A road to food?

Efficacy of nutrient management options targeted to heterogeneous soilscapes in the Teso farming system, Uganda

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Peter Ebanyat

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Abstract

Poor soil fertility in smallholder farming systems in sub-Saharan Africa is recognised as a major factor responsible for low per capita food production and escalating food insecurity. Increasing food production in most smallholder farming systems requires intensification with nutrient inputs. Targeting nutrient management interventions to heterogeneity can greatly enhance the use efficiency of the scarce nutrient inputs and can help in identification of 'best fits' (most suitable options for niches within the systems). This thesis aimed at contributing to understanding how to target nutrient management options to heterogeneity for improved crop production in the Teso farming system in eastern Uganda.

Land use change analysis between 1960 and 2001 showed that 48 -78% more land was brought into cultivation and disappearance of communal grazing lands. Productivity of the farming system is also low. Population growth, political-instability-mediated collapse of institutions that supported production and marketing of cotton, and cattle rustling account for the changes in land use and productivity of the system. Balances of N, P and K were positive on larger farms (LF) and negative on the medium farms (MF), small farms with cattle (SF1) and without cattle (SF2), but were negative at the crop scale on all the farm types. Livestock, crop yield, labour availability and access to off farm income are the sustainability indicators in the system.

There were no topographic-gradients in soil pH, SOC, total N, Exch. Mg, Exch. Ca, Exch. K, CEC, sand and clay in the two villages with different geo-morphological features characterised except for extractable P which was 3-5 times higher in the top soils of the profiles in the valley bottoms than those in the upper landscape position of the toposequences. Soil organic carbon (SOC) concentrations in surface soils significantly differed ($P<0.05$) between landscape positions and differences were even significantly much larger ($P<0.001$) between field types. Fields classified as of good, medium and poor soil fertility by farmers had average SOC concentrations of respectively 9.3-15 g kg^{-1}, 6.6-11 g kg^{-1}, 5.5-7.0 g kg^{-1}. In contrast with other studies on smallholder farming systems in sub-Saharan Africa, spatial analysis did not reveal a particular generalized pattern in variability in soil fertility across farms. Within-farms, larger contents of SOC were associated with larger amounts of silt + clay and on locations of former kraals. The field scale, which is easily recognised by farmers, is an important entry point for targeting soil fertility management technologies.

Heterogeneity in soil fertility affected performance of legumes established with and without P and their residual effect on subsequent finger millet crops. Legume biomass and N accumulation differed significantly ($P<0.001$) between villages, landscape position, field type and P application rate. Mucuna accumulated the most biomass (4.8-10.9 Mg ha^{-1}) and groundnut the least (1.0-3.4 Mg ha^{-1}) on both good and poor fields in the upper and middle landscape positions. N accumulation and amounts of N_2-fixed by the legumes followed a similar trend as biomass, and was increased significantly by application of P. Grain yields of finger millet were significantly ($P<0.001$) higher in the first season after incorporation of legume biomass than in the second season after incorporation. Finger millet also produced significantly more grain yield in good fields (0.62-2.15 Mg ha^{-1}) compared with poor fields (0.29-1.49 Mg ha^{-1}). Farmers preferred growing groundnut and were not interested in growing pigeonpea and mucuna. They preferentially targeted grain legumes to good fields except for mucuna and pigeonpea to poor fields. Benefit-cost ratios indicated that legume-millet rotations without P application were only profitable on good fields. Green grams, cowpea and soyabean without P can be targeted to good fields on both upper and middle landscape positions in both villages but mucuna without P to poor fields on the middle landscape position in Chelekura village and cowpea without P to poor fields on the upper landscape position in Onamudian village.

Application of N, P fertilisers alone (0, 30, 60, 90 kg ha^{-1}), N+P at equal rates of single application, and manure (3 t ha^{-1}) supplemented with N (0, 30, 60 and 90 kg ha^{-1}) to degraded fields closed the within farm yield gap in finger millet by only 24%-43 %. The inability of the options to close the yield differences was because of poor nutrient use efficiencies (<25%) and other nutrient limitations (S and K) and physical limitations due to surface crusting. With large heterogeneity in soil fertility within smallholder farming systems, blanket recommendations are of limited value.

Using the Quantitative Evaluation of Fertility of Tropical Soils (QUEFTS) model calibrated for finger millet, balanced fertiliser requirements for a target millet yield of 2000 kg ha^{-1} was estimated at 83 kg N ha^{-1} and 52 kg P ha^{-1} and 56 kg K ha^{-1} for the sandy loam soils of Chelekura village and 64 kg N ha^{-1} and 31 kg P ha^{-1} and 40 kg K ha^{-1} for the sandy clay loam soils in Onamudian village. Targeting nutrient management options can result in larger benefits from nutrient management interventions and specific attention can be afforded to specific constraints to avoid wastage of resources. Combining organic resources and mineral fertilisers is needed for higher crop yields and nutrient use efficiencies. However, the SOC thresholds for higher mineral fertiliser use efficiencies need to be determined for different soil types (silt + clay) and crops as well as making farm/ system scale reconfigurations of cropping systems that will enhance efficiency in resource use. Supportive policy frameworks should be put in place to enhance investment in soil fertility management and thus increase food production.

Key words: *Land use change; Heterogeneity in soil fertility; Targeting; Integrated soil fertility management; Nutrient use efficiencies; Rehabilitation of degraded fields; Fertiliser requirements Finger millet; QUEFTS model; Smallholder systems; sub-Saharan Africa.*

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Chapter 1

General introduction

1.0 Soil fertility and food security status in Sub-Saharan Africa

Low and declining crop productivity in sub-Saharan Africa (SSA) is attributed to constraints associated with poor soil fertility. In consequence, food insecurity is affecting the rural populations whose livelihoods depend on mainly agriculture (FAO, 2006). The escalating food insecurity jeopardizes the achievement of the first millennium development goal (MDG1) which aims at halving the population by 2015 that are currently hungry and poor (FAO, 2006).

Smallholder African farming systems are diverse and heterogeneous but this has often been less adequately considered in the development of interventions for increasing productivity. As such, the performance of on-station generated technologies is dismal (30 % of on-station yields) when tested on farm (FAO/World Bank, 1999), leading to limited uptake of agricultural technologies such as mineral fertilisers (Bekunda et al., 1997; Morris et al., 2007). A variety of factors lead up to this: poor soil fertility, pests and diseases, poor management and erratic climatic conditions, social preferences and unfavourable socio-economic and institutional environments.

Soils in SSA are generally inherently low in fertility and management devoid of use of adequate nutrient inputs worsens their fertility status (Bationo et al., 2006) and contributes to unsustainable farming systems (Stoorvogel and Smaling, 1990; Smaling et al., 1997; Hilhorst and Muchena, 2000). It is recognised that increasing agricultural productivity is needed if food insecurity in SSA is to be alleviated, and increasing soil productivity is one important aspect. The Abuja summit of 2006, recommended use of organic and inorganic fertilisers but these political guidelines need to be supported with agronomic guidelines complimented with institutional support including improving access by smallholders to input and output markets (Andriesse et al., 2007).

1.1 Challenges in increasing productivity in smallholder farming systems

Maintaining productivity in most smallholder farming systems has in the past depended on the natural processes of shifting cultivation and fallowing. Owing to population increases, expansion of agricultural production through extensification has rendered these approaches impossible in most smallholder farming systems. Many smallholder farming systems have reached a limit in terms of intensity of land use without inputs and are in transitions to intensification. This is the case with the smallholder farming systems in the study areas in Pallisa, eastern Uganda. Intensification requires increased use of nutrient inputs by managing crop sequences (rotations), recycling of crop residues, and application of manures and inorganic mineral fertilisers to achieve and sustain high productivity.

Including legumes in crop rotations is considered the most feasible and cheap option for resource poor smallholder farmers as legumes add nitrogen into the systems through biological nitrogen fixation (BNF) and benefit subsequent crops in rotation (Giller, 2001). To benefit from BNF however, soil conditions need to be suitable for legume growth (Vanlauwe and Giller, 2006). Across sub-Saharan Africa, soils are low in P and tend to be acidic (Bationo et al., 2006) and these constraints must be alleviated to benefit from BNF. The alternative options are using crop residues and manures but often limited quantities on farms and poor residue or manure quality curtails their use. Where organic residues are available the labour costs associated with their use for soil fertility management may be prohibitive. Inorganic mineral fertilizers are highly nutrient concentrated but are inaccessible for smallholder farmers in many countries due to the cost. This has strong implications on the Abuja fertiliser summit recommendation for every farmer to use 50 kg ha^{-1} of fertiliser. At times fertilisers give no yield response, especially when poorly applied or that fertilisers may be applied where they are not needed. Fertiliser recommendations that were developed on the basis of agroecological zones (soil maps and climate) (e.g. Smaling, 1993) are of little value as they do not account for changes due to historical management. Heterogeneity in smallholder farming systems can be as large as agroecological zones to warrant differential management intervention. There is a need to rethink and revisit the strategies to deployment of nutrient management interventions in the context of the heterogeneity in soil fertility. Relevant scales need to be determined at which nutrient management interventions should be applied within the systems.

1.2 Targeting soil fertility interventions to increase crop productivity

There is a renewed effort to address food insecurity issues in SSA. Through the New Partnership for African Development (NEPAD) and the Comprehensive Africa Agricultural Development Programme (CAADP), the African Green Revolution Alliance (AGRA) was instituted to work towards realization of an African green revolution. This revolution should be uniquely African and needs to take onboard amongst other issues, the large diversity and heterogeneity in the farming systems in developing interventions as pointed out by Kofi Annan (Sikkema, 2008). For the continent with the oldest and nutrient depleted soils, high poverty levels and limited use of nutrient resources in crop production, an approach that integrates the use of both inorganic and organic nutrient resources is most plausible. This approach underpins the integrated soil fertility management (ISFM) paradigm based on the important principles of agronomical effectiveness, social acceptance, economic viability and building on the knowledge and skills of all stakeholders (Vanlauwe et al. 2002; 2009). With these underlying principles, targeting of ISFM practices within diverse farming systems can be possible. The paradigm fits well with the socio-ecological niche concept of fitting legumes to niches within farming systems (Ojiem et al., 2006). This approach provides practical steps toward identification of ‘best fits’ from the available best bests for smallholder African farming systems (e.g. Smithson and Giller, 2002; Mafongoya et al., 2006; Okalebo et al., 2006) and improving resource use efficiencies and productivity (Tittonell et al., 2007; Zingore et al., 2007; Vanlauwe et al., 2007). Efficacy of the interventions at a relevant scale in a given biophysical environment and social acceptance, and economic viability are major initial concerns that must be ascertained. Appropriate characterisation of the systems as used in the NUANCES (Nutrient use in Animal and Cropping Systems-Efficiencies and Scales) framework (Giller et al., 2002; 2006) is therefore a first step towards understanding the biophysical and socio-economic environment within which farmers operate. Characterisation of soil fertility in the smallholder farming can reveal the relevant scale for targeting interventions.

