not necessarily in this exercise due to the boundary line approach.

4. Conclusions

This study is a first attempt to explore the potential impact of management changes in cassava-maize based farming systems on several sustainability indicators over time. Our model was only driven by SOC and management and did not take into account other production constraints. Though it is a simple analysis it brings out interesting issues which may be worthwhile exploring in more detail once a functional cassava crop model is available for inclusion in FIELD. Our initial results suggested that all studied changes in land and crop management (adopting cassava cultivation compared to adopting maize cultivation, adopting RD cassava compared to continuing cultivation of cassava landraces, adopting improved crop management compared to continuing with current management and adopting fertilizer use compared to no fertilizer use) may have positive effects on SOC and yield development over time and on nutrient recycling through crop residue return, with the exception of increasing cassava cultivation on higher fertility soils. Nevertheless, all management options, except for fertilizer adoption, will also increase nutrient removal rates and thus may accelerate the development of nutrient limitations. Improving cassava stem management seems an interesting option to improve sustainability of the system. Nutrient redistribution from deeper soil layers to the topsoil through crop residues may be important in maintaining nutrient availability in the topsoil. Quantifying this for cassava and maize through field trials and modelling will improve our understanding of the potential positive contributions cassava can make to maintaining system productivity. Optimal targeting of scarce resources to specific fields and crops depends on the resources in question. Our simple model gives some first indications of possible sensible management choices for farmers.

Chapter 7

General discussion

1. Introduction

This final Chapter brings together the lessons learned with respect to the initial research objectives (section 2), discusses the results in a wider social and scientific context (section 3), with an eye on the future (section 4) and presents an outlook for agronomy research in Africa (section 5). By doing so, we return to the overall aim of this thesis: To better understand the roles and production constraints of cassava in order to explore opportunities to improve the productivity and sustainability of intensifying cassava based smallholder farming systems in East Africa.

2. Lessons learned

2.1 Roles, niches and management of cassava

Cassava is generally known as a subsistence crop, grown by poor farmers who plant it preferentially as an intercrop, using no inputs and little labour. We showed that for the studied farming systems in East Africa these generalizations are either untrue or half truths (Chapter 2). Cassava has important socio-economic roles as a food crop (one third of starchy staple food consumption) and as a cash crop (average cassava income 84 \$ year^{-1}) across all wealth classes. It generated income for more households (63%) than any other crop. Average farm income (972 US\$ year^{-1}) was similar to that of non-cassava based farming systems in East Africa. Farmers planted cassava more as a sole crop than as an intercrop; only poorer farmers in Kenya had a preference for intercropping. Though monthly labour requirements for cassava were less than for other crops, total labour requirements per crop cycle were larger. Labour requirements were high compared to other cassava areas in the world, mostly due to a large number of weed operations (up to 8) per growth cycle (chapter 4). Farmers did use inputs on cassava, mainly improved genotypes (60% of households) and hired labour for weeding (36% of households). In high land pressure sites, farmers also applied manure to fields with a cassava-maize intercrop (45-70% of households). The roles of cassava and its management were influenced by farmer wealth. Whereas cassava played a more important role for less resource endowed farmers in Kenya, the opposite was the case in Uganda.

Currently the average farmer in our study areas plants ca. 0.6 ha of cassava and maize and the farming systems can be classified as continuously cultivated cassava-maize based systems (Chapter 2). Three to four decades ago farming systems in these areas were still classified as millet, cotton, sugarcane or banana-based systems, with a large fallow and/or grazing component and hardly any cassava (Chapter 3). Due to increasing land pressure, the area under grazing, grass/bush fallows and/or single season fallows reduced. At the same time the proportion of cropped land under cassava increased from 1-11% to 16-55%. We argue that declining soil fertility, and not labour or food shortage, is the main trigger for this transformation. This is in line with the farmer perception that cassava regenerates soil fertility. As a consequence of increasing land pressure both the physical and temporal niche of cassava has changed. Farmers no longer plant cassava as the last crop before fallow but use cassava as an 'imitation fallow'. As land pressure increases, farmers increasingly target cassava to poor fertility fields, characterized by low pH and low available P.

2.2 Factors influencing cassava productivity

Average cassava yields (6.1-11.7 t ha^{-1}) as observed in farm surveys across 6 sites were far below attainable yield (35.5 t ha^{-1}) as observed in two years of on-farm trials with NPK fertilizer (Chapter 4). Differences in available labour, access to fertile soils, and harvesting time contributed to the large yield differences observed under farmer management between poorer and wealthier farmers (ca. 6 t ha^{-1} in Kenya and 10 t ha^{-1} in Uganda). The use of an improved management package, consisting of a cassava mosaic resistant genotype, improved crop establishment and 100-22-83 kg ha^{-1} N-P-K fertilizer more than doubled average farmer yields to 20 t ha^{-1}. These results indicate that there is substantial scope to improve cassava yields in East Africa. The observed yield gaps were caused by a multitude of production constraints. When improved genotypes and improved crop establishment, but no fertilizer, were used low soil fertility, early drought stress, sub-optimal weed management and pests and diseases contributed on average 6.7, 5.4, 5.0 and 3.8 t ha^{-1}, respectively, to the yield gap. Abiotic constraints and crop management were thus far more important than believed by scientists and farmers to date, whereas pests and diseases (bacterial blight, green mite, anthracnose and mealy bug) were less important. Production constraints varied strongly between fields and years and fields were often affected by multiple and interacting constraints, e.g. poor rainfall reduced the effectiveness of weed management. Figure 1 gives an overview of the factors influencing cassava production that were observed in this research.

The use of 100-22-83 kg ha^{-1} N-P-K fertilizer increased cassava yields significantly and resulted in greater yield gains than any other individual management practice (Chapters 4 and 5). Yield increases were mostly the result of an increased sink capacity (i.e. increased number of storage roots per plant) and an increased source supply (i.e. increased above-ground biomass). Nutrient limitations varied between

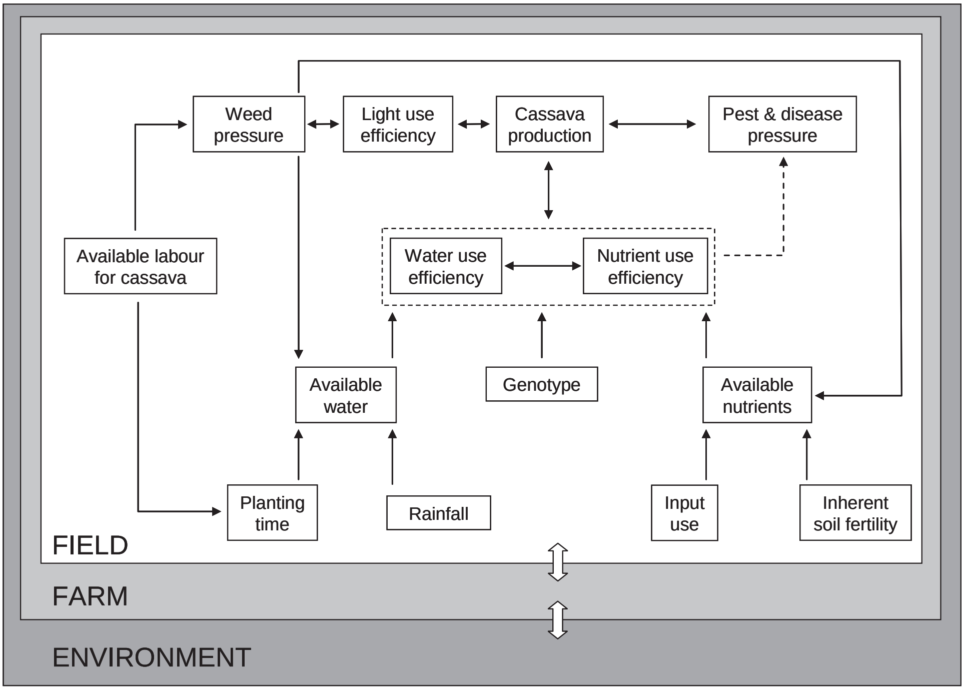


Figure 1: Factors influencing cassava production in East Africa at field level. Factors influencing partitioning of carbohydrates to the storage roots (e.g. harvest index) are not included.

sites, but in general the combined use of NPK gave highest returns to investment in Kenya, whereas the use of K was not economic in Uganda. Response to fertilizer was highly variable between sites and years (-0.2 to 15.3 t ha^{-1}). Consequently, fertilizer use had good profit margins (average VCR of 5.2) and a low risk (83% of fields with a VCR >2) in a wetter year, whereas profit margins were much lower (average VCR of 1.8) and fertilizer use was much more risky (55% of fields with a VCR <2) in a drier year. Fertilizer response was affected by the same factors that limited cassava yield most, e.g. soil fertility, rainfall and weed management. Genotype, pest and disease pressure and harvest age did not influence fertilizer response. Low rainfall during the first 3 months after planting reduced the positive effect of fertilizer on the source and sink capacity of cassava, and thus final yield. Fertilized yields were independent of weed management, unless water availability during initial growth was poor. Although fertilizer response was correlated to soil fertility parameters, it still varied widely on low fertility soils, e.g. on soils with SOC <10 g kg^{-1}, responses ranged from -8.6 to 24.4 t ha^{-1}. This indicates strong interactions between the factors governing soil fertility response.

2.3 Sustainability issues in intensifying cassava-maize based systems

The transformation of the farming systems from systems with an important fallow component into continuous cropping systems has increased nutrient take off and reduced nutrient recycling rates (Chapter 3). Currently, cassava and maize account for about 50-90% of nutrient removal and roughly 70% of nutrient recycling at farm level, whereby the majority (50-70%) of N, P and K are recycled through cassava litterfall. In addition to its relatively good yields on infertile soils, the increase in cassava cultivation on these soils may have contributed positively to SOC contents and nutrient availability for the subsequent crop (Chapter 6). The observed high cultivation intensities on more fertile soils (Chapter 3) may be related to higher N recycling rates of cassava compared with maize (Chapter 6). In case systems would have intensified towards cereal-cereal rotations, crop yields in all likelihood would have decreased due to a lack of N and P, unless farmers had intensified management (Chapter 3). Adoption of new cassava genotypes and/or improved management practices for cassava will increase yields and consequently nutrient removal. Nonetheless, their adoption will positively impact above ground biomass production and probably increase litterfall through the growing season and thus may promote SOC development and nutrient recycling (Chapter 6). Nutrient removal is not set-off by external nutrient use for most crops, except (partially) for maize in areas with high land-pressure (Chapter 3). Low cattle densities (2 cows per farm in most areas) and high fertilizer prices hamper a higher use of external inputs for many farmers. Farmers can, however, reduce nutrient removal rates in cassava fields by returning a larger proportion of cassava stems after harvesting. This may additionally have positive effects on SOC and nutrient availability for the subsequent crops in the rotation (Chapter 6). Nonetheless, the evidence that cassava production in all studied systems is already limited by N, P and sometimes K (Chapter 5) and reports of N and P limitations in maize production (Vanlauwe et al., 2006) show that an increased use of external nutrients will be inevitable in the near future.

2.4 Overall conclusions

The roles and niches that cassava takes up in the farming systems in East Africa have changed considerably over time due to increasing land pressure (Chapter 2 and 3). This demonstrates the versatile nature of cassava and farmers, alike. The substantial increase in cassava cultivation and targeting of cassava to infertile soils have allowed farmers to postpone intensification of crop management. It seems, however, that the elasticity of the traditionally low-input systems is coming to an end as production of the two most important crops (cassava and maize) is limited by nutrients (Chapter 4 and 5) and farmers facing high land pressure have started to use fertilizer, manure and improved crop management practices (Chapter 3). Farmers perceive cassava as a soil fertility regenerator. This research does not verify nor falsify this perception, but it does point out possible mechanisms that could explain a positive impact of cassava cultivation on subsequent crops. These include (i) the redistribution of nutrients from deeper soil layers into more labile nutrient pools in the topsoil, whereby N redistribution through cassava litterfall may be especially important; and (ii) a positive impact on SOC development on infertile soils compared to other crops.

Closing the considerable yield gap between actual and attainable cassava yields at farm level, can not be achieved by integrated pest management (IPM) and breeding alone (Chapter 4). Instead, research and development organizations should focus on addressing the whole range of interacting production constraints through the development and evaluation of integrated management packages that includes resistant, higher yielding genotypes, improved weed management, early drought avoidance and integrated soil fertility management (ISFM) strategies and IPM. Since the introduction of improved genotypes presents an ideal entry point to promote alternative crop management options, dissemination of these genotypes may form the backbone of any management package. Because cassava is such an important component of the farming systems (Chapter 3), any (adopted) management practice that improves yields, nutrient balances, nutrient recycling and/or SOC contents will contribute to improving overall sustainability of the system.

Since food security is high and cassava is an important cash crop for such a substantial part of the farm community (Chapter 2), efforts to increase cassava production in cassava-based farming systems will improve the livelihoods of smallholder farmers mainly through an improved scope for commercialization of cassava, unless the area is strongly affected by the cassava mosaic disease (CMD) or cassava brown streak disease (CBSD) pandemics.

3. Opportunities and challenges in closing the cassava yield gap

Efforts to improve cassava productivity in Africa have been limited to programmes that combat the effect of pests and diseases (e.g. mealy bug and green mites and the CMD and CBSD epidemics) through the introduction of natural enemies or dissemination of resistant genotypes (Neuenschwander, 2001; Alene et al., 2006; Legg et al., 2006). These efforts will return yields to those obtained prior to the pest or disease epidemic or, in case cassava genotypes with a higher yield potential are used, to a somewhat higher level (Figure 2). To close the yield gap more effectively, efforts

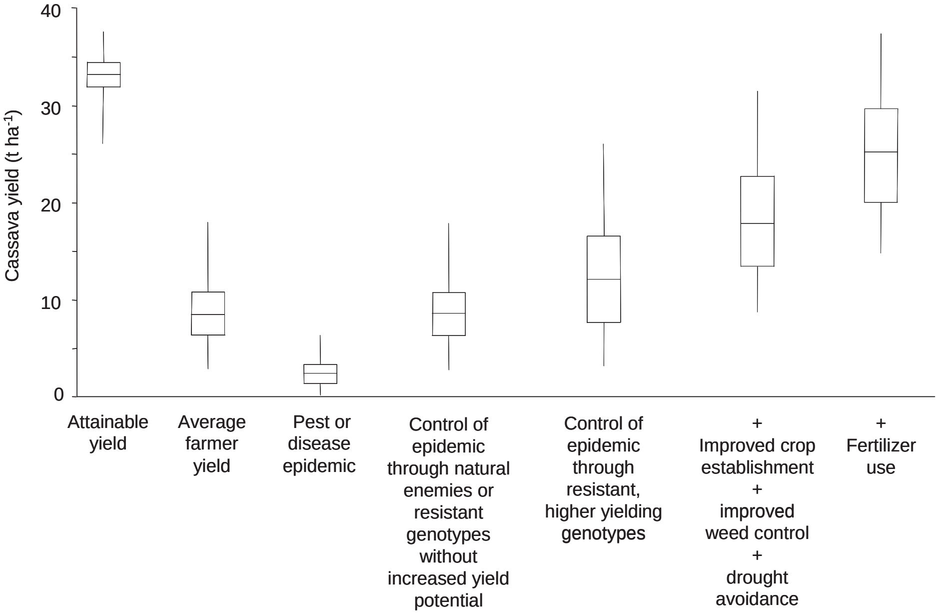


Figure 2: Overview of attainable cassava yields and cassava yields at different management regimes in East Africa. Box plots give an indication of the range in cassava yields at each regime only.

should focus on combining improved genotypes with improved management practices. This requires a strong reappraisal of the current research priorities of existing cassava research programmes (Chapter 4). Considering the false conceptions that many extension and staff of research and development projects may have on the roles and management of cassava, the effective promotion of improved production practices will require educating these staff on the actual roles and management of cassava (Chapter 2). Due to the high variability and interaction between production constraints, any cassava agronomy program should have an important on-farm component to develop technologies that are robust over a larger range of conditions than are normally found in research stations. This requires more effort, logistically and financially, than the traditional on-station research.

Adoption of improved genotypes and cropping practices is generally related to wealth indicators (Chapter 4; Wargiono et al., 2001; Mugwe et al., 2009), whereby poorer farmers are less likely to adopt than wealthier farmers. However, poorer farmers are more in need of improved management practices for cassava than their wealthier counterparts because they are more likely to have low yields due to multiple production constraints: their soils are less fertile, they have less manure available and they have less access to financial and social capital than wealthier farmers (Chapter 2, 4 and 5). The implication of this is that extension efforts should include tailor-made technology packages for less resource endowed farmers. This could entail e.g. low-input ISFM options in combination with weed control methods that are less demanding of labour. Cropping systems and management practices for cassava (e.g. weed control, manure use) varied widely between areas (Chapter 2). Recommendations of best-fit cropping practices may therefore need to be region-specific. In practice, this could translate to e.g. limiting the promotion of early planting to avoid drought stress to areas with animal traction, as the use of animal traction for soil tillage reduces labour constraints and improves the timeliness of planting operations (Willcocks and Twomlow, 1993). The need for region-specific and/or wealth specific recommendations is known for other crops (van Asten et al., 2008; Tittonell et al., 2008a), but it may be a challenge to get the message out to farmers.

The number of agronomists with specialist knowledge of cassava in Africa can be counted on two hands. The lack of scientific capacity will hamper the development and promotion of improved management practices and will slow down improvements in cassava productivity. The growing interest in cassava agronomy in the research community is a good opportunity to start building strong cassava teams that can tackle the most important production constraints for cassava through integrated efforts of breeders, IPM specialists, agronomists, economists and extension workers. These intentions may be frustrated by the general lack of donor interest. Donors may not yet have realised the contribution that improved management strategies can make to cassava production or may be too focussed on dissemination projects that are easy to monitor and reach large number of farmers, without realizing the window of opportunities that are available for farmers through improved management packages.

It has been shown in countries like Thailand and Vietnam that the aggressive promotion of cassava as a cash crop for industrial use improves the livelihoods of smallholder farmers. Following this example, African countries could create attractive investment climates and good supply-demand linkages to benefit from the opportunities that are offered by the growing markets for biofuel, animal feed and starch. Good markets for cassava will motivate farmers to adopt improved technology packages, including fertilizer use, that contribute to increasing the profitability of cassava production and will likely have a positive impact of overall farm productivity, smallholder livelihoods and sustainability of the systems (Chapter 6).

4. The future: possible changes in the roles of cassava

4.1 Drivers of change

Farms are heterogeneous and complex, in terms of natural resources, their management, and livelihood strategies (Tittonell, 2008). The environments in which they operate are also highly diverse, both at a spatial and a temporal scale. Agricultural systems will change over time. Hazel and Wood (2008) define drivers of change as any natural or human induced factor that directly or indirectly bring about change in agricultural production systems. They consider a range of drivers at three scales, which include (i) at global scale, international trade, world prices and climate change; (ii) at country scale, per capita income growth, urbanization and agricultural policies; and (iii) at local scale, poverty, population pressure, infrastructure and non-farm opportunities. IFPRI (2007) considers agro-ecological potential and market opportunities as important criteria for the targeting of interventions to improve livelihoods of smallholder farmers.

Across the studied farming systems, I believe that land pressure, market opportunities, fertilizer prices, climate change and farmer wealth may be the most important drivers for changes with respect to the importance and roles/niches of cassava in the next decades. Increasing land pressure has been a major driver behind the substantial increase in cassava cultivation in our research areas (Chapter 3). Total population in East Africa is expected to increase from 301 million in 2008 to 440 million in 2025 (Haub and Kent, 2008). Land pressure will therefore continue to increase. Market opportunities can change drastically over time and have considerable impact on farming systems and the livelihoods of farmers. Declining prices will result in a decrease in production, as has been the case for coffee in Africa (Hillocks, 2001; Soini, 2005), whereas increasing market opportunities may be a catalyser for production, as has been the case for cassava in Asia following the installation of animal feed, starch and biofuel factories (Pham Van Bien et al., 2001; Sritoth et al., 2001, Charoenrath, 2008). Current fertilizer prices in Africa are high due to, amongst others, lack of economies of scale and high transportation costs. Improving on the economy of scale and/or introducing subsidies may reduce fertilizer prices and increase its use by African farmers (Gregory and Bump, 2006). The Africa Fertilizer Summit in Abudja, Nigeria in 2006 showed that African leaders are committed to making fertilizer more accessible. The impact of climate change in East Africa is thought to affect the distribution of rainfall throughout the year (Hulme et al., 2001), resulting in increased variability in crop production (Case, 2006). In some cases drivers of change can be expected to have rather uniform consequences for the importance and roles/niches of cassava over a larger area (e.g. increasing land pressure), but in other cases (e.g. fertilizer price) it is too simplistic to assume that every farm family will respond in a similar manner.

At field level, factors that will likely affect adoption of new cassava genotypes and crop management practices include genotype characteristics, the CBSD epidemic, market demand, extension efforts, farm type and land pressure. Genotype attributes that influence adoption include pest and disease resistance, yield potential, quality aspects, drought resistance and early maturity (Tongglum et al., 2001; Abele et al., 2005; Agwu and Anyaeche, 2007). Quality aspects may relate to taste, texture and dry matter content in case of home consumption or specific traits in case of commercial marketing. In Uganda and Kenya farmers often prefer landraces over improved genotypes for home consumption. CBSD is taking on epidemic forms in the mid altitude area of East Africa and many landraces and improved genotypes currently available are not resistant to the new virus (Alicai et al., 2007). Following the widespread adoption of new genotypes in response to the CMD pandemic, farmers are likely to widely adopt CBSD resistant genotypes when their cassava production becomes severely affected. In Thailand, intensive extension efforts and market demand resulted in the majority of farmers adopting improved genotypes and fertilizer use and one third adopting chemical weed control. Tongglum et al. (2001) and Wargiono et al. (2001) further observed that farmers with more access to capital and progressive or commercial farmers were more likely to adopt improved management practices. In Kenya, farmer wealth, education level, market demand and/or access to information affected the adoption rate of improved genotypes (Chapter 4; Abele et al., 2005), farmer wealth also influenced weed management in Kenya and Uganda (Chapter 4), whereas land pressure motivated farmers to advance the first weed operation in maize and groundnuts (Chapter 3).