1.3 Rationale of the research

Biophysical variation between- and within farms is determined by inherent characteristics such as topography, soil type and field types (Deckers, 2002; Tittonell et al., 2005). Topographic positions, soil types and fields may be fixed on the landscape but soil fertility is variable due to anthropogenic activities. The scales at which the magnitudes of variation in heterogeneity in soil fertility are large enough (such as between soil types, field types or agroecological zones) to warrant differentiation of management practices need to be identified. Thorough systematic characterisation and evaluation of the impacts heterogeneity has on the efficacy of nutrient management technologies is vital in guiding site specific nutrient management and to allow best fitting of ISFM recommendations within smallholder farming systems. Recent studies have shown heterogeneity in soil fertility to affect nutrient use efficiencies and crop performance (Vanlauwe et al., 2006; Wopereis et al., 2006; Tittonell et al., 2007; Zingore et al., 2007). Nutrient use efficiencies are useful for development of appropriate fertiliser recommendations compared to soil tests which generate fertility classes (Janssen, 1998; Doberman et al., 2003). In this study, characterisation and evaluation of the impacts of soil fertility heterogeneity on efficacy of integrated nutrient management practices underlines the basis for understanding how to target integrated soil fertility management in the Teso farming system in eastern Uganda.

1.4 Objectives

This thesis concentrates on soil heterogeneity and its functioning in a low input Teso farming system in Uganda with the broad objective of contributing to understanding of how to improve productivity of the farming system through targeting of integrated soil fertility management practices to spatial soil variability. Specific objectives were to:

1. Identify the main drivers of change in land use in the farming system from 1960 -2001 and assess the sustainability of the smallholder farming systems;
2. Determine the relevant scale for targeting soil fertility management interventions in the smallholder farming systems;
3. Evaluate the impacts of heterogeneity on the agronomic and socio-economic performance of legume based integrated soil fertility management practices;
4. Evaluate the effectiveness of organic and inorganic mineral fertilisers to increase crop productivity on degraded fields;
5. Develop fertiliser recommendations for millet production.

1.5 Research Approach

The research employed an empirical approach and combined historical analysis, characterisation and experimentation to gain understanding of how to target nutrient management practices. How past changes in the farming system contributed to the low productivity and lack of sustainability in farming system was explored. Through characterisation, the magnitudes and the nature of variability in soil fertility were established and underlined the intervention with soil fertility management practices in the quest to improve productivity of finger millet; a crop neglected in national research yet important as a food security crop and income source for many smallholders in Uganda (Oryokot, 2001). A variety of tools were used to collect and synthesise information to contribute to understanding of how to target soil fertility management practices in the smallholder farming systems. Approaches and techniques used included satellite image analysis, interviews and literature reviews, place-based analysis in understanding the dynamics of the farming systems. Characterisation of soil fertility along toposequences and within farms with the participation of the farmers was chosen to ensure learning from their local knowledge and to establish a relevant scale for targeting integrated soil fertility management practices. Farmer participation in evaluation of technologies tested was helpful in understanding which of the technologies could possibly be accepted. Benefit: cost ratios were calculated to assess the profitability of the options as affected by heterogeneity in soil fertility. Through experimentation, the potential of soil fertility management practices to improve productivity of degraded fields in the short-term were explored and further insights gained on what other nutrients were limiting. Experimental data was used to calibrate the QUEFTS (Quantitative Evaluation of the Fertility of Tropical soils) model to support derivation of site specific nutrient management recommendations for finger millet.

1.6 Thesis outline

Chapter 2 explores the causes of land use change in the Teso farming systems over a 41 year period through a combination of methodological approaches including satellite imagery, household and key informant interviews. A place-based analysis was used to compare the trends in development of the smallholder systems with a similar system in southern Mali to identify ultimate drivers of land use change. The sustainability of the smallholder farming systems was explored through nutrient balance analysis and determinants of sustainability identified.

Heterogeneity in soil fertility between and within farms is characterised through soil analysis and spatial farm mapping. The relevant scale for targeting soil fertility management practices is identified in Chapter 3. Chapter 4, addresses the impacts of heterogeneity in soil fertility on the effectiveness of legume based integrated soil fertility management. Legume biomass productivity, N_2-fixation and residual benefit to finger millet grown in rotation were measured. As well, farmers preferential targeting and acceptance of the legume species and the impact of heterogeneity on profitability of the legume-millet rotations were assessed. The potential of manure and mineral fertilisers to improve productivity of degraded fields is considered in Chapter 5. The effectiveness of these nutrient options was rated against the former kraals which are benchmarks of soil fertility recognised by farmers to produced highest millet yield in the farming system. Through a greenhouse experiment, other nutrients limiting millet productivity on degraded fields were also identified.

Chapter 6 is about site specific nutrient management in finger millet. The QUEFTS model was calibrated and fertilizer requirements of finger millet to produce target yields as obtained on the former kraals were derived. In the final chapter (Chapter 7) information from earlier chapters is integrated to discus challenges and opportunities with the interventions tested to improve crop productivity of the farming system from both the technical and institutional standpoints. Ideas for further research are also introduced.

Chapter 2

Drivers of change in land use and household determinants of sustainability in smallholder farming systems in eastern Uganda[†]

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Abstract

This study identifies the factors that have driven change in land use in a low input farming system in eastern Uganda from 1960 to 2001 and in farm characteristics that influence sustainability of the farming system. During the period of analysis more land was brought into cultivation, and swamps were encroached. Cropping diversified and cassava overtook cotton and millet in importance, and rice emerged in swamps as an alternative cash crop. These changes are explained by population growth and political instability-mediated effects arising from the collapse of cotton marketing and land management institutions, communal labour arrangements and cattle rustling. Sustainability of the farming system is driven by livestock, crop productivity, labour availability and access to off farm income. Private-public partnerships around market-oriented crops could encourage investment in use of external nutrient inputs to boost and sustain productivity in such sub-Saharan Africa farming systems.

Key words: *Population growth; Political instability; Land use change; Nutrient balances; Farm typology*

2.0 Introduction

Land use change in African farming systems has been attributed largely to population growth with the common conclusion that it has resulted in widespread environment degradation (Cleaver and Schrieber, 1994). This ascribes to the neo Malthusian theory, which postulates that once carrying capacity of the land is surpassed degradation occurs (Malthus, 1989). There are, however, well-documented examples where environmental quality has improved with increases in population density (Tiffen et al., 1994; Tappan and McGahuey, 2007), supporting the Boserupian theory (Boserup, 1965) that technological innovations driven by rising population prevent starvation and degradation. Thus population growth alone is insufficient to explain land use change in most tropical farming systems – rather it interacts with other underlying factors such as politics, cultural norms and the prevailing economic climate (Lambin et al., 2003). Depending on the socio-economic factors and household resources, farming systems may undergo intensification or extensification (Crowley and Carter, 2000; Siren, 2007; Malmberg and Tegenu, 2007).

Land use and land cover in the Teso farming system in eastern Uganda has changed substantially over the past century. This farming system is a mixed, agro-pastoral system based on production of annual crops and livestock for subsistence that supports one fifth of the population of Uganda. In the 1960s, the dominant annual cropping systems were cotton and millet (Parsons, 1970) but these have been overtaken by cassava in importance since the mid 1990s (Fermont et al., 2008). There is widespread soil degradation (Wortmann and Kaizzi, 1998; Walaga et al., 2000; Nkonya et al., 2005), wetland encroachment (NEMA, 2001) and poor crop productivity in the system (Kidoido et al., 2002). Livelihoods of the smallholders are threatened and recurrent episodes of famine have been reported (Ssali et al., 2002)

The drivers of the population-farming-environment interactions in this system are poorly understood yet are vital in guiding future policy for development in the region. Studies of the population-farming-environment nexus in African farming systems are often based on correlations between land use and population growth and use inferential analysis to examine the influence of policy and institutional factors (Hamandawana et al., 2005; Baijukya et al., 2005; Kamusoko and Aniya, 2007). This study uses a place-based analysis combined with a comparative case study (cf. Lambin et al., 2003) to identify the underlying policy-institutional factors which, apart from population growth, have resulted in land use change in the Teso farming system. The cotton-cereal farming system of southern Mali is used as a comparative case study because of the similarity with the Teso system. Both systems have experienced rapid population increase during the period of analysis (1960 to 2001) with cotton being the major cash driver in the 1960s. Cotton remained a major source of cash income in the Mali system and productivity of the farming system improved with time. Cotton yields rose from 0.23 t ha^{-1} to over 1 t ha^{-1} and cereal yields from 0.7 t ha $^{-1}$ to 1 t ha^{-1} (Benjaminsen, 2001; Tefft, 2004). Mali has enjoyed relative political stability and institutional support (Bingen, 1998) whilst the Ugandan system has operated under political instability with no supportive institutions. In this way we are able to identify policy-institutional factors that have influenced the Teso system.

Observed land use and land cover is a reflection of aggregated land use decisions at the household level (Lambin et al., 2003; Browder et al., 2004). Land use and cover changes and environmental quality are also associated (Nepstad et al., 1999; Fearnside, 2000) particularly through the management practices applied on given land use types. Empirical studies have explored the interactions between household characteristics, socio-economics and land use (Pinchón, 1997; Perz, 2001; Browder et al., 2004; VanWey et al., 2007) but have rarely examined effects on soil quality.