4.2 Scenarios of change

We discuss four contrasting scenarios of change and the consequences for the importance, roles and management of cassava and for the sustainability of the farming systems. We assume that under all scenarios land pressure will continue to increase and that farmers have access to new cassava genotypes and information about improved crop management practices through extension services and development projects. We assume for scenario c and d that farmers have access to industrial cassava markets, though in reality this may not be the case for all farmers as cassava industries are likely to be established in areas with a comparative advantage for cassava production.

a. No industrial cassava market and current high fertilizer price

This scenario describes the situation for the majority of poorer farmers who do not have sufficient financial capital to buy fertilizers, have access only to local cassava markets and face increasing land pressure. External nutrient inputs will be virtually non-existent as farmers have very limited access to manure (1 cow per farm). As soil fertility in these farms is generally poor (Chapter 4), cereal productivity will decline over time (Chapter 6) and farmers will likely adopt more cassava into their system and increasingly target cassava to the poorest soils in their farm, as was observed in Ugunja (Chapter 3). The role of cassava as a 'soil fertility regenerator' will thus become increasingly important over time for farmers. Most farmers will likely increasingly adopt higher yielding cassava genotypes in order to maintain productivity and control the impact of the CBSD epidemic. Those who have sufficient amounts of labour available may be able to improve crop management, thereby preferentially targeting the most fertile fields to improve labour use efficiency (Chapter 6). The importance of cassava as a food and cash crop will increase. Over time, the sustainability of these systems is endangered due to the aggravation of nutrient limitations, which will exacerbate the impact of other production constraints (Chapter 4). The increase in cassava cultivation, adoption of higher yielding genotypes and improving management will most probably delay decline in system productivity. Adoption of improved stem management and other low-input strategies to reduce nutrient removal and/or increase nutrient inputs (e.g. legumes, manure) will be required to maintain production at baseline levels.

b. No industrial cassava market and fertilizer is affordable

This scenario describes the situation of medium and wealthier farmers, who have sufficient financial capital to buy fertilizer, have access to local cassava markets only and face increasing land pressure. This group of farmers is likely to start using (Uganda) or increase (Kenya) fertilizer use if markets for cash crops, maize and/or groundnuts remain stable or improve. Cassava may benefit from these additional inputs through its rotation with maize and groundnuts (Chapter 3) or being intercropped with maize (Chapter 2). For farmers using large amounts of fertilizer, the role of cassava as a 'soil fertility regenerator' is likely to decline as they can sustain crop yields with fertilizer and may replace cassava with maize/groundnuts/cash crops if markets are good. For farmers using moderate amounts of fertilizer cassava's perceived role as a 'soil fertility regenerator' will likely remain important and thus these farmers will be less likely to replace cassava with other crops. For the first group, the importance of cassava as a cash crop and a food crop will decline, whereas for the second group cassava will probably remain an important food and cash crop (Chapter 2). Farmers will only adopt higher yielding cassava genotypes if these have good cooking/taste qualities compared to their current genotypes or if the CBSD epidemic strongly affects their current cassava genotypes. They may take advantage of the higher cassava yields by concentrating cassava on a smaller acreage, thereby ‘releasing’ land for other crops. Farmers in this scenario are unlikely to adopt improved crop management practices for cassava. Systems will be reasonably sustainable in terms of crop productivity and soil quality (Chapter 6).

c. Industrial cassava markets available and current high fertilizer prices

This scenario describes the situation for the majority of poorer farmers who do not have sufficient financial capital to buy fertilizers, have access to industrial cassava markets and face increasing land pressure. Farmers will likely make similar management decisions as under scenario ‘a’, but will introduce changes in management (e.g. increasing cassava acreage, adopting higher yielding genotypes, improving crop management) much faster due to market opportunities. Consequently, the roles of cassava as a ‘soil fertility regenerator’ and a cash crop will be stronger than in scenario ‘*a*’ but the systems may be quickly affected by nutrient limitations.

d. Industrial cassava markets available and fertilizer is affordable

This scenario describes the situation of medium and wealthier farmers, who have sufficient financial capital to buy fertilizers, are supplying cassava to starch, biofuel and/or animal feed industries and face increasing land pressure. These farmers are likely to adopt complete improved management packages for cassava (higher yielding genotypes – with specific traits required by the industry, improved management and fertilizer use) and may increase the acreage under cassava, though the latter will depend on the profitability of cassava versus other market crops. The installation of outgrower schemes with credit schemes, input supplies and extension will support the adoption of fertilizer use and improved crop management. Fertilizer use should be preferentially targeted to higher yielding genotypes and to infertile soil (Chapter 6). The importance of cassava as a cash crop, and likely as well as a food crop, will increase, whereas the increased biomass recycling may also contribute to higher SOC contents and nutrient recycling. In case stem management is also improved, the overall sustainability of the farming systems will most likely improve on most aspects (Chapter 6).

The above scenarios are only valid for farming systems that have a good yield potential for maize and cash crops. Farmers in the drier, much less densely populated areas of central Uganda (e.g. Kikooba) are much more dependent on cassava (e.g. ca. 60% of cropped land under cassava; Chapter 2), but also still have considerable amounts of land under grass or bush fallow (ca. 45% of the farm). Considering their labour limitations (Chapter 2) farmers are most likely not able to increase the cropped acreage on their farm, unless animal traction is introduced. Depending on markets and fertilizer prices, farmers will adopt higher yielding cassava genotypes and possibly fertilizer use. Adoption of improved crop management will be likely linked to the introduction of animal traction.

4.3 Impact of climate change

Arguably one of the most important, widespread impacts of climate change in East Africa will be changes in frequency, intensity and predictability of rainfall events (Case, 2006). Hulme et al. (2001) predict for East Africa that rainfall may possibly increase with 5-30% during the long dry season (December-February) and decline with 5-10% at the end of the long rains/start of the short dry season (June-August) by 2050. The increased variability in precipitation will make the planning of agricultural production for smallholder farmers more difficult and risky. Farmers will probably change their cropping practices as was observed for Zimbabwe where farmers with access to weather forecasts altered planting time and/or planted different varieties of crops and/or a planted larger proportion of early maturing maize varieties (Patt et al., 2005). Cassava is more drought tolerant than cereals (El-Sharkawy and Cock, 1986) and is being promoted by governments, the NEPAD Pan-Africa Cassava Initiative and IITA in drought prone areas of southern Africa as an alternative to maize (IITA, 2006; Sitko, 2008). For the cassava-maize based systems in East Africa it can be expected that an increase in rainfall variability and predictability will push farmers to increase the relative importance of cassava in all four of the discussed scenarios to reduce risks associated with crop production. However, more irregular rainfall patterns may also increase early water stress for cassava, thereby impacting on other production constraints (e.g. weed control) and directly and indirectly negatively impact on cassava production (Chapter 4). Breeding for adaptation to early drought stress will therefore be indispensable. Poorer farmers will be more affected by the impact of climate change than wealthier farmers as they often already face multiple production constraints (Chapter 4).

5. The way forward: strengthening cassava agronomy in Africa

Cassava agronomy research in Africa is still in its infancy and thus there is an almost endless list of future research topics that are of interest to increase the productivity of cassava-based farming systems in sustainable ways. Nonetheless, many lessons can be learned from cassava agronomy research in Asia and Latin America and from agronomy research on other crops in Africa. In many cases it will be possible to identify a selected number of best-fit options, which can be evaluated for cassava using a participatory approach.

The biggest challenge faced by cassava agronomists in Africa is to identify priority research areas in order to develop and promote cropping practices that address the most important production constraints as well as stand a good chance of being adopted. Up to date no quantitative information is available on the importance of the various production constraints in the main cassava growing areas of Africa, except for this research in the mid altitude areas of East Africa. Due to the observed interactions between constraints, results can not be easily extrapolated to other agro-ecological zones. To be able to set the research for development (R4D) agenda on cassava agronomy in Africa, the first step will be to carry out yield gap studies in other main agro-ecological zones where cassava is a major crop.

To develop technology packages for cassava, individual management strategies (e.g. weed control, drought avoidance strategies, ISFM) need to be evaluated alone, and in combination with others, to identify best-fit options. Advantage can be taken from the many lessons learned for cassava in Asia and for ISFM strategies for other crops in Africa (e.g. combined manure-fertilizer use; dual purpose legumes). Evaluation should be done as much as possible in the heterogeneous conditions of smallholder farmers and across sites, years and soil types to take the existing variability in production factors into account. Intensive farmer participatory evaluation will be critical to understand the acceptability of the various options to farmers of different wealth classes and with different production objectives. An important theme for research on weed management is the reduction of labour requirements. When productivity of cassava is increased the more closed canopy that forms can help to shade and suppress weeds. Agronomic studies need to be complemented with economic evaluations and trade-off studies comparing the economic returns for scarce inputs (labour, fertilizer, manure, herbicides) for cassava versus other crops.

Specific emphasis should be given to the identification of management options for low-input systems to enhance their sustainability on the longer-term. A key research theme in this respect it the verification/falsification of cassava’s perceived role as a ‘soil fertility regenerator’. Understanding the mechanisms underlying the potentially positive contribution of cassava cultivation to the subsequent crop, may generate new insights in how to improve the sustainability of low-input cassava-based farming systems. Other themes may include evaluating improved cassava stem management (Chapter 6) and low-input options to improve cassava-intercropping systems since poorer farmers intercrop cassava more than wealthier farmers (Chapter 2).

This thesis has attempted to improve the general understanding of the roles and production constraints of cassava in order to explore opportunities to improve the productivity and sustainability of intensifying cassava based smallholder farming systems in East Africa. One of its main conclusions is the need to invest in agronomy and ISFM research and to reform existing R4D programmes with a strong emphasis on breeding and IPM into integrated R4D programmes that are able to address the multiple production constraints of cassava and thereby significantly contribute to improving the livelihoods of smallholder cassava farmers.

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Summary

In large parts of sub-Saharan Africa soil fertility is poor as a result of inherently infertile parent materials and/or due to continuous cropping without external inputs. Rapid population growth throughout Africa increases land pressure and aggravates the strain on natural resources. Farming systems can be characterized as smallholder systems which are highly diversified, heterogeneous and dynamic. Consequently, management strategies that may work in one part of the farm, may not work in another part. Wealthier households generally have a better access to resources than poorer households and therefore have a wider choice of management options. Cassava (*Manihot esculenta* Crantz) is an important crop throughout Africa. Its production has almost quadrupled in the last five decades. With an eye on climate change NEPAD identified cassava, a relatively drought tolerant crop, as a key commodity in Africa to reduce the dependence on maize.

This thesis focuses on cassava-based smallholder farming systems in the mid altitude zone of East Africa. The area is characterized by high land pressure, bimodal rainfall patterns and relatively poor soils. Land pressure is especially high in western Kenya (>250 persons km^{-2}). This area may therefore well represent the direction in which many farming systems in Africa with comparable climate and soils will develop. East Africa accounts for ca. 11% of total cassava production in Africa. Average farmer yields (6.5 – 12 t ha^{-1}) are far below average yields in breeding trials (15-40 t ha^{-1}), indicating an important scope for yield improvement. Production has been and still is severely affected by the cassava mosaic disease (CMD) pandemic, which is controlled through the wide-scale introduction of resistant genotypes. However, little is known about the importance and management of other production constraints. The overall aim of this research was to better understand the roles and production constraints of cassava in order to explore opportunities to improve the productivity and sustainability of intensifying cassava based smallholder farming systems in East Africa.

To evaluate the various roles, niches and management of cassava in relation to common perceptions about the crop, we carried out a series of farm surveys (n = 120) in six villages across Uganda and Kenya (Chapter 2). Socio-economic factors varied widely between and within sites: for instance, annual income ranged from 633 to 1283 US\$ year^{-1} between sites and from 287 to 2456 US\$ year^{-1} between wealth classes. Management factors generally varied stronger between than within sites: for instance manure use ranged from 0 to 904 kg ha^{-1} between sites and from 263 to 458 kg ha^{-1} between wealth classes. Cassava was an important food and cash crop across all sites and wealth classes. Average food security (>10 months year^{-1}) was higher than in maize-based systems in the area. On average, cassava was planted on 0.6 ha, contributed one third of starchy staple consumption and generated an income of 84 US$ year^{-1}. In terms of income cassava was more important in Uganda for wealthier farmers (439 US$ year^{-1}) than for poorer farmers (18 US$ year^{-1}), but its importance as a food crop did not vary between wealth classes. In Kenya poorer farmers consumed 11% more cassava than wealthier farmers and earned a larger proportion of crop income from cassava (16 versus 35 %). Farmers intercropped 30% of their cassava acreage in Uganda and 51% in Kenya, whereby poorer farmers had the largest preference for intercropping. As farmers weeded cassava 3 to 6 times, total labour requirements for cassava (287 man days ha^{-1}) were higher than for other crops. Nevertheless, due to its long growth cycle (12 months), monthly labour requirements for cassava were relatively low. The majority of households (60%) planted improved cassava genotypes and one third hired labour for cassava weeding. In high land pressure sites, the majority of households (45-70%) applied manure to cassava-maize intercrops. Our results demonstrate that in East Africa the general perceptions of cassava as a food crop, grown by poor farmers that plant cassava mostly as an intercrop, without inputs and using little labour are either false or only half true.

To evaluate the impact of increasing land pressure on the physical and temporal niche of cassava, results from the farm surveys were combined with a study on changes in population and land use (Chapter 3). In western Kenya population increased from 159-232 in 1982 to 291-387 persons km^{-2} in 2004, whereas in Uganda population increased from 14-98 in 1959 to 41-328 persons km^{-2} in 2005. Farmers in all sites responded alike: they reduced land under grazing, grass/bush fallow and/or single-season fallow, while substantially increasing the acreage under cassava (1-11% to 16-55% of cropped acreage). The large majority of farmers (62-100%) believes that cassava regenerates soil fertility. Consequently, they started to use cassava as a replacement for single-season fallows. In four high land pressure sites with low pH soils (< 5.8) farmers targeted cassava specifically to less fertile soils and targeting was especially strong if soils had a pH < 5.4 and available P < 5.5 mg kg^{-1}. The observed land use changes have roughly doubled nutrient removal rates for cropped fields to an estimated 30-40 kg ha^{-1} N, 4-8 kg ha^{-1} P and 25-50 kg ha^{-1} K, whereby cassava and maize currently are responsible for the majority of nutrients removed (50-90%). Crop residues of cassava and maize account for roughly 70% of nutrient recycling, whereby the majority (50-70%) of N, P and K is recycled through cassava litterfall. In case systems would have intensified to cereal-cereal rotations, crop productivity would probably have declined due to a lack of N and P.

To identify production constraints for cassava we combined farm surveys with agronomic trials (Chapter 4). The first data set demonstrated a large variability in average cassava yields under current farmer management (2.7-17.8 t ha^{-1}) and a difference of 6.1 for Kenya and 9.7 t ha^{-1} for Uganda between the lower and upper quartile yields. Largest yields were observed on farms with greater annual income that had more access to (hired) labour and fertile soils, weeded better and postponed cassava harvest. Two years of agronomic trials (n = 122) in six villages and two research stations across Uganda and Kenya showed that stepwise upgrading crop management by: (i) improving crop establishment (early planting, 1 m x 1 m spacing, no intercrop); (ii) + improved genotypes; and (iii) + 100-22-83 kg ha^{-1} N-P-K fertilizer resulted in average yield increases of 1.5, 3.5 and 7.2 t ha-1 between steps. The full management package more than doubled average farmer yields. Cassava yields at Management regime ii varied widely (2.8-27.3 t ha^{-1}). Multiple linear regression analysis, explaining 38% of observed variability in Kenya and 82% in Uganda, identified rainfall, weed management and soil fertility variables as important explanatory variables. Boundary line analysis quantified the average contribution of soil fertility, rainfall, weed management, soil texture and pest and diseases to the yield gap as 6.7, 6.0, 5.4, 4.3 and 3.8 t ha^{-1}. Individual constraints varied strongly between fields and years and cassava production was often affected by multiple constraints simultaneously. We observed important interactions between production constraints, e.g. low rainfall reduced the effectiveness of weed management. Poorer farmers are more likely to face multiple constraints than wealthier farmers, as their soils are less fertile and they have less access to financial and social capital.

With soil fertility being the main production constraint, we subsequently evaluated the response of cassava to mineral N, P and K and assessed the factors that influenced fertilizer response (Chapter 5). We installed fertilizer trials in eight sites across Uganda and Kenya, using 100-22-83 kg ha^{-1} N-P-K fertilizer and 3 genotypes per country in the first year and using a nutrient omission approach and one genotype per country in the second year. NPK fertilizer increased yields, above ground biomass and the number of storage roots per plant, but did not affect quality parameters of cassava nor pest and disease pressure, except for CMD. The nutrient omission trials showed that cassava production in Uganda was limited by N and P and in Kenya by N, P and K. While yields varied between genotypes, yield response to fertilizer did not. Average fertilizer response varied strongly between sites and years (-0.2 to 15.3 t ha^{-1}). Our results show that fertilizer response was governed by the same factors and interactions that determined unfertilized cassava production, e.g. soil fertility, rainfall and weed management. This may partially explain the large variability in fertilizer response observed on infertile soils (i.e. on soils with SOC <10 g kg^{-1}, responses ranged from -8.6 to 24.4 t ha^{-1}). Low rainfall during initial growth reduced the positive effect of fertilizer on source supply and sink capacity. As fertilizer increased initial plant growth, weed management in fertilized plots only paid off when initial growth was slow (e.g. water stress).

In Chapter 6, we explored the consequences for several sustainability indicators of four levels of increasingly intense management: (i) increasing cassava cultivation; (ii) adopting improved cassava genotypes; (iii) adopting improved crop management; and (iv) NPK fertilizer use. Due to the lack of a calibrated cassava model, we combined a SOC model with boundary line functions describing yield and above ground biomass/stover of cassava and maize versus SOC in western Kenya. We complemented the modelling with yield and nutrient data of cassava landraces, early released and recently developed cassava genotypes. Our simulations indicate that the observed increase of cassava cultivation on infertile soils may have contributed to yield and SOC maintenance and may have increased nutrient recycling in comparison to maize. The wide-scale adoption of early released cassava genotypes most likely did not affect system sustainability as yields, above ground biomass, nutrient concentrations and therefore nutrient removal, recycling rates and effects on SOC were similar to those of landraces. Adoption of recent developed genotypes and improved crop management will have positive effects on yields and thus increase nutrient removal rates, but may simultaneously also promote nutrient recycling and improve SOC levels due to larger above ground biomass production. Adoption of NPK fertilizer will improve nutrient balances and probably promote nutrient recycling and increase SOC levels. Currently, farmers use ca. 80% of stems for planting material and firewood. The adoption of recently developed genotypes, which also produce more biomass than cassava landraces, will allow farmers to return larger proportions of the stems to the field and thus reduce considerably reduce nutrient removal, while maintaining similar use of planting material and firewood.

In Chapter 7 we conclude that the roles and niches that cassava takes up in the farming systems in East Africa have changed over time due to increasing land pressure. The substantial increase in cassava cultivation has allowed farmers to postpone intensification of crop management, but it seems that the elasticity of the traditionally low-input systems is coming to an end as production of the two most important crops (cassava and maize) is limited by nutrients and farmers that face high land pressure have started adopting fertilizer, manure and are improving crop management. We also conclude that the yield gap between actual and attainable yields at farm level is large. Integrated pest management (IPM) and breeding alone cannot close the yield gap as abiotic constraints and crop management are much more important than previously thought. Closing the yield gap calls for the development and evaluation of integrated management packages to address the often multiple and interacting production constraints. This represents a strong reappraisal of the current agenda of cassava research programmes that have tended to focus particularly on biotic constraints. The development and promotion of improved cropping practices may be hampered by the false perceptions researchers and extension workers may have concerning cassava and by the lack of scientific capacity in cassava agronomy. Because food security is high and cassava is an important cash crop for the majority of smallholder farmers, efforts to increase cassava production in cassava-based farming systems will improve livelihoods mainly through improving the scope for cassava commercialization, unless cassava production is threatened by a serious pest or disease. It will be more challenging to do this for the poorer section of the farm community as these farmers are more likely to face multiple production constraints and have less access to the financial and/or social capital required to improve production. Because cassava is such an important component of the farming systems, any (adopted) management practice that improves nutrient balances, nutrient recycling and/or SOC contents will contribute to improving overall sustainability of the system. We hypothesize that across the studied farming systems, land pressure, market opportunities, fertilizer prices, climate change and farmer wealth are the most important drivers of changes with respect to the importance and roles/niches of cassava in the next decades. We discuss the consequences of several possible scenarios for the roles of cassava and system sustainability. Although cassava agronomy in Africa is still in its infancy, many valuable lessons can be learned from cassava research in Asia and Latin America and from agronomy research on other crops in Africa. To identify production constraints across Africa and set research for development priorities will require yield gap studies across the main agro-ecologies where cassava is grown. Once priorities are known, the development and participatory evaluation of best-fit management practices should take place in the heterogeneous environments of smallholder farmers and take into account labour and input trade offs between cassava and other crops/farm activities.

Résumé

Dans de nombreuses régions de l'Afrique Subsaharienne, les sols sont peu fertiles due à l'héritage de matériel infertile et/ou à la culture ininterrompue et sans intrant externe. L'augmentation rapide de la population partout en Afrique aggrave la pression démographique et la pression sur les ressources naturelles. Les systèmes culturels peuvent être caractérisés comme systèmes de petits paysans qui sont hautement diversifiés, hétérogènes et dynamiques. Par conséquent, les stratégies de gestion qui pourront fonctionner d'un coté du ferme échoueraient de l'autre coté. Les paysans plus aisés ont généralement plus d'accès aux ressources que les paysans démunis et comme corollaire, ont plus d'options de stratégie de gestion. Le manioc (*Manihot esculanta* Crantz) est une culture important dans toute l'Afrique. Sa production a pratiquement quadruplé durant les 5 dernières décennies. Dans l'optique du changement climatique, le NEPAD a identifié le manioc, une culture relativement tolérante à la sécheresse, comme une culture clef en Afrique en vue de réduire la dépendance du maïs.

La présente thèse vise les systèmes de production de manioc chez les petits paysans dans la zone de mi-altitude de l'Afrique de l'Est. La zone d'étude est caractérisée par une forte pression démographique, une pluviométrie bimodale et des sols relativement pauvres. La pression démographique est spécialement élevée dans l'Ouest du Kenya, (>250 personnes au kilomètre carré). Cette zone représente par conséquent la tendance de beaucoup de systèmes culturaux en Afrique ayant le climat et des sols similaires. L'Afrique de l'Est produit environ 11% de la production totale africaine du manioc. Les rendements moyens des paysans (6,5–12 T par ha) sont de loin en deça des rendements moyens obtenus dans les champs expérimentaux d'amélioration des plants (15–40 T par ha), indiquant une immense capacité d'amélioration des rendements. La production fut et continue d'être sévèrement affectée par la pandémie de la maladie de mosaïque du manioc (CMD), contrôlée par l'introduction à grande échelle de cultivars résistants. Toutefois, l'importance et la gestion d'autres contraintes à la production du manioc sont peu connues. L'objectif général de la présente recherche fut de mieux comprendre les rôles et la gestion des contraintes liées a la production du manioc et ainsi explorer les opportunités pour améliorer la productivité et la durabilité des systèmes de cultures intensives à base du manioc chez les petits paysans en Afrique de l'Est.

En vue d'évaluer les divers rôles, niches et gestion du manioc en relation des perceptions générales sur la culture, nous avions effectué une série d'enquêtes auprès des paysans (n= 120) dans six villages en Ouganda et au Kenya (Chapitre 2). Les facteurs socio-économiques ont varié largement à l'intérieur et entre les sites: par exemple, les revenues annuelles ont varié de 633 à 1283 $US par an entre sites et de 287 à 2456 $US par an entre classes sociales. Les facteurs de gestion ont varié généralement plus fortement entre les sites qu'à l'intérieur des sites: par exemple, l'utilisation du fumier a varié de 0 à 904 kg par ha entre sites et de 263 à 458 kg par ha entre classes sociales. Le manioc fut une culture importante aussi bien pour la subsistance que pour la vente à travers tous les sites et toutes les classes sociales. La sécurité alimentaire moyenne (>10 mois par an) fut plus élevée que dans les systèmes à base de maïs dans la région. En moyenne, le manioc fut cultivé sur 0,6 ha, contribua au tiers de la consommation de féculents de base et généra des revenus de 84 $US par an. En termes de revenues, le manioc fut plus important en Ouganda dans les familles plus aisées (439 $US par an) que pour les paysans démunis (18 $US par an). Toutefois, son importance en tant que culture de subsistance ne varia pas entre les classes sociales. Au Kenya, les paysans les plus démunis ont consommé 11% plus de manioc que les familles plus aisées et ont gagné une plus grande proportion de leurs revenues grâce au manioc (16 contre 35%). Les paysans ont adopté des cultures associées sur 30% de leur surface cultivée en manioc en Ouganda contre 51% au Kenya, avec les paysans démunis ayant la plus grande préférence pour l'association de cultures. Comme les paysans sarclaient le manioc 3 à 6 fois, le besoin total de main d'œuvre pour le manioc (287 personnes-jours par Ha) fut plus élevé que pour d'autres cultures. Toutefois, due à son long cycle de développement (12 mois), les besoins mensuels de main d'œuvre pour le manioc furent relativement bas. La majorité des familles (60%) ont cultivé des variétés de manioc améliorées et le tiers a recruté la main d'œuvre pour le sarclage. Sur les sites ayant de grandes pressions démographiques, la majorité des familles (45-70%) ont utilisé de l'engrais pour l'association maïs-manioc. Nos résultats ont démontré qu'en Afrique de l'Est, la perception générale selon laquelle le manioc est une culture de subsistance cultivée par des paysans démunis qui le cultivent majoritairement en association avec d'autres cultures sans aucun intrant agricole et avec peu de main d'œuvre est soit fausses ou seulement à moitié vraie.