Soil fertility and hence crop productivity is related to the nutrients available for plant growth (the essential elements), three of which are required in large amounts: nitrogen (N), phosphorus (P) and potassium (K). N, P and K are also the nutrients most commonly limiting crop production in sub-Saharan Africa (Vlek, 1990). Input-output balances of these nutrients in agro-ecosystems can indicate the sustainability status of the farming system (Pol and Traore, 1993). Relating the nutrient balances with farm household characteristics can therefore help to identify factors that influence sustainability of farming systems - an approach we apply in this study. Nutrient balances are a reflection of management practices that influence movement (flows) of nutrients into, within and out of a given farming system, and therefore reflect the effects of aggregated management decisions of different farm types in response to the prevailing policy-institutional environment (Defoer and Budelman, 2000). Nutrient balances are computed as the difference between total nutrient inflows and total nutrient outflows and can be measured at various scales ranging from the plant, plot, field, farm, community, region, nation or continent (Jager et al., 1998).

This study recognizes the diversity in farm households and heterogeneity in soil fertility within farming systems (Tittonell, 2007), which have been ignored in developing management recommendations and yet are important to farmers in deciding land use /management practices to adopt (Smaling, 1993). The objectives of this study were: (i) to identify the drivers of land use change in the Teso farming system from 1960 to 2001 and its impacts on soil productivity; and (ii) to determine the farm level characteristics that influence farming systems sustainability. The paper presents a review of relevant literature on farming system change in relation to land use decisions; followed by a description of the study area and villages, of procedures for data collection on land use and land cover and farm surveys to obtain farm characteristics. Farmer's perceptions of soil productivity are described as well as farm nutrient management including nutrient flows. Some suggestions for future improvement of the sustainability and productivity of the farming system are presented in the conclusion.

2.1 Farming systems/ land use and household decisions

Spatial-temporal patterns in land use observed at higher scales are an aggregation of land use and management decisions at micro-scale by households in response to policy and institutional environment over time (Lambin et al., 2003). As households are diverse in terms of resources and operate within heterogeneous biophysical and policy and institutional environments, the land use patterns are found to exhibit spatial and temporal dynamics (Dixon et al., 2001). To explain patterns of land use and land cover changes, studies have built on the Chayanovian theory in which the household demographic cycle was used to explain the differences in land areas cultivated by households (Thorner et al., 1986). Households with lower dependency ratios (more labour units compared with consumer units) cultivated more land than those with higher dependency ratios. The dependency ratios however change with maturation of households and so did land use types (Perz, 2001). This theory holds under assumptions of land abundance, absence of labour markets, with no input, credit and output markets (Perz, 2001); conditions that do not hold for most tropical farming systems.

The model has been modified to include labour markets, access to input and output markets in addition to the household demographic structures and tested in the Amazon forest frontiers (conditions of land abundance still exist) to explain empirically changes in deforestation based on relationships between land use types and household characteristics (Browder et al., 2004), and in few cases to explore underlying factors that influence land use decisions of farm households (Pinchón, 1997; VanWey et al., 2007). Generally, the household's internal demands for survival and subsistence in the context of prevailing socio-economic and political environment determine choices in farming (Walker et al., 2002).

Several factors have been used to explain land use decisions including soil quality, farm size, farm labour, level of household education, farming experience, land tenure security, distance to market, farm age, off farm income, participation, initial wealth status of households, access to credit, and technical knowledge (Browder et al., 2004). No consistent effects of these independent variables were usually observed in

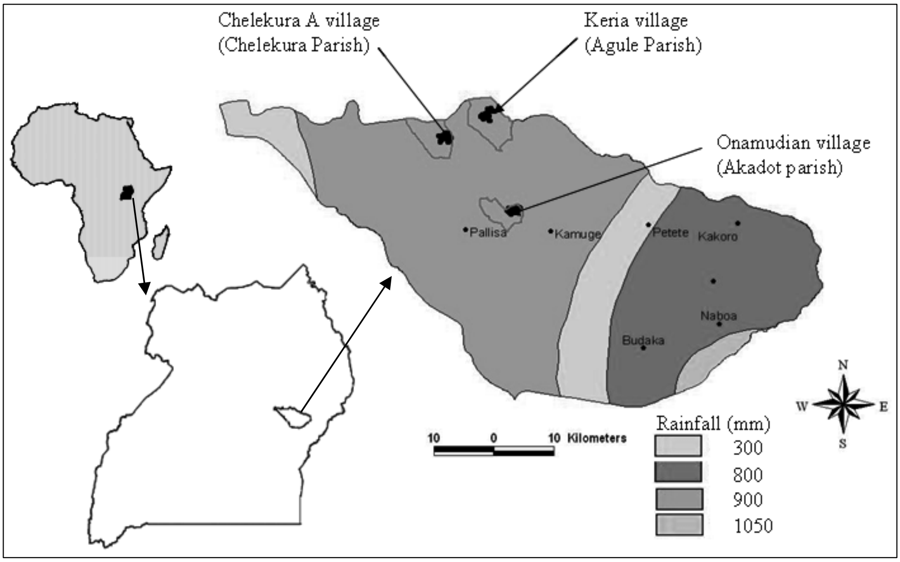


Figure 1 Location of study sites and rainfall distribution in Pallisa district, Uganda

terms of relationships between land use and household characteristics. Pinchón (1997) working in the Ecuadorian Amazon found soil fertility, topographical location of farmland, the duration of settlement (farm age) and household resource endowments to significantly influence land use decisions. Ownership of larger cattle herds left large farm areas under pasture and negatively influenced the share of farm area allocated to food crops. Smaller farms used land more intensively and cleared most of the forest for annual and perennial cropping. Families with larger farms cleared less proportions of forest and pastures were more important on the larger rather than the small farms and closely related to ranching land use. Further, farm household demographic characteristics such as education level of household head, family and wage labour, and consumer units had significant effects on land use decisions. Security of land tenure also significantly influenced land-allocation decisions. Farm household's titled to land converted less forest to agricultural land and had smaller shares of farm area cultivated in perennial and food crops and pastures than households without formal tenure. Perz (2001) also found that demographic household variables, the institutional context, off-farm income, farmers' background and belonging to groups (neighbourhood context) exerted significant effects on land use. By contrast, VanWey et al. (2007) found that cropping activities depended mainly on women and children for labour provision and not men as reported by Pichón (1997). They also found strategies for accessing cash for investment in farming was important in influencing cropping activities. Browder et al.

(2004) found only farm size to be important in influencing decisions on annual and perennial cropping. Larger farms allocated more land to pasture and cattle ranching than small size farms. They found no significant effects of household demographic characteristics, gender and age (except total family size) nor of policy environment factors (access to technical assistance, off farm incomes) on land use. This contradicts the findings of Pichón (1997), Perz (2001) and of VanWey et al. (2007) who argued that the household life cycle influenced land use decisions. Such mixed responses suggest that investigations of household land use decisions are context specific to regions, which was an impetus for us to apply the approach to low-input subsistence farming systems in Africa.

2.2 Material and methods

2.2.1 The study area

Pallisa district (1^{o} 43’ N, 33^{o} 37’ E) in eastern Uganda (Figure 1) was selected for study as it is representative of the mixed annual crop-livestock Teso farming system that supports a fifth of the country’s population (Wortmann and Eledu, 1999). The landscape is characterized by wide gently convex interfluves separated by wide swampy valleys (Ollier et al., 1969). The topo-sequence can be divided into three sub-zones; the upland zone at the summits (upper landscape positions), the midland zones located on pediments (middle landscape positions) and the valleys which may be seasonally or permanently wet (lower landscape positions). Soils on convex interfluves are derived from either lake deposits with basement complex rocks or from only basement complex rocks and gneisses (Harrop, 1970). The soils on the uplands and midlands are classified as Ferralsols and those in the valleys are Fluvisols.

Mean annual rainfall (800-1200 mm) is distributed in a bimodal pattern. The first rains are from March to June with a peak in April and the second rains from August to October or November with a peak in September or October. There are dry spells stretching from November to March. Monthly average temperatures range from 15^{o}C to 36^{o}C, with an annual mean of 25^{o}C (Yost and Eswaran, 1990). On the basis of spatial distribution of rainfall however, the district is divided into four rainfall zones and the study area falls with a region of 900 mm per annum (Figure 1).

Major crops grown include cassava *(Manihot esculenta* Crantz*),* finger millet *(Eleusine coracana* L. Gaertn*),* sorghum [*Sorgum bicolor* (L.) Moench], groundnut *(Arachis hypogaea* L.), cowpea [*Vigna unguiculata* (L.) Walp.], greengram [(*Vigna radiata* (L.) R. Wilczek], sweet potato (*Ipomea batatas* Poir.), cotton (*Gossypium hirsutum* L.), and maize (*Zea mays* L.). Rice (*Oryza sativa* L.) is grown in the valleys.

Livestock kept include cattle, sheep, goats, pigs and poultry. Annual crops dominate the upland and midland cropping during the rainy seasons, with free grazing of livestock after crop harvest and in the dry seasons. Valleys, which in earlier years were gazetted as communal grazing lands, are now predominantly used for rice cultivation and only support grazing to a limited extent after harvest. Where wetlands exist, they are used for fishing but may also be used for collecting thatch grass, and papyrus for craft making.

2.2.2 Site selection

The studies were embedded within an on-going research project on integrated nutrient management using a 'farmer field school' approach entitled 'Integrated nutrient management to attain sustainable productivity increases in East African farming systems' (INMASP). At the initiation of the INMASP project in 2002, a multistage approach was used to select pilot sites. The two sub-Counties of Agule and Pallisa were selected due to differences in population densities and soil productivity status. Agule subcounty has lower population density and soil fertility while Pallisa subcounty has medium population density and moderate soil fertility status (Ssali et al., 2002). The project operated in one village in each of the three parishes - Agule and Chelekura in Agule subcounty and Akadot parish in Pallisa subcounty (Figure 1). Detailed results on participatory diagnosis of constraints and opportunities for soil productivity improvement in these villages are summarised elsewhere (Ebanyat et al., 2003).

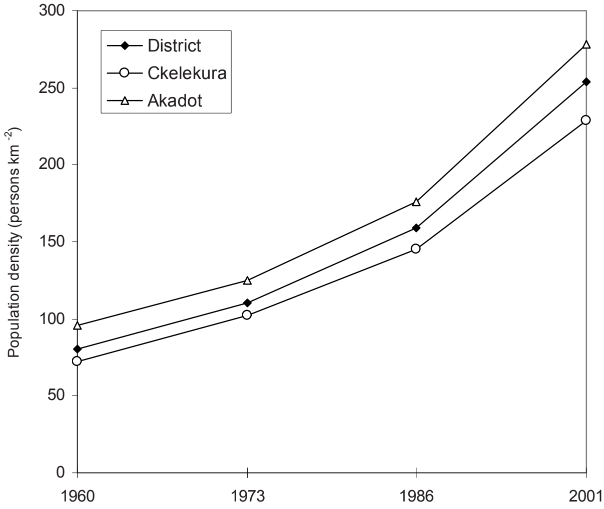


Figure 2 Population densities of Pallisa district and the study parishes from 1960 to 2001.

2.2.3 Data collection methods

Land use cover analysis was done in two parishes: Chelekura (1°24′N; 33°30′E) and Akadot ($1^0$11'N; $33^0$43'). Black and white aerial photographs (1:50,000) obtained from the Department of Surveys and Mapping, Entebbe, Uganda were analysed from 1960 and Landsat images from 1973 (Multi-Spectral Scanner), 1986 (Multi Scanner) and 2001 (Enhanced Thematic Mapper), all taken between the period December and February (a period when rice fields are prepared and cotton harvesting is done). Controlled photo mosaics were constructed. The central portion of the air photos were cut out and aligned with adjacent air photos to correct for aircraft height and tilt variations. The controlled mosaics of each parish were then further oriented by matching features with survey control points for the area. Eight control points were used to georeference the constructed controlled photo mosaic i.e. the constructed control mosaics were analysed under stereoscope, and land use types classified according to National Biomass Survey (MLWE, 2002). Satellite images were classified using both unsupervised and supervised classification in Integrated Land and Water Information System (ILWIS) version 3.3. Broad land use/cover classes used in the study included forest, cultivated land, swamps, bush land, grassland, water bodies and rice cultivation - introduced as a new land use type. Preliminary maps produced after analogue and digital image interpretations were validated with existing land cover maps of the area (such as the GLC2000 and the Africover maps), ground observations and through historical reconstruction. Four key informants were identified in each village and were interviewed on land use types that existed in some locations and on change that occurred over time. Information obtained was used to produce land use/cover maps of the two villages for 1960, 1973, 1986 and 2001.

To understand the factors that have caused land use change and to confirm farmer's perceptions, a literature review was conducted. Data on district scale changes in human and livestock populations, acreages for finger millet and cotton were collected and used for inference since disaggregated data at parish scale were lacking. The review also included national research institutes, government ministries and departments and private sector organisations to identify the national policies that were implemented during the period of analysis. Population data for the district and study parishes (Figure 2) were computed on the basis of the population growth rates between census years available from the Uganda National Bureau of Statistics.

Two household surveys were conducted. The first one in March 2002 included 89 farm households participating in the INMASP project. The objective was to obtain perceptions on soil productivity trends, current soil fertility status and its driving factors, and soil fertility management practices. The second was a rapid survey conducted in

April 2005 that included 90 farms, 60 non-participating farm households (rapid survey farms - RSF) and 30 farm households (case study farms - CSF) participating in the INMASP project. Farm typologies were constructed using data collected from the CSF. However, knowing that the farm households participating in the project were self-selected on the basis of interest (Braun et al., 2000), data collected during this survey were used to ascertain if all the farm types in the community were represented. Data from the RSFs were collected using questions described by Tittonell et al. (2005) to obtain information on resource endowments and livelihood strategies of the farm households to enable construction of functional farm typologies (Tittonell, 2007).

Data for quantification of nutrient balances were collected using questionnaires in the NUTMON toolbox (Vlaming et al., 2001) from the 30 case study farms in March 2003. Nutrient flows into and out of the farms and distribution within the farms was captured during a one-time recall survey for the two seasons of the previous year 2002 using resource flow mapping. Inflows were mainly imports of nutrients and outflows in the form of farm products. To quantify the soil nutrient stocks, soil samples were taken from 0-30 cm depth from fields on major local soil units identified with farmers on respective farms for analysis of total N, P and K, particle size distribution and bulk density following standard methods for tropical soils (Anderson and Ingram, 1993).

2.2.4 Data analysis

Relationships between land use and cover data and population density were explored using correlation analysis and the strengths of the relationships inferred from the square of the correlation coefficients. Differences in respondent's perceptions between sites were tested using Pearson Chi square. Farm resource data was subjected to (di) similarity agglomerative cluster analysis using the cosine similarity index because of sensitivity to both quantitative and qualitative data (Jongman et al., 1995) to generate farm typologies. Nutrient balances were computed using the NUTMON software version 3.5 from the inflow and output data at both farm and crop level and significance tested using a T test for farm balances and ANOVA for crop level balances. Regression analyses were performed to identify farm household characteristics influencing nutrient balances and nutrient balances to stock ratios (NBSR) of the major nutrients at both farm and crop level. Only variables that were not significantly correlated were used as explanatory variables. All statistical analysis was performed using SPSS version 12.

2.3 Results and discussion

2.3.1 Land use change

The major land use types identified in the studied parishes in Pallisa district were forest, cultivated lands/homesteads, bush lands, grasslands, papyrus swamps, rice cultivation and water. These land use types have undergone drastic change over the 41 years of analysis in both parishes (Figure 3 - Chelekura and Figure 4 - Akadot). Their proportional spatial coverage is summarised in Table 1. In 1960, cultivated land and homesteads occupied 24% and 53% of the total land area in Chelekura and Akadot parishes respectively indicating comparatively more intensive land use in the latter parish. Land cultivated declined in both parishes in 1973 but again increased in 1986 to areas comparable, but not surpassing those of 1960. By 2001, land brought into cultivation increased by 90% and 48% respectively in Chelekura and Akadot compared with 1960. The increases in cultivated lands were however paralleled by declines and eventual disappearance of some land use types. After 1986, grasslands, which were mainly grazing lands and closer to swamps, and bushlands, declined very rapidly leaving none by 2001 in both parishes. The swamps also declined but at a much faster rate in Akadot than in Chelekura parish and by 2001 swamps covered only 6% of total land area in Chelekura and none remained in Akadot parish.

In 1960, more land was cultivated in Akadot than in Chelekura parish because cotton growing was more intense in this parish than in Chelekura which mainly had livestock and more grazing/grasslands and bushlands (Table 1). According to key informants Chelekura was comparatively less inhabited and from census records population density at that time was estimated at 72 persons km^{-2} (Figure 2). Akadot parish had two cotton ginneries at Akadot and Kaboloi and most farmers grew cotton which they sold at the ginneries. At that time cotton was promoted as a major crop for households to raise cash for paying poll tax so that men were more involved in its production.

The increase in cultivated land and disappearance of other land use types over the period of analysis was associated with population growth. Population density was negatively correlated with all land use types except for cultivated land ($r = 0.70$) and rice cultivation ($r = 0.78$) that were positive and significant (Table 2). From these results, population explained only 49% and 60% of the increase in cultivated land and rice cultivation. Cultivated land was significantly negatively correlated with grasslands ($r = -0.84$) and bushlands ($r = -0.64$), as was bush land with rice ($r = -0.71$) implying that over time they were converted to cultivated land and rice respectively. There has been immigration into the area during the 41 years of analysis (although exact statistics

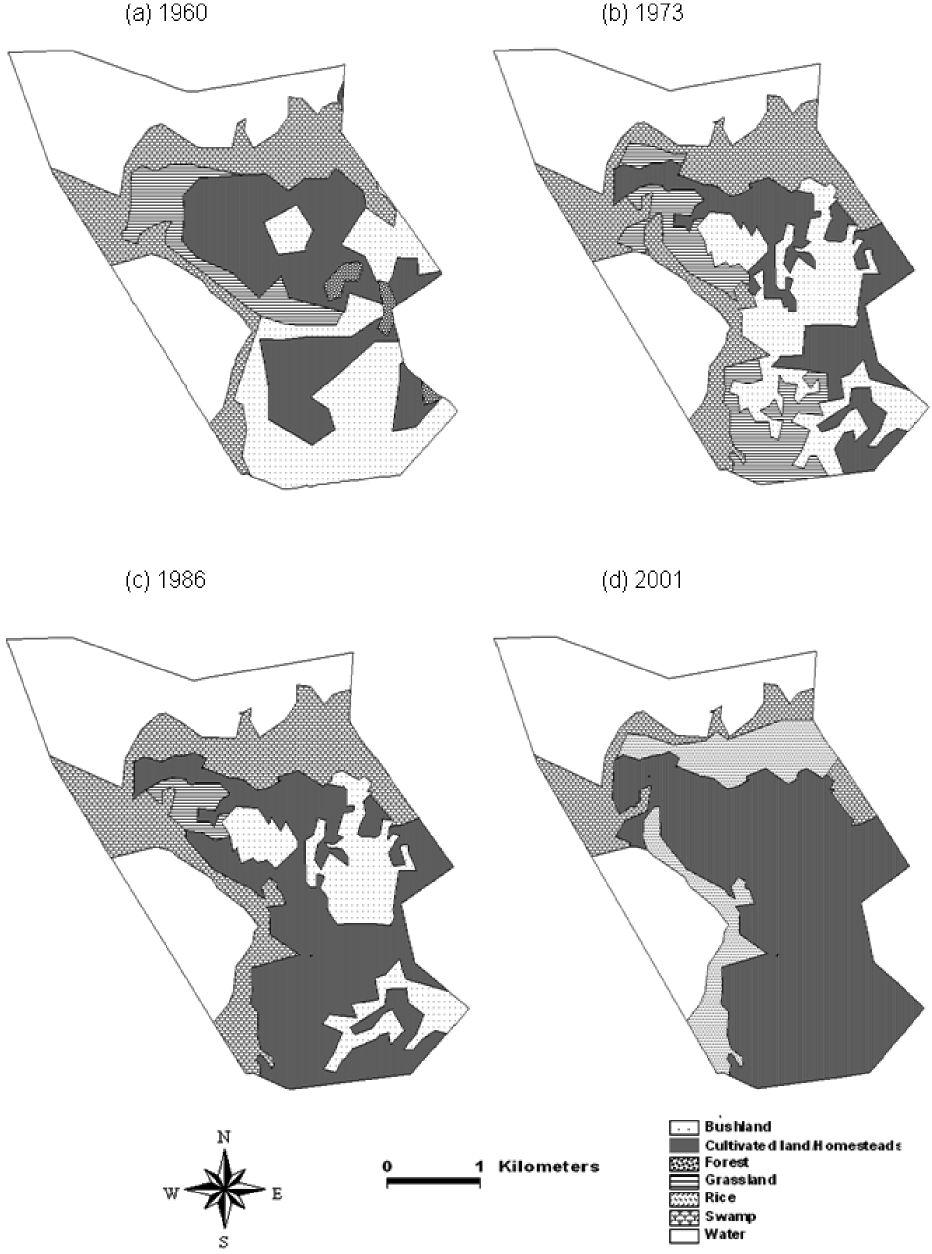


Figure 3 Land use change in Chelekura Parish, Pallisa district from 1960 to 2001.