L'effet de la croissance de la pression démographique sur les niches physiques et temporelles du manioc fut évalué en combinant les données recueillies durant les enquêtes avec une étude sur les changements de la pression démographique et de l'utilisation des terres (Chapitre 3). A l'Ouest du Kenya la densité de la population a augmenté de 159 – 232 habitants au kilomètre carré en 1982 à 291 – 387 en 2004 alors qu'en Ouganda la densité augmenta de 14 – 98 habitants au kilomètre carré en 1959 à 41 – 328 en 2005. Les réponses des paysans furent similaires: ils ont réduit la taille des pâturages, des jachères arbustive et des jachères saisonnières, tout en augmentant clairement la superficie occupée par le manioc (de 1-11% à 16-55% de superficie cultivée). La grande majorité des paysans (62-100%) croit que le manioc régénère la fertilité des sols. Par conséquent, ils ont commencé à utiliser le manioc pour remplacer les jachères saisonnières. Sur quatre sites de forte pression démographique ayant un bas pH du sol (<5,8), les paysans ont choisi le manioc spécialement sur les sols moins fertiles et ce choix fut plus poussé pour les sols ayant un pH <5,4 et le phosphore disponible <5,5 mg par kg de sol. Ces modifications observées dans l'utilisation du sol ont en général doublé les prélèvements de nutriments sur les sols cultivés jusqu'à des valeurs estimées de 30-40 Kg par ha pour N, 4-8 Kg par ha pour P et 25-50 Kg par ha pour K. Actuellement, le manioc et le maïs sont responsables de la majorité des prélèvements de nutriment des sols (50-90%). Les résidus des cultures de maïs et de manioc interviennent à hauteur d'environ 70% dans le recyclage de nutriment où la majorité (50-70%) de N, P et K est recyclée par la chute des feuilles du manioc. Au cas où les systèmes évolueraient vers une rotation céréale-céréale, la productivité aurait probablement décrue due au manque de N et P.

Dans le but d'identifier les contraintes de la production de manioc, les données des enquêtes furent combinées aux études phytotechniques (Chapitre 4). Le premier groupe de données démontra une grande variabilité dans les rendements moyens du manioc en milieu paysan (2,7-17,8 T par ha) et une différence de rendement entre les 25% des fermes avec les rendement les plus faibles et les 25% des fermes avec les rendement les plus hauts de 6,1 T par ha pour le Kenya et de 9,7 pour l'Ouganda. Les rendements les plus élevés furent obtenus dans les champs de paysans à haut revenu annuel, qui, de plus, ont eu accès à plus de main d'ouvre (recrutée) et aux sols fertiles, ont appliqué un meilleur sarclage et ont récolté le manioc plus tardivement. Deux ans de recherches phytotechniques (n=122) dans six villages et deux stations de recherche en Ouganda et au Kenya ont montré que les étapes graduelles de gestion améliorée des cultures à savoir: (i) amélioration de l'établissement des cultures (plantation précoce, 1m x 1m d'écart, pas d'association) ; (ii) + amélioration variétale et (iii) + 100-22-83 Kg par ha d'engrais NPK, ont induit une augmentation de rendement de 1,5, 3,5 et 7,2 T par ha entre étapes. Le paquet entier de gestion a permis l'obtention de plus du double du rendement moyen des paysans. Les rendements du manioc sous le deuxième (ii) régime de gestion des cultures ont largement varié (2,8-27,3 T par ha). L'analyse de régression linéaire multiple, expliquant 38% de la variabilité observée au Kenya et 82% en Ouganda, identifia la pluviométrie, le désherbage et la fertilité du sol comme les facteurs les plus importants. L'analyse de la line de limite (Anglais : boundary line analysis) quantifia la contribution moyenne de la fertilité du sol, la pluviométrie, le sarclage, la texture du sol ainsi que les ravageurs et maladies au rendement respectivement comme 6,7, 6,0, 5,4, 4,3 et 3,8 T par ha. Les contraintes individuelles ont largement varié entre les champs et les années; et la production de manioc fut souvent simultanément influencée par divers contraintes. D'importantes interactions furent observées entre les contraintes de production, par exemple, la faible pluviométrie réduite l'influence positive du sarclage. Les paysans les plus démunis souffrent plus de contraintes que les nantis, comme leurs sols sont moins fertiles et qu'ils ont moins d'accès aux capitaux sociaux et financiers.

La fertilité des sols étant la principale contrainte de production, nous avons évalué la réponse du manioc aux minéraux N, P et K et étudié les facteurs qui influencent la réponse à la fertilisation (Chapitre 5). Nous installâmes des essais de fertilité sur huit sites en Ouganda et au Kenya, en utilisant 100-22-83 Kg par ha d'engrais NPK et 3 variétés par pays dans la première année et en utilisant l'approche d'omission de nutriments et une variété par pays dans la seconde année. L'engrais NPK a augmenté les rendements, la biomasse aérienne et le nombre de tubercules par plant, mais n'a pas affecté les paramètres de qualité du manioc ni la pression des ravageurs et maladies, exception faite pour la mosaïque. L'essai d'omission de nutriments montra que la production de manioc en Ouganda fut limitée par N et P alors qu'au Kenya N, P et K étaient les facteurs limitants. Alors que les rendements ont varié entre variétés, la réponse à l'engrais ne fut pas fonction de variétés. La réponse moyenne à l'engrais a fortement varié entre sites et années (-0,2 T par ha à 15,3). Nos résultats ont montré que la réponse aux engrais était gouvernée par les mêmes facteurs et interactions qui déterminent les rendements de manioc sans fertilisant (fertilité du sol, pluviométrie et désherbage). Ceci explique partiellement la grande variabilité dans la réponse aux engrais observée sur les sols infertiles (sur des sols ayant le carbone organique du sol (COS) <10 g par Kg de sol les réponses variant de -8,6 à 24,4 T par Ha). La faible pluviométrie pendant la phase initiale a réduit l'effet positif du fertilisant sur la production potentielle des hydrates de carbone dans la biomasse aérienne et le stockage potentiel des hydrates de carbone dans les tubercules (Anglais: source supply and sink capacity). Comme l'engrais augmentait la croissance initiale de la plante, le désherbage dans les parcelles fertilisées a été seulement payant quand la croissance initiale était lente (stress hydrique).

Dans le chapitre 6, nous avons exploré les conséquences de quatre niveaux graduels de gestion intense sur divers indicateurs de durabilité : (i) augmentation de la culture du manioc; (ii) adoption de variétés améliorées de manioc; (iii) adoption de gestion amélioré de culture; et (iv) utilisation d'engrais NPK. A cause du manque de model calibré de manioc, nous avons combiné un model de COS avec des fonctions de courbe limite décrivant le rendement et la biomasse aérienne de manioc et du maïs par rapport au COS à l'Ouest du Kenya. Nous avons complété le modelage avec des données de rendement et nutriment des variétés locales de manioc, les variétés améliorées récentes et anciennes. Nos simulations ont indiqué que l'augmentation de culture de manioc observée sur les sols pauvres aurait contribué à la maintenance du rendement et du COS et aurait augmenté le recyclage des nutriments en comparaison avec le maïs. L'adoption à grande échelle des anciennes variétés améliorées n'a très probablement pas affecté la durabilité de systèmes tels que le rendement, la biomasse aérienne, la concentration de nutriments et par conséquent le prélèvement de nutriment, le ratio de recyclage ainsi que les effets sur le COS furent semblables à ceux des cultivars locaux. L'adoption des nouvelles variétés ainsi que la gestion améliorée aura des effets positifs sur le rendement et donc augmentera le ratio de prélèvement de nutriments, mais va simultanément promouvoir le recyclage des nutriments et augmenter le niveau du COS due à une plus grande production de biomasse aérienne. L'adoption d'engrais NPK améliorera la balance de nutriments et probablement aussi le recyclage de nutriments et le niveau de COS. A présent, les paysans utilisent environ 80% des tiges de manioc comme bouture ou bois de feu. L'adoption de variétés nouvellement développées, qui produisent aussi plus de biomasse que les variétés locales, permettra aux paysans de retourner au champ une plus grande fraction de tiges et réduire par conséquent considérablement le prélèvement de nutriments tout en maintenant la même pratique pour bouture et bois de chauffage.

Dans le chapitre 7 nous avons conclu que les rôles et niches que joue le manioc dans le système de production en Afrique de l'Est ont changé avec le temps comme résultat de la pression démographique. L'augmentation substantielle de la culture de manioc a permis aux paysans de reporter l'intensification de la gestion des cultures, mais il semblerait que l'élasticité du système traditionnel avec peu d'intrant arrive à sa fin puisque la production des deux cultures les plus importantes (manioc et maïs) est limitée par les nutriments et les paysans qui font face a des pressions démographiques de plus en plus élevées ont commencé par adopter l'engrais, la fumier ainsi que la gestion améliorée des cultures. Nous avons aussi conclu que le gap entre le rendement actuel et celui attingible au niveau paysan est encore énorme. Le control intégré des ravageurs et l'amélioration des plantes à eux seuls ne peuvent pas rattraper ce retard d'autant plus que les contraintes abiotiques et la gestion des cultures sont bien plus importantes que conçu dans le passé. La fermeture du décalage de rendement requiert le développement et l'évaluation de paquets de gestion intégrée pour faire face aux multiples et interactives contraintes de production. Ceci représente une forte réévaluation de l'agenda actuel des programmes de recherche sur le manioc qui ont tendance à se focaliser sur les contraintes biotiques. Le développement et la promotion de pratiques culturales améliorées peuvent être empêché par la fausse perception qu'ont les chercheurs et les agents de divulgation à propos du manioc et par le manque de capacité en phytotechnie sur le manioc. A cause de la forte sécurité alimentaire et aussi du fait que le manioc est une importante culture de vente pour la majorité des paysans de petite échelle, les efforts pour augmenter la production du manioc dans les systèmes de production à base du manioc amélioreraient le quotidien des paysans surtout par l'amélioration du domaine de commercialisation du manioc, à moins que la production soit menacée par de sérieux ravageurs et maladies. Ce serait plus difficile à faire pour les paysans démunis du fait que ceux-ci ont plus de chances d'être confronté avec de multiples contraintes de production avec moins d'accès aux capitaux sociaux et financiers nécessaires pour améliorer la production. Du fait que le manioc est un composant si important dans les systèmes de production, toute pratique de gestion (adoptée) qui améliorerait la balance de nutriments, le recyclage de nutriments et/ou la quantité de COS contribuerait à améliorer la durabilité générale du système. Nous formulons l'hypothèse qu'à travers toutes les systèmes de production étudiés, la pression démographique, les opportunités de marché, les coûts d'engrais, le changement climatique et la situation financière des paysans sont les plus importants mobiles de changement en ce qui concerne le rôle/niche et importance du manioc dans les prochaines décennies. Nous avons discuté les conséquences de plusieurs scénarios possibles du rôle du manioc et de la durabilité des systèmes. Bien que la phytotechnie du manioc soit encore dans sa phase infantile en Afrique, plusieurs leçons valables pourront être apprises des recherches sur le manioc en Asie et en Amérique Latine et des recherches de phytotechnie sur d'autres cultures en Afrique. Pour identifier les contraintes de production à travers l'Afrique, et fixer les priorités pour la recherche pour le développement, il sera nécessaire de conduire des études d'écarts de rendement à travers les principales zones agro écologiques où le manioc est cultivé. Une fois que les priorités seraient connues, le développement et l'évaluation participative des meilleurs complexes de pratiques culturales devront avoir lieu dans les environnements hétérogènes de petits paysans en prenant en considération la balance de main d'œuvre et intrants entre le manioc et les autres cultures et activités champêtres

Samenvatting

De bodemvruchtbaarheid in grote delen van Afrika ten zuiden van de Sahara is laag als gevolg van inherent onvruchtbaar moedermateriaal en/of door continu gebruik van het land zonder externe inputs. De snelle bevolkingsgroei in heel Afrika vergroot de druk op het land en versterkt de uitputting van natuurlijke hulpbronnen. Agrarische bedrijfssystemen worden gekenmerkt door kleine bedrijven met een erg divers, heterogeen en dynamisch karakter. Derhalve werken sommige managementstrategieën wel in één gedeelte van een bedrijf, maar niet in een ander gedeelte. Rijkere huishoudens hebben over het algemeen een betere toegang tot middelen dan armere huishoudens en hebben daarom een bredere keuze aan managementopties. Cassave (*Manihot esculenta* Crantz) is een belangrijk gewas in heel Afrika. De productie is bijna verviervoudigd in de afgelopen vijf decennia. Met het oog op klimaatsveranderingen heeft NEPAD cassave, een relatief droogtetolerant gewas, in Afrika aangewezen als strategisch landbouwgewas om zo de afhankelijk van maïs te verminderen.