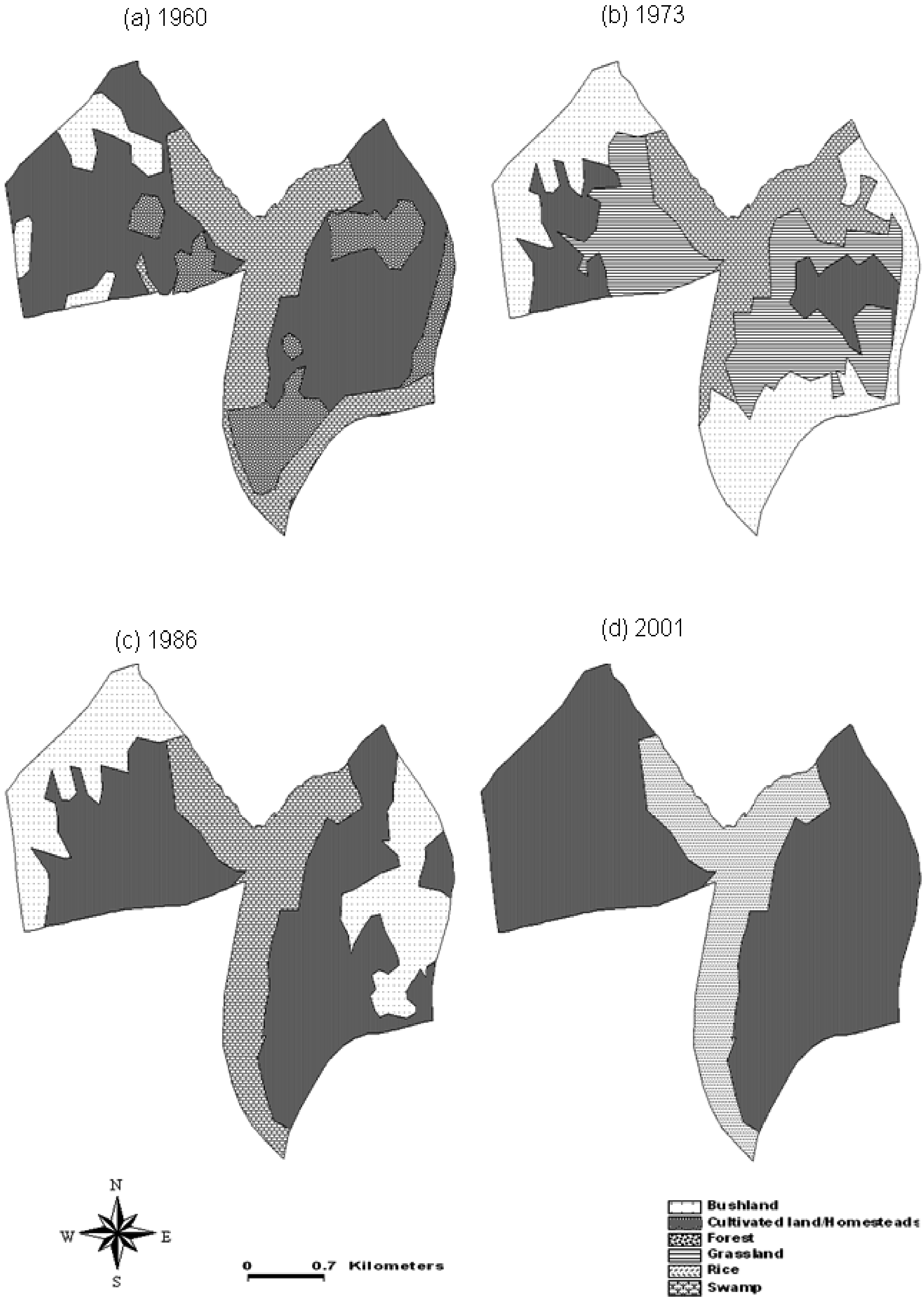


Figure 4 Land use change in Akadot Parish, Pallisa district from 1960 to 2001.

Table 1 Land use/cover and changes in Chelekura and Akadot Parishes, Pallisa district, eastern Uganda from 1960 to 2001.

Parish/land use	Cover								Changes*		
	1960		1973		1986		2001		1973	1986	2001
	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)		
Chelekura											
Cultivated land/homesteads	592	24	441	18	518	21	1127	46	-151	-74	535
Forest	30	1	0	0	0	0	0	0	-30	-30	-30
Grasslands/trees	324	13	231	9	231	9	0	0	-93	-93	-324
Bush lands	586	24	455	18	417	17	0	0	-131	-169	-586
Papyrus swamps	202	8	606	25	567	23	148	6	404	365	-54
Rice cultivation	0	0	0	0	0	0	458	19	0	0	458
Water	730	30	730	30	730	30	730	30	0	0	0
Total	2463	100	2463	100	2463	100	2463	100	0	0	0
Akadot											
Cultivated land/homesteads	627	53	177	15	606	51	926	78	-450	-21	298
Forest	195	16	0	0	0	0	0	0	-195	-195	-195
Grassland/trees	0	0	480	40	195	16	0	0	480	195	0
Bush lands	69	6	288	24	319	27	0	0	219	250	-69
Papyrus swamps	301	25	246	21	71	6	0	0	-55	-229	-301
Rice cultivation	0	0	0	0	0	0	266	22	0	0	266
Total	1192	100	1192	100	1192	100	1192	100	0	0	0

* Base year for computation is 1960

were not available in the district) in search of more land and due to insecurity in the north-eastern region of Uganda from the mid 1980s. Other factors however modify the effects of population growth in explaining the temporal and spatial changes in land use. We argue that the underlying effects of national political instability and changing economic policies that rippled through the country had a share in this.

The country was affected by political instability and economic decline for half of the period of analysis (Figure 5). The period 1960-1970 was characterised by agriculture-led economic growth (GOU, 1965) and political stability. The post-independence government continued to pursue colonial economic development policies which prioritised export of cotton and coffee for earning of foreign exchange. Implementation of colonial policies continued, although in a rather less punitive way than during colonial administration. Model farmers were promoted and agricultural implements and fertilisers were subsidised. However, large scale farmers with plantation estates (sugarcane and tea) rather than subsistence farmers benefited from the subsidies even though export growth was from cotton and coffee produced by subsistence farmers. Cotton and finger millet were popular crops respectively grown by 85% and 66% of farmers for cash and subsistence in the Pallisa region (MAC, 1966). At this time, there was a strong crop-livestock interaction in the system. Ox-ploughing, a practice which was introduced in the area at around the same time with cotton in 1910 (Mahadevan and Parsons, 1970), enabled opening of large land areas and preparation of fine seed beds. For finger millet in particular, labour for the tedious weeding and harvesting was communally organised to help one another ('*Ebole*'), rewarded with a meal and local brew, '*ajon*' at the end of the season.

The decline in cultivated land in 1973 was associated with a change in the political governance and economic policies of the country following the take over by Idi Amin in 1971. Economic war was declared and the Asian community that dominated the business and trade sector including cotton marketing were expelled. This demoralised smallholders who withdrew from cultivation of the crop and in Akadot and Chelekura parishes cultivated area declined to 38% and 6% of total land respectively. The political instability from the 1970s until the mid 1980s impacted on all the sectors of the economy including agriculture culminating in a complete collapse of cotton marketing in the early 1980s. Farmers had to explore alternative crops to generate cash income. According to key informants from both parishes of Chelekura and Akadot, farmers soon started to grow rice on grasslands (grazing areas) on the flanks of the swamps from 1982 onwards but initially left the seasonal swamps to provide pastures for dry season grazing. The Obote II government (1980-1985) adopted some economic recovery programmes but the escalating guerrilla war continued to increase insecurity

Table 2 Pearson's correlation coefficients for land use types and population density in Pallisa District.

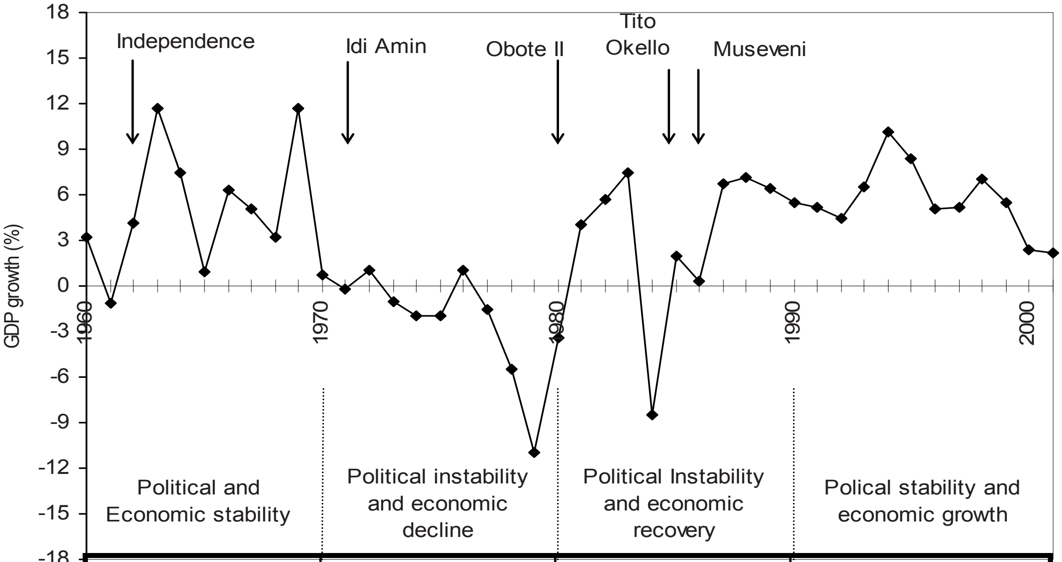
	Cultivated land/homesteads	Forest	Grasslands	Bushlands	Papyrus swamps	Rice	Pop. density
Cultivated land/homesteads	1						
Forest	–0.07	1					
Grasslands	–0.84*	–0.38	1				
Bushlands	–0.64*	–0.27	0.75*	1			
Papyrus swamps	–0.49	0.41	0.20	0.51	1		
Rice	0.87**	–0.24	–0.62	–0.71*	–0.47	1	
Pop. density	0.70*	–0.40	–0.56	–0.71*	–0.51	0.78*	1

Significance: * $P < 0.05$; ** $P < 0.01$

and weakened institutions. Policies, including land management policies, could not be enforced (Tukahirwa, 1994) making it difficult to restrain encroachment of wetlands by rice cultivation. Farmers diversified into growing other crops for both domestic consumption and cash, i.e. grain legumes and cassava (Kidoido et al., 2002; Fermont et al., 2008) leading to expansion of cultivated areas again in the uplands.

Cattle population in Pallisa district dropped drastically from over 123,000 in 1985 to only 20,000 in 1991 (MAAIF, 1993) following extensive cattle rustling and insecurity in the region. Further expansion of rice cultivation into the valley bottoms became much easier because competition from grazing no longer existed. From 1987 the economic liberalisation policies and export drive further encouraged crop diversification. Cultivation soon started in the dry seasons (November to February) where valleys accumulated water leading to double cropping. In effect, all the swamps and grazing lands in Akadot parish were brought into cultivation and 94% in Chelekura parish by 2001 (Table 1). These examples illustrate that farmers are flexible and search for farming strategies that enable them to cope with externally imposed constraints arising from political and economic forces (Berry, 1993). Expanding cultivated land and intensifying use of valley bottoms seemed to less driven by population increase in this case, as was concluded from other literature by Crowley and Carter (2000).

The above political trends and their effects on institutional arrangements contrast with the Malian system which experienced relatively political stability throughout the period of analysis. The Mali government prioritised the cotton sector in national development and initiated the establishment of Compagnie Malienne pour le Développment des Fibres Textiles (CMDT), which has supported the cotton sector since 1960. CMDT co-ordinated all production and marketing arrangements. It stabilised input and output markets for cotton, maintained partnerships with supportive institutions in cotton production like research and extension and empowered local farmer organisations like the Syndicat des Producteurs de Cotton et Vivriers (SYCOV) and village producer associations (Bingen, 1998; Tefft, 2004). Because of assured markets from cotton sales, farmers were able to increase livestock numbers, oxen and carts. Thus manure production increased, opening of larger acreages was possible through ox-ploughing and transport of manure to the fields became easier as oxen for traction and ox carts are available. Input credit availability ensured timely availability of seed, pesticides and fertiliser. There were also well-organised family labour structures provided by extended family units around specific production activities taking care of farm operations in a timely manner. As a consequence, productivity of the farming system improved with time because coordination ensured good crop husbandry and marketing (Tefft, 2004). The institutional arrangements that were created through good



•Stable post independence government up to 1966 that continues to pursue economic development policies hinged on agriculture •Implementation of the soil and water conservation (SWC) policy continued although in less punitive way. In Pallisa District, sheet erosion control by having grass strips between fields, crop rotation and no bush burning were upheld • Strong extension support through progressive farmers • Cotton promoted as a cash crop and strong marketing arrangements and structures were in place	• Following Idi Amin's take over of power, economic war declared against Asians • Insecurity increased •Skilled manpower was replaced by unskilled manpower to manage the economy in the name of nationalisation •Eventually the economy collapsed •Collapse of input distribution systems •Non enforcement of SWC policy •Decline in cotton cultivation and farmers reverting to cereal cultivation	• Following overthrow of Idi Amin, economic recovery programmes started and again agriculture being prioritised •Cotton sector did not recover because of centralised marketing through marketing boards; cooperative unions were unable to pay farmers •Farmers started exploring alternative income crops like rice •The economy picked up within three years but increasing insecurity due to NRA guerilla war affected growth momentum gained in the economy	• Political stabilisation of most of the country but insecurity in the noth and north east continued and rustling of cattle between 1987 and 1991 •Economic growth through decntralisation, liberalisation and privatisation policies •Agriculture again fronted as the engine for poverty eradication •Diversification encouraged in agriculture •Rebuilding of supporitve institutions including extension (NAADS demand driven extension services approach) •Cotton growing revamped in Pallisa by the private sector

Figure 5 Uganda's political timelines and economic performance and their impacts on land use from 1960 to 2001. (Sources: GOU, 1967, 1976, 1996; MFPED, 1990; UBOS, 1999 and 2004; Kamugisha 1993; Tukahirwa 1994; Walaga et al., 2000).

national policies and stable political environment ensured improvement and sustained cotton production in Mali. This is an example of how politics and economic stability, and institutional support to market-oriented crop production are important in the quest to improve livelihood security and productivity of smallholder farming systems in Africa. Political instability, lack of supportive input-output markets and land management services, apparently attributed to the break down in communal labour arrangements and loss of cattle together with population growth drive land use changes in the Teso farming system.

2.3.2 Farm typologies in the farming system

To obtain a better understanding of impacts of decisions on land use, farm characterisation is important. Data on household characteristics was used in generation of farm typologies and their allocation of land to various land use types. The latter was subsequently also related with land use at the parish scale. No differences in the farm typologies existed between villages thus categorisation was done across the villages. Four major farm typologies were identified in the RSF as shown in the dendrogram (Figure 6) and these were all represented in the CSF. They included larger farms (LF), medium farms (MF), small farms with cattle (SF1) and small farms without cattle (SF2). Their respective proportions in the RSF were 11, 30, 39% and 20%. The typologies were distinguished by the wealth indicators, land and cattle combined with indicators of livelihood strategies, labour sale/hire, food security status and income sources (Table 3). These criteria tallied with those prioritised by farmers (land, livestock, food security, and type of housing). This combination of indicators improved the classification above using only land and livestock as done by Awa et al. (1999) for the Teso farming system. The resource endowments differed between farm types but also note that LF and SF2 farms were over-represented in the CSF (Table 4). On average, the LF farms owned 5 ha of land, 9 cattle and 4 goats. The MF farms had on average 2 ha of land, 3 cattle and 1 goat. The SF1 farms had at least 1 ha of land and owned at least 1 cattle and 1 goat. The SF2 farms had less than 1 ha of land, no cattle but at least one goat. The latter were also the most food insecure among the four typologies because of limited production resources. Per typology, the farmers in the CSF had similar wealth resources as in RSF.

Dependency on off-farm income was another important livelihood strategy for the farmers in Pallisa. Fifty eight percent of total farm income of LF farms was derived from off-farm activities, especially small scale businesses. They also produced some specific crops for sale like maize and rice. These types of farms had land to labour ratios of 2.1. The MF farms have some off-farm employment in civil service but

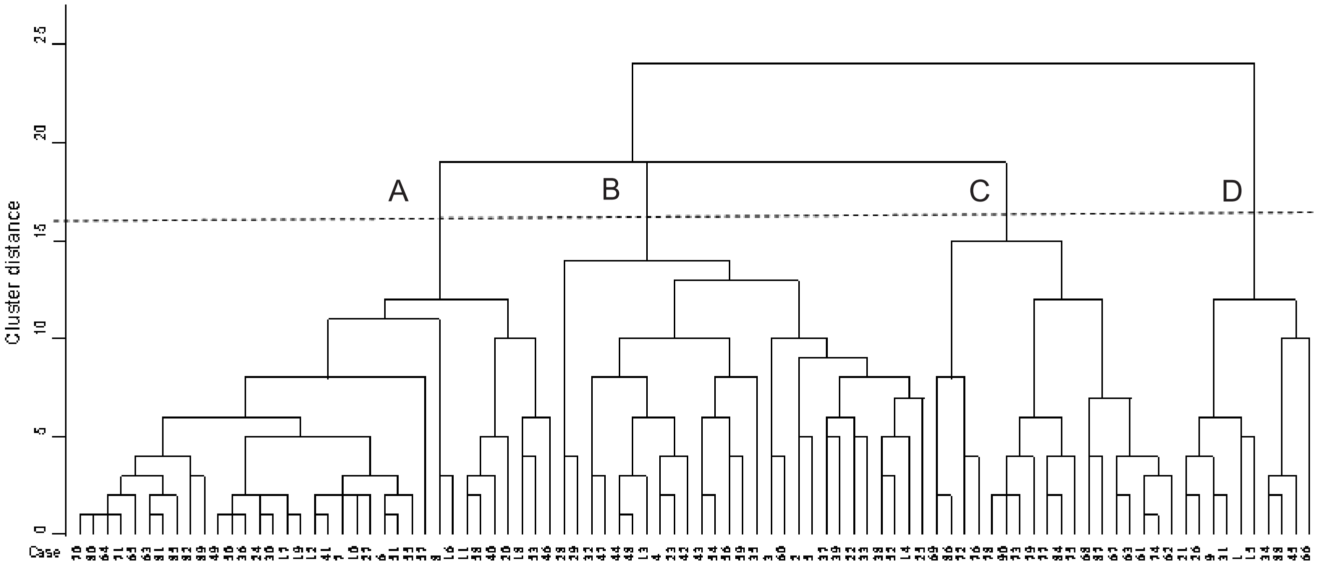


Figure 6 Average linkage dendrogram using similarity index for resource endowments data of smallholder farms showing typologies in the rapid survey sample (n= 90): A= Small farms with cattle (SF1); B= Medium farms (MF); C= Small farms without cattle (SF2); and D= Larger farms (LF).