Dit proefschrift concentreert zich op agrarische bedrijfssystemen van kleine boeren in de middelhoge gebieden van Oost-Afrika met een belangrijke cassavecomponent. Het gebied wordt gekenmerkt door hoge landdruk, twee regenseizoenen per jaar en relatief arme bodems. De landdruk is vooral hoog in West-Kenia (>250 personen km^{-1}). Dit gebied vertegenwoordigt daarom mogelijk de richting waarin veel agrarische bedrijfssystemen in Afrika met vergelijkbaar klimaat en bodems zich zullen ontwikkelen. Oost-Afrika is goed voor ca. 11% van de totale cassaveproductie in Afrika. Gemiddelde boerenopbrengsten (6.5-12 t ha^{-1}) liggen ver beneden de gemiddelde opbrengsten in veredelingsexperimenten (15-40 t ha^{-1}). Dit duidt op veel ruimte om de opbrengsten te verbeteren. De productie van cassave had en heeft nog steeds veel te lijden onder de cassavemozaïekplaag (Engels acroniem: CMD), die wordt bestreden door de grootschalige introductie van resistente genotypes. Er is echter weinig bekend over het beheer van andere productiebeperkingen en hoe belangrijk deze zijn. De algemene doelstelling van dit onderzoek was om de rollen en productiebeperkingen van cassave binnen kleine boerenbedrijven beter te begrijpen, om zo mogelijkheden te bestuderen om de productiviteit en duurzaamheid van deze intensiverende systemen met een belangrijke cassavecomponent in Oost-Afrika te verbeteren.

Om de rollen, niches en management van cassave te evalueren in relatie tot algemeen bestaande percepties over het gewas, hebben we een serie van bedrijfsenquêtes (n =

120) uitgevoerd in zes dorpen in Oeganda en Kenia (Hoofdstuk 2). Sociaaleconomische factoren varieerden sterk, zowel tussen als binnen gebieden: het gemiddeld jaarinkomen varieerde bijvoorbeeld van 633 tot 1283 US$ jaar^{-1} tussen gebieden en van 287 tot 2456 US$ jaar^{-1} tussen groepen van boeren met verschillende rijkdom. Managementfactoren varieerden over het algemeen sterker tussen dan binnen gebieden: mestgebruik varieerde bijvoorbeeld van 0 tot 904 kg ha^{-1} tussen gebieden en van 263 tot 458 kg ha^{-1} tussen groepen met verschillende rijkdom. Cassave was een belangrijk voedselgewas en inkomstenbron in alle gebieden en voor alle inkomensklassen. De gemiddelde voedselzekerheid (>10 maanden jaar^{-1}) was beter dan in agrarische gebieden met een belangrijke maïscomponent. Gemiddeld werd cassave op 0.6 ha verbouwd, leverde het een derde van de totale zetmeelconsumptie en genereerde het een inkomen van 84 US$ jaar^{-1}. Als inkomstenbron was cassave in Oeganda belangrijker voor rijkere boeren (439 US$ jaar^{-1}) dan voor armere boeren (18 US$ jaar^{-1}), maar als voedselgewas was het even belangrijk voor alle inkomensklassen. In Kenia, daarentegen, aten armere boeren 11% meer cassave dan rijkere boeren en verdienden zij ook een groter gedeelte van hun gewasinkomsten uit cassave (16 tegen 35%). Oegandese boeren plantten 30% van hun cassaveareaal als mengteelt en Keniaanse boeren 51%, waarbij armere boeren een grotere voorkeur voor mengteelt hadden dan rijkere boeren. Omdat boeren hun cassavevelden drie tot zes keer wiedden, was de totale arbeidsbehoefte (287 mandagen ha^{-1}) hoger dan voor andere gewassen. De maandelijkse arbeidsbehoefte van cassave was echter relatief laag door de lange groeiduur (12 maanden) van het gewas. De meerderheid van de huishoudens (60%) plantte verbeterde cassavegenotypes en een derde huurde arbeid voor het wieden van cassavevelden. In gebieden met een hoge landdruk diende de meerderheid van de huishoudens (45-70%) mest toe aan velden met een cassave-maïs mengteelt. Onze resultaten laten zien dat in Oost-Afrika de algemeen bestaande percepties van cassave als voedselgewas, verbouwd door arme boeren, meestal als mengteelt, zonder inputs en met weinig arbeid, onjuist of maar half waar zijn.

Om de invloed van de toenemende landdruk op de fysische en temporele niches van cassave te beoordelen, hebben we de resultaten van de boerenenquêtes gecombineerd met een studie naar de veranderingen in bevolking en landgebruik (Hoofdstuk 3). In West-Kenia is de bevolkingsdruk toegenomen van 159-232 mensen km^{-2} in 1982 tot 291-387 mensen km^{-2} in 2004, terwijl in Oeganda de bevolkingsdruk is toegenomen van 14-98 mensen km^{-2} in 1959 tot 41-328 mensen km^{-2} in 2005. In alle gebieden reageerden boeren hetzelfde: ze verminderden het areaal aan begrazingsgronden, gras/struik braaklegging en/of een-seizoens-braaklegging, en vergrootten tegelijkertijd het areaal aan cassave aanzienlijk (van 1-11% naar 16-55% van het bebouwde oppervlakte). De grote meerderheid van de boeren (62-100%) gelooft dat cassave de bodemvruchtbaarheid herstelt en begon daarom cassave als vervanging voor een-seizoens-braaklegging te gebruiken. In vier gebieden met een hoge landdruk en bodems met een lage pH (<5.8) werd cassave doelbewust op minder vruchtbare bodems geplant. Dit doelbewust planten was het sterkst als bodems een pH <5.4 en beschikbaar P <5.5 mg kg^{-1} hadden. Door de geobserveerde veranderingen in landgebruik is de verwijdering van nutriënten van bebouwde velden verdubbeld tot een geschatte 30-40 kg ha^{-1} N, 4-8 kg ha^{-1} P en 25-50 kg ha^{-1} K, waarbij de grote meerderheid (50-90%) van de nutriënten verwijderd wordt door cassave- en maïsteelten. Gewasresten van cassave en maïs nemen ruwweg 70% van de nutriëntenrecycling voor hun rekening, waarbij de meerderheid (50-70%) aan N, P en K hergebruik voor de rekening van cassavebladval komt. Indien de landbouwsystemen geïntensiveerd waren tot een vruchtwisseling van graan-graan, dan zouden de gewasopbrengsten hoogstwaarschijnlijk achteruitgegaan zijn door een gebrek aan N en P.

De boerenenquêtes werden gecombineerd met landbouwkundige experimenten om de productiebeperkende factoren in de cassaveteelt te identificeren (Hoofdstuk 4). De eerste set gegevens liet een grote variabiliteit in gemiddelde cassaveopbrengsten zien onder huidig boerenmanagement (2.7-17.8 g ha^{-1}). Het verschil tussen boeren met de 25% laagste en 25% hoogste opbrengsten bedroeg 6.1 t ha^{-1} in Kenia en 9.7 t ha^{-1} in Oeganda. De hoogste opbrengsten werden behaald op bedrijven met een hoog jaarinkomen, die meer beschikking hadden over (gehuurde) arbeid en vruchtbare bodems, hun velden beter wiedden en de cassaveoogst uitstelden. De resultaten van twee jaar landbouwkundige experimenten (n = 122) in zes dorpen en twee onderzoeksstations in Kenia en Oeganda lieten zien dat het stapsgewijs opwaarderen van het gewasbeheer door: (i) verbeterde gewas aanplant (vroeg planten, 1 m x 1 m plantafstand, geen mengteelt); (ii) + verbeterde genotypes; en (iii) + 100-22-83 kg ha^{-1} N-P-K kunstmestgift resulteerde in een gemiddelde opbrengsttoename van 1.5, 3.5 en 7.2 t ha^{-1} tussen de stappen. De gemiddelde boerenopbrengsten werden meer dan verdubbeld door het gebruik van het totale managementpakket. Cassaveopbrengsten op managementniveau ii liepen sterk uiteen (2.8-27.3 t ha^{-1}). Met behulp van meervoudige lineaire regressieanalyse kon 38% van de geobserveerde variabiliteit in Kenia en 82% in Oeganda verklaard worden en regenval, onkruidbeheer en bodemvruchtbaarheid als belangrijke verklarende variabelen aangewezen worden. Met behulp van een ‘boundary line’ analyse werd de gemiddelde bijdrage van bodemvruchtbaarheid, regenval, onkruidbeheer, bodemtextuur en ziekten en plagen aan het verschil tussen werkelijke en mogelijke opbrengsten gekwantificeerd als 6.7, 6.0, 5.4, 4.3 and 3.8 t ha^{-1}. Individuele beperkingen varieerden sterk tussen velden en jaren en de productie van cassave leed vaak onder het gelijktijdig optreden van meerdere beperkingen. We observeerden belangrijke interacties tussen productiebeperkende factoren, bv. lage regenval verminderde de effectiviteit van onkruidbeheer. Armere boeren lopen een groter risico op meervoudige productiebeperkingen dan rijkere boeren omdat hun bodems minder vruchtbaar zijn en ze minder beschikking hebben over financieel en sociaal kapitaal.

Omdat bodemvruchtbaarheid de belangrijkste productiebeperkende factor was, hebben we vervolgens de response van cassave op N, P and K kunstmest geëvalueerd en de factoren bepaald die de reactie op kunstmest beïnvloedden (Hoofdstuk 5). We hebben kunstmestexperimenten geïnstalleerd op 8 plaatsen in Kenia en Oeganda, waarbij we in het eerste jaar een kunstmestgift van 100-22-83 kg ha^{-1} N-P-K en drie genotypes per land gebruikten en in het tweede jaar een nutriëntenomissie experiment en één genotype per land. Het gebruik van NPK kunstmest vergrootte de opbrengsten, bovengrondse biomassa en het aantal opslagwortels per plant, maar had geen effect op de kwaliteit van de wortels en op de ziekte en plaagdruk, afgezien van CMD. De nutriëntenomissie experimenten lieten zien dat cassaveproductie in Oeganda beperkt werd door N en P, en in Kenia door N, P en K. Hoewel onbemeste opbrengsten varieerden tussen gebieden en genotypes, was dit niet het geval voor de response op kunstmest. Nochtans varieerde de gemiddelde response sterk tussen gebieden en jaren (-0.2 tot 15.3 t ha^{-1}). Onze resultaten laten zien dat de response op kunstmest werd bepaald door dezelfde factoren en interacties die de onbemeste cassaveproductie beïnvloedden, i.e. bodemvruchtbaarheid, regenval en onkruidbeheer. Dit verklaart wellicht voor een deel de grote variabiliteit in kunstmestresponse op onvruchtbare bodems (i.e. op bodems met een organisch stofgehalte <10 g kg^{-1} varieerden de responsen van -8.6 tot 24.4 t ha^{-1} Een lage regenval gedurende de initiële groei verminderde het positieve effect van kunstmest op de potentïele hoeveelheid koolhydraten die in de bovengrondse biomassa kan worden geproduceerd en op de potentïele hoeveelheid koolhydraten die in de opslagwortels kan worden opgeslagen (Engels: source supply and sink capacity). Omdat kunstmest de initiële plantgroei bevorderde, was onkruidbeheer in bemeste velden alleen de moeite waard als de initiële groei langzaam was (door bv. waterstress).