Table 3 Wealth indicators and characteristics of the different resource groups in Pallisa district, Uganda

Wealth indicator	Resource category[a]			
	LF	MF	SF1	SF2
Farm size	Have about 5 ha	Have about 1.6 ha	Approximately 1 ha	Less than 1 ha
Livestock	Have about 9 cattle with at least one pair of oxen Have about 4 goats	Have about 3 cattle with either one ox or a pair of oxen Have about 4 goats	At least have 1 ox to team with another farmer for draught power May have about 3 goats	Do not have cattle, but at least have goats
Hire/sale of labour	Hire labour for livestock and casual labour for cropping activities	Hire labour for cropping activities. Also hire out labour particularly oxen for ploughing	Sell and hire labour for cropping	Sell labour
Farm implements	Own ox plough, hoes and wheel barrows	Own ox plough, hand hoes	May own an ox plough and hand hoes	Own only hand hoes
Production orientation	Grow some root and grain crops specifically for sale	Produce mainly for home consumption and some crops for sale	Produce for home consumption and can sell any crop for income	Produce for basically home consumption
Income sources	Have small scale businesses and remittances from working relatives	Rely on crop sales and salary as civil servants (e.g. teachers)	Sale of crop products and local brew	Sale of labour and a little of crop products
Food security	Buy food for periods less than one month in a year	Buy food for periods of 1-3 months	Buy food for 3-5 months in a year	Buy food for more than 5 months in a year

[a] LF= Larger farms; MF = Medium farms; SF1= Small farms with cattle; SF2 = Small farms without cattle.

Table 4 Proportions and mean resource endowments of farm types in the rapid survey farms (n=90) (RSF) and the case study farms (n=30) (CSF) in Pallisa District, Uganda

Farm type[a]	Proportions in				Household size		Farm size		Cattle		Oxen		Goats	
	RSF		CSF		RSF	CSF	RSF	CSF	RSF	CSF	RSF	CSF	RSF	CSF
	(no)	(%)	(no)	(%)	(no)		(ha)		(no)		(no)		(no)	
LF	10	11	6	20	11	11	5.9	6.2	9	12	2	3	4	6
					(5-17)	(7-17)	(2.5-12.7)	(2.4-12.7)	(2-19)	(3-19)	(0-4)	(2-4)	(0-12)	(2-12)
MF	27	30	6	20	7	8	1.6	3.1	3	4	1	2	1	2
					(2-15)	(2-15	(0.1-4)	(1.6-4.9)	(0-4)	(3-6)	(0-2)	(1-2)	(0-4)	(0-4)
SF1	35	39	10	33	8	9	1.1	2.2	1	1	1	1	1	2
					(2-15)	(6-17)	(0.2-3.6)	(0.7-4.2)	(0-2)	(1-4)	(0-2)	(0-2)	(0-2)	(0-4)
SF2	18	20	8	27	6	7	0.8	1	0	0	0	0	1	1
					(1-12)	(2-16)	(0.7-2.0)	(0.4-2.8)					(0-7)	(0-7)

[a] LF = Larger farms; MF = Medium farms; SF1 = Small farms with cattle; SF2 = Small farms without cattle; values in parentheses are ranges.

supplemented their income by growing crops for sale in particular cotton. Off-farm income constituted 42% of their total income and they had an average land to labour ratio of 1.2. For the SF1 farms, income was generated from sale of both food and cash crops. The proportion of total incomes from off-farm on these farms was 21% and the land to labour ratios was 1. For the SF2 farms off-farm income was less important (average of 14% of total income) but these farmers mainly survived on sale of own labour in the community. This category was land limited and had a land to labour ratio of 0.95.

2.3.3 Farm-level land use

Land allocation to crops was used to explore change in the cropping systems. The land allocation to crops varied between farm types (Figure 7) and reflected differences in farmer's production objectives for domestic consumption or cash. Cassava however occupied the second largest share in area of land after fallow in each farm type. Since there were no significant differences between farm types between villages, we used the average land allocation fractions per farm type (Figure 7) and the household numbers in each parish - being 914 for Chelekura and 804 for Akadot (UBOS, 2005) - to estimate the crop coverage of the cultivated land in each parish. The estimates had an error of ±18%. Crop shares of land between the parishes differed significantly ($P<0.05$) but there were notable variations in the proportions of land allocated to each crop within each site (Figure 8). In both parishes cassava occupied more that 250 ha of the cultivated land overtaking the earlier important crops, cotton and finger millet in importance in the region.

In the 1960s farmers owned on average 2 ha of land (Carr, 1982) of which over 75% was occupied by cotton and finger millet; cassava was then very minor in the farming system (MAC, 1963). Four decades later with diminishing average farm sizes, cassava occupied the leading share of 20% reflecting a change in the cropping system compared with the 1960s. District level estimates also support changes in cropping although accuracy of land area estimates may be questionable. In 1960, cotton covered approximately 50,000 ha and finger millet, 60,000 ha - respectively 25% and 30% of the total land area in the district. By 1991, the areas cultivated with both crops drastically reduced with millet occupying only 5% of the land area and cotton less than 2% (GOU, 1976; MAAIF, 1993). The area cropped with cotton then increased to 9% and that of millet remained at 5% in 2001 (UIA, 2002; MAAIF, 2003). The change in the cropping systems occurred because of economic pursuits by farmers to improve their income but also due to biophysical constraints especially declining soil fertility. Cassava is an important food security crop as well as a tradable food crop that is well adapted to poor

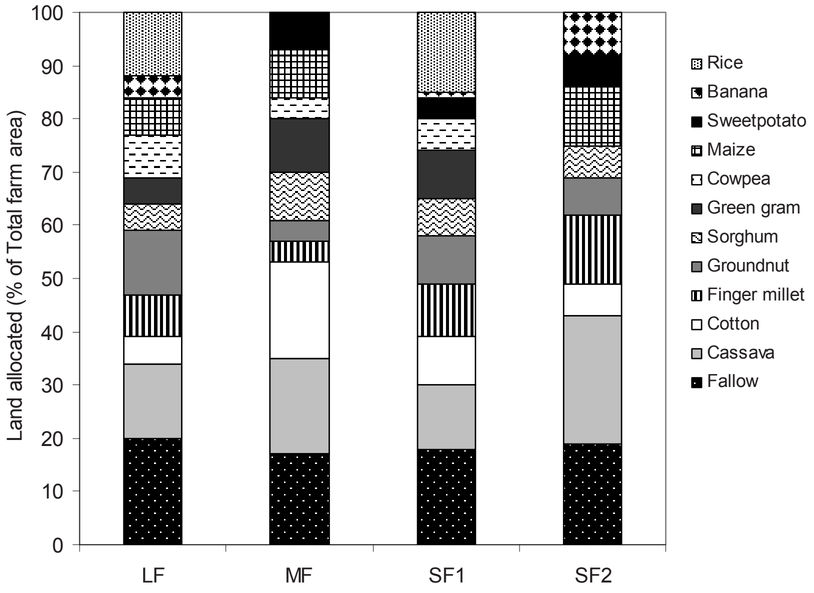


Figure 7 Percentage land allocation to primary production activities per farm type in the study area.

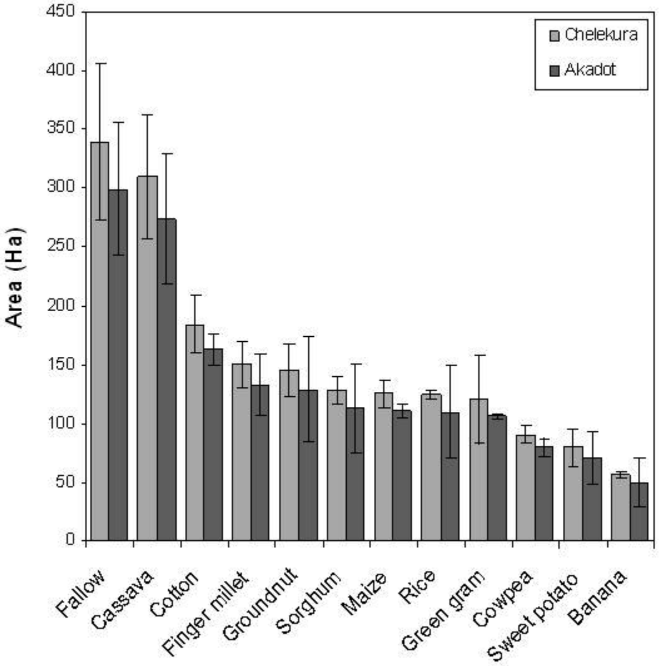


Figure 8 Average land area allocated to different crops in Chelekura and Akadot parishes, 2003. Bars are standard deviations.

soil fertility (Howeler, 2002). These reasons could explain why it has become a dominant crop over time. Diminishing land holdings and collapse of communal labour arrangements for weeding might explain declines in land area cropped with finger millet whereas the collapse of markets explain decline of cotton production in the district during the period of analysis. This agrees with Crowley and Carter (2000) who report that farmer's responses to constraints such as lack of inputs and market failures feed back to the biophysical environment, especially to soil fertility. The emergence of rice was because farmers sought alternative cash crops and, with failure of responsible institutions to implement land management policies, swamps have been encroached.

2.3.4 Nutrient flows and balances

Farm level nutrient flows were variable between farm types (Table 5). The inflow of major nutrients on the farms due to grazing amounted to 84%, 80% and 94% of the total farm inflows for N, P and K respectively for LF, 67%, 50% and 86% for MF, 62%, 50% and 86% for SF1 and 23%, 5% and 40% for SF2. The variation in contributions corresponded with the cattle endowments of the farms (see Table 4). Contributions of other inflows that included organic residues (IN2a), atmospheric deposition (IN3) and biological nitrogen fixation for N (IN4) were small, while no external fertilisers (IN1) were used on any of the farms. Manure losses (OUT2b) were significantly different between farms because of cattle numbers and hence manure accumulated on the farms. They respectively accounted for 46%, 67%, 81%; 32%, 50%, 69%; 27%, 50%, 69%; and 3%, 5%, 20% of the total losses of N, P and K on LF, MF, SF1 and SF2 farms respectively. Although not significantly different between farms, leaching (OUT3) was generally a more important pathway for N loss than through manure on all the farms.

Nutrient balances differed between farm types. However, T tests showed only SF1 (– 9 kg N ha^{-1}) and SF2 (– 16 kg N ha^{-1}; – 1 kg P ha^{-1}) farm types had balances significantly less than zero (Table 5) implying higher depletion rates on these farms. The reason may be due to few cattle and no cattle respectively on these farms and management practices in which there was frequent cultivation of the little land available. Total balances across the farms showed deficits for N (–16 kg ha^{-1}), balanced for P (0 kg ha^{-1}) and a surplus for K (+23 kg ha^{-1}). The negative balances for N are mainly attributed to high losses of manure and leaching in the sandy soils. Because P is immobile, losses of P through erosion are easily compensated by grazing that brings in manure to the farms. Surplus K could be explained by high K contents in manure because grasses grazed by cattle grow on soils that are rich in K (Ollier and Harrop, 1959). The results suggest a need for better management of manure collection and storage to minimise N losses for farm types that have cattle.