In Hoofdstuk 6 bestudeerden we de gevolgen van vier niveaus van toenemend management intensiteit op verschillende duurzaamheidindicatoren: (i) toename van cassaveareaal; (ii) adoptie van verbeterde cassavegenotypes; (iii) adoptie van verbeterd gewasbeheer; en (iv) NPK kunstmestgebruik. Aangezien er geen gekalibreerd cassavemodel bestaat voor Oost-Afrika, hebben we een bestaand organisch stof model gekoppeld aan ‘boundary line’ functies die de relatie tussen opbrengst en bovengrondse biomassa van cassave en maïs en organische stof beschrijven in West-Kenia. De modelsimulaties werden aangevuld met opbrengst- en nutriëntengegevens van cassavelandrassen, vroeg uitgebrachte en recent ontwikkelde cassavegenotypes. Onze simulaties geven aan dat de waargenomen toename van cassaveareaal op onvruchtbare bodems bijgedragen zou kunnen hebben aan het op peil houden van opbrengsten en organisch stof gehalte en het hergebruik van nutriënten vergroot zou kunnen hebben in vergelijking met maïs. De grootschalige adoptie van vroeg uitgebrachte cassavegenotypes heeft hoogstwaarschijnlijk geen gevolg gehad voor de duurzaamheid van de landbouwsystemen aangezien opbrengsten, bovengrondse biomassa, nutriëntenconcentraties en dus nutriëntenverwijdering, nutriënten hergebruik en effecten op organische stof gelijk waren aan die van cassave landrassen. De adoptie van recent ontwikkelde genotypes en de adoptie van verbeterd gewasbeheer zullen de opbrengsten verhogen en dus resulteren in meer nutriëntenverwijdering, maar tegelijkertijd bevorderen ze wellicht de hoeveelheid nutriënten die worden hergebruikt en verbeteren ze mogelijk het organische stofgehalte door een grotere bovengrondse biomassaproductie. De adoptie van NPK kunstmestgebruik zal de nutriëntenbalansen verbeteren en waarschijnlijk bijdragen aan meer nutriëntenrecycling en hogere organisch stofgehaltes. Op dit moment gebruiken boeren ongeveer 80% van de cassavestammetjes als plantmateriaal of als brandhout. De adoptie van recentelijk ontwikkelde genotypes, die meer biomassa produceren dan de landrassen, geeft boeren de mogelijkheid om een groter gedeelte van de stammetjes op het veld achter te laten, en dus de hoeveelheid nutriënten die verwijderd worden flink te verminderen, terwijl dat niet ten koste gaat van de hoeveelheid plantmateriaal en brandhout.

In Hoofdstuk 7 concluderen we dat de rollen en niches die cassave heeft binnen de landbouwsystemen in Oost-Afrika door de tijd heen veranderd zijn door de toenemende landdruk. De substantiële toename in cassaveareaal heeft het boeren mogelijk gemaakt het intensiveren van gewasbeheer uit te stellen, maar het lijkt erop dat er een einde aan het komen is aan de elasticiteit van de traditionele laag-input systemen: de productie van de twee hoofdgewassen (cassave en maïs) is beperkt door nutriënten en boeren die te maken hebben met een hoge landdruk zijn begonnen met het adopteren van kunstmestgebruik en verbeterd gewasbeheer. We concluderen ook dat het gat tussen werkelijke en bereikbare opbrengsten op bedrijfsniveau groot is. Omdat abiotische productiebeperkingen en gewasbeheer veel belangrijker zijn dan vroeger werd gedacht, zijn integraal beheer van ziektes (Engels acroniem: IPM) en veredeling alleen niet genoeg om dit gat te dichten. Dit vereist de ontwikkeling en evaluatie van geïntegreerde managementpakketten om zo de vaak inter-acterende en simultaan optredende productiebeperkingen effectief te kunnen aanpakken. Dit houdt in dat cassaveonderzoeksprogramma's hun huidige agenda, die vaak voornamelijk op biotische productiebeperkingen gefocust is, structureel zullen moeten aanpassen. De ontwikkeling en promotie van verbeterde gewaspraktijken kan bemoeilijkt worden door de verkeerde percepties die onderzoekers en voorlichters mogelijkerwijze hebben met betrekking tot cassave en door het gebrek aan wetenschappelijke capaciteit op het gebied van cassaveagronomie. Omdat de voedselzekerheid hoog is en cassave een belangrijke bron van inkomsten is voor de meerderheid van de kleine boeren, zullen inspanningen om de cassaveproductie te verhogen in landbouwsystemen met een belangrijke cassavecomponent vooral bijdragen aan het verbeteren van de leefsituatie van kleine boeren door het verruimen van de mogelijkheden voor cassavecommercialisatie. Het zal moeilijker zijn om dit te bereiken voor armere boeren omdat zij vaker met meervoudige productiebeperkingen te maken hebben en minder toegang hebben tot het financiële en/of sociale kapitaal dat benodigd is om de productie te verbeteren. Omdat cassave zo'n belangrijk onderdeel uitmaakt van de bestudeerde systemen, zal elke (geadopteerde) managementstrategie die de nutriëntenbalans en/of nutriëntenrecycling en/of organisch stof gehalte positief beïnvloedt, bijdragen tot het verbeteren van de algehele duurzaamheid van het systeem. We veronderstellen dat voor alle bestudeerde landbouwsystemen de belangrijkheid en rollen/niches van cassave in de volgende decennia met name bepaald zullen worden door de volgende sturende factoren: landdruk, afzetmogelijkheden, kunstmestprijzen, klimaatsverandering en boerenvermogen. We bediscussiëren de gevolgen van enkele mogelijke scenario's voor de rollen die cassave vervult en de duurzaamheid van de systemen. Ondanks het feit dat cassaveagronomie in Afrika nog in haar kinderschoenen staat, kunnen we veel waardevolle lessen leren van cassaveonderzoek in Azië en Latijns-Amerika en van agronomieonderzoek aan andere gewassen in Afrika. Om de productiebeperkingen voor cassave te identificeren en zo prioriteiten op te stellen voor cassave onderzoek in Afrika, zal het nodig zijn om meer studies uit te voeren naar de opbrengstbeperkende factoren in de belangrijkste agro-ecologische zones waar cassave verbouwd wordt. Als de prioriteiten eenmaal bekend zijn, zal de ontwikkeling en participatieve evaluatie van bestpassende managementstrategieën bij voorkeur moeten plaatsvinden in de heterogene omgeving van kleine boeren en zal rekening moeten houden met trade-offs van arbeid en input tussen cassave en andere gewassen/bedrijfsactiviteiten.

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At the start of 2003 I took up a job as an Associate Professional Officer (APO) at the International Institute of Tropical Agriculture (IITA) in Kampala, Uganda. The job description turned out to be vague and not linked to an existing project. After some initial disappointment that I did not find a ‘spread bed’, I realised the advantages this gave me: the freedom to develop my own ideas. After a year of getting to know cassava and identifying potentially interesting topics to work on, I approached Ken Giller to discuss the possibility to develop a PhD project. I had first met Ken in August 2003 at the PhD defence of Piet, my husband, where he was one of the opponents. Ken’s systems approach to and his profound knowledge of African agriculture caught my attention. Ken enthusiastically welcomed me as an external PhD student. He has critically challenged my ideas throughout the past years and taught me to extract the stories worth telling from my data. Since discussions per email were not always very effective, I was glad that he convinced me to spend two months at his department in the summer of 2008. Mark van Wijk has been a great support in statistics and the modelling exercise. I enjoyed his friendly criticism and appreciated the time he spent working with me last December. Mariana, thank you for the beautiful artwork for the cover of this thesis, your advice on the final process of preparing my thesis, and your friendship.

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At IITA, I owe a lot to Paula Bramel, the woman behind IITA's science. Paula believed in me and gave me the opportunity to stay with IITA as a visiting scientist after my APO contract finished. I hope my work will contribute to IITA's efforts to improve the livelihood of smallholder cassava farmers in Africa. John Wendt, my initial supervisor at IITA, gave me plenty of freedom and the occasional chocolate treats. Steffen Abele, who took over from John in 2006, improved my knowledge on the economical aspects of farming systems analysis and supported my research within IITA. It has been a pleasure to be part of the IITA-Uganda team for over 6 years. Pheneas Ntawuruhunga, James Legg and their cassava teams have shared their knowledge on IPM and cassava breeding, taught me to recognise pest and diseases, and advised me on management issues in the ACDI/VOCA cassava project. Danny Coyne, Fen Beed, Jim Lorenzen, Leena and Jay Tripathi, Thomas Dubois, Komi Fiaboe, and of course Piet van Asten, have ensured that I am not a complete cassava freak, but also know something about bananas. So did Lydia Wairegi, my fellow PhD student, who shared with me the joys and pains of publishing articles. They and the admin/support team of IITA-Uganda, consisting of Beatrice, Suzan, Doreen, Janet, Prossy, Maria, Millie, Barbara, Antony, Johnson, Patrick and others, have been great colleagues. Thanks to Sarah Hearne, Ranajit Bandyopadhyay, Sicco Kolijn, Morag Ferguson, Robert Asiedu, Stefan Hauser, Jelle Duindam, Alfred Dixon, Nzola Mahungu and Abbas Adebayo of IITA-Nigeria, IITA-Kenya, IITA-DRC, IITA-Cameroun, IITA-Mozambique and IITA-Malawi for sharing their knowledge and ideas on cassava agronomy, physiology, breeding, commercialization and pests and diseases with me. A special thankyou to Chris Legg, the former head of the IITA GIS lab for his help in preparing the cassava production map in the introduction chapter and to Komi Fiaboe and my mum for translating the summary into French.

'My own' cassava team was lead by two strong women, Annet Babirye in Uganda and Josephine Lubondi in Kenya. Apart from being a good research assistant, Annet is a fantastic interviewer and has such good people skills that farmers would willingly spend half a day showing her every single field they used. They would be proud instead of annoyed if Annet returned the next day to check on some inconsistencies she had found within the interview data. Annet and I spend many nights together in small hotels, or even bare rooms in Ugandan villages, and it is mainly because of her that I now have some understanding of Ugandan culture. Annet was assisted by Alfred Omongole, Emmanuel Ntege and Jeremiah Musimami, who cheerfully helped us with the on-station and on-farm trials. Dennis Nteza assisted with soil and plant sample preparation and Godfrey Taulya took great care of all issues surrounding quality control management before, during and after analysis. Symon Wandiembe provided some excellent statistics support. In Kenya, Josephine worked extremely independent, leading the Kenyan team meticulously. Although she and her team had to get by with public transport most of the time, they were fully on-top of the roughly 15 on-station trials and the 80 on-farm trials we installed over the years in 5 sites across western Kenya. She was assisted by Joseph Kizimi, who turned out to have much more capacity than the average casual labourer. Joseph worked together with Pablo Gonzalez, an MSc student from Wageningen University, carrying out farm surveys in three of the Kenyan sites and later gathering additional information by himself.

My research work was carried out in close collaboration with the Kenyan Agricultural Research Institute (KARI) and the National Crops Resources Research Institute (NaCRRI) in Uganda. Dr. Anton Bua, Dr. Yona Baguma and Dr. Titus Alicai of NaCRRI and Dr. Martin Odendo, Mr. Hannington Obiero of KARI-Kakamega and Mr. Lazarus Kisuya of KARI-Alupe have been indispensable in this collaboration, teaching me the ins and outs of cassava production in their country, inviting me onto their research stations and allowing me to work with their staff, assisting in site selection and with the general logistics of field operations. Mozes Wambulwa, Alice Were, Geoffrey Mafura of KARI-Alupe and John Robert Oba, Haruna Kalumba and Nelson Erimu of NaCRRI have kindly assisted us with the field work and data collection. Thanks as well to the staff of the National Agricultural Research Organisation (NARO) laboratory in Kawanda, in specific to Markstuart Kibirango, for all assistance given.

The central, and most enjoyable, part of my research took place on-farm. Without the assistance we received from farmer communities around Uganda and western Kenya, this research would not have been possible. We have worked with over 200 families from Kikooba, Minani Kisiro, Bubutya and Chelekura in Uganda and from Kwang’amor, Mungatsi, Nambale and Ugunja in western Kenya. They all warmly received us, taught us about the various roles of cassava within their farming systems or participated in the agronomic trials. I hope they have benefited from the exchange of knowledge and the new cassava genotypes that were introduced. They can be proud of their contributions to the development of cassava agronomy knowledge in East Africa! Our on-farm work was kindly facilitated by Save the Children (Kikooba), RAPTA (Minani), NALG (Kisiro and Bubutya), Amora Ican women’s group (Chelekura), Punjuza Umaskini (Kwang’amor), Fanya Field School (Mungatsi), Agrofarmers (Nambale) and Ugunja Community Resource Centre (Ugunja).

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Piet and I have lived and worked for the past 12 years in Africa, moving from South Africa to West Africa (Senegal) and to East Africa (Uganda). I have been extremely lucky in finding someone to share my life with, who is not only a fantastic husband and father to our children, but who also shares my ideals and generally has the same vision on life as I have. We hebben het goed samen. As an agronomist/soil scientist himself, Piet has been involved in this research from its conception. His down to earth approach to science and life, his systems thinking, combined with good knowledge on soil and plant processes, and his positive criticism have been a great help all along. We arrived in Uganda on the first birthday of Eva Coumba, our daughter. Then, at the end of 2004 our son Guido Kito was born. They are bringing such great joy to our lives! I am therefore extremely happy that, after finishing my APO contract, I have had the opportunity to work part-time on this research. In doing so, I managed to strike a good balance between work and private life, which probably made me one of the least stressed PhD students ever.

Anneke

Kampala, 8 Maart 2009

List of Publications

1. Journal papers

Fermont, A.M., Babirye, A., Obiero, H.M., Abele, S.,Giller, K.E., 2009. Testing generalizations about cassava in East Africa and consequences for policy and development interventions. Submitted to Agronomy for Sustainable Development.

Fermont, A.M., Tittonell, P., Baguma, Y., Ntawuruhunga, P., Giller, K.E., 2009. Towards understanding factors that govern fertilizer response in cassava: lessons from East Africa. Nutrient Cycling in Agroecosytems. In press.

Fermont, A.M., van Asten, P.J.A., Tittonell, P., van Wijk, M.T., Giller, K.E., 2009. Closing the cassava yield gap: an analysis from small-holder farms in East Africa. Field Crops Research 112, 24-36.

Van Asten, P.J.A., Kaaria, S., Fermont, A.M., Delve, R. J., 2009. Challenges and lessons when using farmer knowledge in agricultural research and development projects in Africa. Experimental Agriculture 45, 1-14.

Fermont, A.M., van Asten, P.J.A., Giller, K.E., 2008. Increasing land pressure in East Africa: The changing role of cassava and consequences for sustainability of farming systems. Agriculture, Ecosystems and Environment 128, 239-250.

Metternicht, G.I., Fermont, A.M., 1998. Estimating erosion surface features by linear mixture modelling, Remote Sensing Environment 64, 254-265.

Droogers, P., Fermont, A., Bouma, J., 1996. Effects of ecological soil management on workability and trafficability of a loamy soil in the Netherlands. Geoderma 73, 131-145.

2. Technical papers and reports

Kebbeh, M., Wopereis, M.C.S., Miézan, K., Diack, B.S., Fermont, A.M., 2004. Assessing profitability and productivity gaps in irrigated rice in the Sahel. Sahelian studies and research 10, Institute du Sahel, Bamako, Mali.

Fermont, A.M., 2002. Amélioration de la Riziculture sur des Sols Dégradés dans la Vallée du Bignona, au Sénégal – Résultats de l’Hivernage 2001/2002. Technical report, WARDA, St. Louis, Senegal, 26 p.

Fermont, A.M., 2001, Rice Cultivation and Soil Degradation in the Bignona Valley, Senegal, Developing Management Options for Rice Cultivation on Degraded Soils using a Participatory Approach. Technical report, WARDA, St. Louis, Senegal, 76 p.

Fermont, A.M., van Asten, P.J.A., Keet, J.D., van Boom, E.M., 1998. Urban Vegetable Production in the Cape Flats. School of Environmental Studies, Occasional Publication Series 1, University of the Western Cape, Cape Town, South Africa, 88 p.

3. Abstracts and proceedings

Fermont, A.M., 2008. The importance of agronomy and fertilizer us for cassava productivity; Some lessons from East Africa. First scientific meeting of the Global Cassava Partnership, 21-25 July 2008,Ghent, Belgium.

Duindam, J., Fermont, A.M., Hauser, S., 2008. Improving smallholder cassava production by new varieties and best agronomic practices on Ultisols in southern Cameroun. Tropentag, 7-9 October 2008, University of Hohenheim, Stuttgart, Germany.

Babirye, A., Fermont, A.M., 2007. Understanding cassava yield difference at farm level: Lessons for research. AfNet symposium, 17-21 September 2007, Arusha, Tanzania.

Fermont, A.M., Obiero, H.M., van Asten, P.J.A., Baguma, Y., Okwuosa, E., 2004. Improved cassava varieties increase the risk of soil nutrient mining: an ex-ante analysis for western Kenya and Uganda, AfNet symposium, 16-22 May 2004, Yaounde, Cameroun.

van Asten, P.J.A., Fermont, A.M., van Boom, E.M., Keet, J.D., 1998. Management options for vegetable gardening in the Cape Flats, with special emphasis on the feasibility of agroforestry. International conference on Urban agriculture, March 1998, Pretoria, South Africa.

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 (4.2 ECTS)

- Managing nutrients: developing management practices for cassava-based cropping systems in Eastern Africa (2003)

Writing of Project Proposal (2.8 ECTS)

- Managing nutrients: developing management practices for cassava-based cropping systems in Eastern Africa (2003)

Laboratory Training and Working Visits (1.4 ECTS)

- Soils laboratory training; IITA & Kawanda Soils lab (2004)

Post-Graduate Courses (4.4 ECTS)

- DSSAT version 4: assessing crop production, nutrient management, climate risk and environmental sustainability with simulation modelling; Arusha, Tanzania; AFNET, Univ. of Florida, ICRISAT, TSBF-CIAT (2004)
- Analyzing farming systems and rural livelihoods in a changing world: vulnerability and adoption; Harare, Zimbabwe; University of Wageningen & Harare (2008)

Deficiency, Refresh, Brush-up Courses (2.8 ECTS)

- Statistical computing and data analysis with SAS; Kawanda, Uganda; IITA (2003)

Competence Strengthening / Skills Courses (3.1 ECTS)

- How to write a convincing proposal; IITA; Kampala, Uganda (2003)
- Women’ s leadership and management development course; CGIAR Gender and Diversity Program & Training Resources Group, Inc.; Aleppo, Syria (2005)

Discussion Groups / Local Seminars and Other Scientific Meetings (17.7 ECTS)

- FAO Regional cassava workshops; Kampala or Entebbe, Uganda (2003, 2005, 2007)
- Annual IITA planning meetings; Ibadan, Nigeria (2003, 2005, 2008)
- Half-day seminars by IITA scientists and visiting scientists to IITA-Uganda (2003-2009)
- Project D review; Kampala, Uganda (2004)
- EC Review of IITA-ESARC, Kampala, Uganda (2005)
- Project D meeting of IITA; Jinja, Uganda (2005)
- ACDI-VOCA Cassava project meetings; Kampala, Uganda (2005 & 2006)
- KARI & NARO and farmer exchange visits in Kenya and Uganda (2005 & 2006)
- Farmer training and feedback workshops, various villages (2005 & 2006)
- IITA Cassava meeting; Kampala, Uganda (2006)
- KARI-IITA Seminar; Kakamega & Alupe, Kenya (2007)
- EPMR IITA-Uganda (2007)

PE&RC Annual Meetings, Seminars and the PE&RC Weekend (1.1 ECTS)

- Wageningen University PhD meeting for PhD' s working in East Africa; Kakamega, Kenya; Western Kenya, Eastern Uganda (2005)

International Symposia, Workshops and Conferences (10.2 ECTS)

- AFNET Conference: varieties increase the risk of nutrient mining: an ex-ante analysis for western Kenya and Uganda; oral presentation; Yaounde. Cameroun (2004)
- Inaugural meeting of the Consortium for Agricultural Research and Rehabilitation of Southern Sudan (CARRSS): contribution and opportunities to support the rehabilitation of the agricultural sector in Southern Sudan; oral presentation; YEI, Sudan (2005)
- CIAT/IITA Workgroup on cassava proposals to BMGF; Dar es Salaam, Tanzania (2007)
- Drivers of change discussion group; CGIAR, regional plan for collective action in East and Southern Africa; Nairobi, Kenya (2008)
- First global cassava partnership congress: the importance of agronomy and fertilizer use for cassava productivity; lessons from East Africa; oral presentation; Ghent, Belgium (2008)
- Cassava root and tuber workgroup, IITA planning meeting: cassava agronomy: lessons from East Africa; oral presentation (2008)

Supervision of MSc students (2 students; 30 days)

- Pablo Gonzalez (WUR): socio-economic role and physical niche of cassava in smallholder farming systems of Western Kenya (2005)
- Thomas Ondara; Kenyatta University, Nairobi, Kenya: in process (2009)

Curriculum Vitae

Anneke Marijke Fermont was born on 13 March, 1973 in de Bilt, the Netherlands. She attended primary school ‘de Runnebeek’ in de Bilt and secondary school ‘het Christelijk Gymnasium’ in Utrecht. From 1991 to 1996 she studied at Wageningen University, where she completed the MSc course ‘Soil, Water and Atmosphere’. Her MSc thesis researches included a study on the impact of farm management on soil physical properties in the Netherlands and a study on mapping soil degradation in a watershed in the Bolivian Andes. Her practical period was spend at ITC in Enschede, the Netherlands using GIS and Remote sensing to detect soil degradation processes in the Andes. In 1997-1998 Anneke worked as a researcher and project coordinator with the Western Cape University (UWC) in Cape Town, South Africa. Her research, in collaboration with Abalimi Bezekhaya, a South African NGO, focused on management options to improve the profitability and sustainability of urban agriculture in townships on the sandy ‘Cape Flats’. Mid 1998, Anneke followed her husband-to-be, Piet van Asten, to St. Louis, Senegal. After a short study on irrigated tomato production with the Institute Senegalaise de Recherche Agricole, she joined the West African Rice Development Association (WARDA) as a research fellow in a project on improved crop and water management for irrigated rice in Mauritania. Subsequently, she worked for two years on a participatory research project to improve rice production affected by acid-sulphate soils, salinization droughts, in the Casamance, South Senegal. In 2003, Anneke, Piet and their daughter Eva, moved to Kampala, Uganda, where Anneke took up a position with the International Institute of Tropical Agriculture (IITA), first as an Associate Professional Officer (APO), then as a visiting scientist. During the past 6 years she has been working as a cassava systems agronomist and project manager and took the opportunity to use her research to develop this PhD thesis for Wageningen University.

Photo captions

Chapter 1: Paulina Auma of Fanya Field School in Mungatsi (Busia district, Kenya) with cassava harvested in her on-farm trial

Chapter 2: Family of Ibrahim Mayungule of Minani (Iganga district, Uganda) peeling cassava for processing

Chapter 3: Annet Babirye and Joseph Kizimi carrying out a farmer survey in Kikooba (Nakasongola district, Uganda)

Chapter 4: Margaret Wandamba of Ugunja (Siaya district, Kenya) packing cassava she just harvested in her on-farm trial

Chapter 5: Cassava genotype Nase 3 planted without and with NPK fertilizer in the field of Nakirima Arajabu of Kisiro (Iganga district, Uganda)

Chapter 6: A man carrying bags of dried cassava chips from a cassava mill in Pallisa town (Pallisa district, Uganda) to a truck for transport to Kampala

Chapter 7: Josephine Nabwire Lubondi discussing results of on-farm trials with members of Agrofarmers in Nambale (Busia district, Kenya)

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