Table 5 Average flows and balances of major nutrients (kg ha^{-1}) on farms of different resource endowments in Pallisa district, Uganda.

Flows	Nitrogen				Phosphorus				Potassium			
	LF	MF	SF1	SF2	LF	MF	SF1	SF2	LF	MF	SF1	SF2
Inflows												
IN1	0	0	0	0	0	0	0	0	0	0	0	0
IN2a	0	1	1	4	0	0	0	1	0	0	0	3
IN2b	36	14	13	3	4	1	1	0.1	51	19	18	4
IN3	5	5	5	5	1	1	1	1	3	3	3	3
IN4	2	1	2	1	0	0	0	0	0	0	0	0
$\sum IN$	*43*	*21*	*21*	*13*	*5*	*2*	*2*	*2*	*54*	*22*	*21*	*10*
Outflows												
OUT1	0	–1	–1	–3	0	0	0	–1	0	0	–1	–3
OUT2a	0	0	0	–1	0	0	0	0	0	0	0	0
OUT2b	–15	–7	–8	–1	–2	–1	–1	–0.1	–21	–9	–11	–2
OUT3	–12	–9	–13	–15	0	0	0	0	-2	–2	–1	–1
OUT4	–3	–2	-3	–3	0	0	0	0	0	0	0	0
OUT5	–1	0	–1	–1	0	0	–1	–1	–2	–1	–2	–2
OUT6	–2	–3	–4	–5	–1	–1	–1	–1	-1	–1	–1	–2
$\sum OUT$	*–33*	*–22*	*–30*	*–29*	*–3*	*–2*	*–3*	*–3*	*-26*	*–13*	*–16*	*–10*
Balance	10^{Ns}	$–1^{Ns}$	–9**	–16**	2^{Ns}	0^{Ns}	$–1^{Ns}$	–1*	28^{Ns}	9^{Ns}	5^{Ns}	0^{Ns}

IN1 = Mineral fertilisers; IN2a = Organic manures; IN2b = Grazing; IN3 = Atmospheric deposition; IN4 = Biological nitrogen fixation; OUT1 = Crop products; OUT2a = crop residues; OUT2b = Manure; OUT3 = Leaching; OUT4 = Gaseous losses; OUT5 = Erosion; OUT6 = Human excreta
Balance = $\sum IN – \sum OUT$; Significance: * = $P<0.05$, ** = $P< 0.01$, Ns = not significant

Nutrient balances for crops were negative but not significantly different between farm types (Table 6). Crops in LF farms had high negative nutrient balances because of higher off-take in crop products and higher losses through manure and leaching. The N balances of crops on the SF2 farm types were also highly negative because of leaching (–15 kg N ha^{-1}). Cotton and finger millet extracted more N than other crops. It is also noteworthy that the fallows in the short-term have limited soil fertility restorative capacity for only K that could be related to recycling K from the soil stocks.

The discrepancy between farm level and crop level balances on farms with higher cattle numbers can be explained by the fact that manure is accumulated in kraals but not redistributed to cultivated fields. This reiterates the importance of scale in nutrient balance analysis (Haileslassie et al., 2007). Historically, livestock in the Teso system were confined to kraals near homesteads for safety against theft in the night and little consideration was given to use of manure as a nutrient resource for fertility maintenance (Mahadevan and Parsons, 1970). Such management contributes to soil fertility heterogeneity in smallholder farms (Augustine, 2003; Giller et al., 2006) and inefficient use of nutrients from manure. Even when farmers appreciate the soil fertility improvement role of manure, farm labour constraints curtail redistribution to crop production fields. Some farmers attempt to distribute manure within the proximity of the homestead by moving cattle to new kraals once the current ones are full (Walaga et al., 2000). After some time, the former kraal (niches of high fertility) can be planted with vegetables and cereals like maize for roasting. Variability in soil fertility was also further reinforced by the nutrient mining of the cultivated fields.

2.3.6 Farming system productivity and associated management challenges

Crop productivity of the Teso system was poorer compared to the Mali system (Table 7). The respective productivity of cotton, millet and sorghum are 12, 31 and 59% higher in Mali and as expected, crop level nutrient balances were also accordingly more negative because of higher removal in products and losses through leaching and erosion (Lesschen et al., 2004). The exception, however, was cotton which received more P and K from fertilisers and manure inputs than are lost from the system. The higher productivity of the Mali system could be explained by the stable long rainy season of 5 months compared with shorter bi-modal rainfall seasons (4 and 3 months) in Pallisa. Better soil fertility, however, resulting from continuous nutrient application over a long-term as a result of the market-oriented cotton production can lead to higher water use efficiency. For crops cultivated in both systems, these are indeed consistently higher in Mali (Table 7). The capital accumulation at household level (cattle), access to input credit and improved production skills because of extension support allowed farmers in

Table 6 Nutrient balances for selected crops and nutrient stocks per farm type in Pallisa District Uganda (kg ha^{-1}).[a]

Crop	Nitrogen				Phosphorus				Potassium K			
	LF	MF	SF1	SF2	LF	MF	SF1	SF2	LF	MF	SF1	SF2
Cassava	–8	–6	–6	–13	–1	–2	0	0	–3	–1	3	–1
Finger Millet	–11	–11	–5	–17	–4	–3	–1	0	–5	–2	3	–5
Cotton	–21	–2	–7	–24	–4	–1	–2	–4	–9	0	7	–7
Groundnut	–11	–3	–2	–3	–4	–1	–1	–1	–8	–1	–1	–1
Fallow	–2	–2	–3	–3	1	0	0	3	4	1	1	2
Nutrient stocks	3533	2384	4436	4351	3579	3274	3051	3474	11650	6636	7434	13561

[a] Nutrient balances are weighted averages per farm type.LF= Larger farms; MF= Medium farms; SF1=Small farms with cattle;
SF2= Small farms without cattle. Balances are averages of 2 seasons.

Table 7 Average yield, productivity and nutrient balances for selected crops grown in Pallisa, eastern Uganda and Koutiala, southern Mali[a]

Crop	Pallisa					Koutiala[b]				
	Yield ($t\ ha^{-1}$)	Productivity ($t\ ha^{-1} mm^{-1}$)	N ($kg\ ha^{-1}$)	P ($kg\ ha^{-1}$)	K ($kg\ ha^{-1}$)	Yield ($t\ ha^{-1}$)	Productivity ($t\ ha^{-1} mm^{-1}$)	N ($kg\ ha^{-1}$)	P ($kg\ ha^{-1}$)	K ($kg\ ha^{-1}$)
Cassava [c]	1.21	1.3	–8	–1	–0.1	-	-	-	-	-
Finger millet	0.39	0.7	–11	–2	–2	-	-	-	-	-
Cotton	0.41	1.0	–13	–3	–1	0.96	1.1	–14	12	23
Groundnut	0.32	0.6	–4	–2	–4	0.56	0.8	–7	–3	–11
Sorghum	0.30	0.5	–5	–2	–2	0.99	1.2	–16	–2	–25
Maize	-	-			-	1.72	2.0	–26	–1	–19
Pearl millet	-	-	-		-	0.86	1.0	–20	–6	–24
Fallow	-	-	1	1	2	-	-	–3	1	0.1

[a] Pallisa receives bimodal rainfall; long rains (560 mm) and short rains (408 mm). Rainfall for Koutiala is unimodal (850 mm)

[b] Data adapted from Lesschen *et al*., 2004)

[c] Cassava yield is expressed as dry matter

Table 8 Reasons for declines in food and cash crop production by village in Pallisa district, Uganda

.

Reason for decline in	Percent respondents Chelekura A (n=25)	 Onamudian (n=26)	 Keria (n=30)	Average	χ^2
Food crops					
Soil infertility	84	73	83	80	***
Unreliable rainfall	44	54	43	47	***
Pests and diseases	8	39	13	20	***
Limited land	16	12	23	17	***
Lack of improved seed	20	19	0	12	***
Inadequate labour	4	4	0	3	ns
Lack of knowledge and skills	0	4	0	1	ns
Cash crops	(n=28)	(n=23)	(n=29)	(n=80)	
Soil exhaustion	57	57	79	65	ns
Lack of agricultural inputs	30	54	14	33	***
Pests and diseases	26	36	17	26	***
Fluctuating market	9	25	31	23	***
Labour intensive	9	14	17	14	***
Lack of improved seed	17	11	10	13	***
Limited land	9	14	7	10	***
Limited knowledge and skills	4	18	0	8	***

Significance: *** $P<0.001$, ns = not significant

Mali to produce higher crop yields. Further, they were motivated by the assured markets. This demonstrates that soil fertility is considered by farmers when they have tangible direct benefits because often farmers are not interested in improving soil fertility for its own sake. In systems with poor soils, it is worth investing in soil fertility improvement to gain higher returns especially when the nutrient inputs are accessible (Kanté, 2001). Extension support to the farmers also improved their skills in use of manure and fertilisers. The farmers practiced targeted application of the nutrient resources (manure and fertilisers) to the high value crop cotton and the cereals grown in rotation benefited from their residual effects. Farmers have also adopted maize, a high value crop and apply manure preferably to this crop compared to with other cereal crops (Kanté, 2001; Lesschen et al., 2004).

In the Teso farming system over 90% of the farmers reported that both food and cash crop production had declined over the years. They associated the trends in crop production with declining soil fertility, unreliable rainfall and infestation by pest and diseases in the case of food crops but also included lack of agricultural inputs and fluctuating markets in the case of cotton production (Table 8). Farmers judged declines to be due to poor crop yields (88%), presence of Striga (57%), tired soils (44%) and stunted crops (1%), indicators that have been used by other smallholder farmers in east Africa (Maruge et al., 2000). Continuous cultivation without adequate nutrient replenishment accounted for declining productivity. Often, cultivating improved crop varieties without any soil fertility improvement results in low yields (Kaizzi et al., 2004) and continued nutrient depletion. From Table 8 it also could be noted that there are between site differences in responses implying that intervention efforts should take variation into account.

There is hardly any use of external inputs in the farming system. Farmers rely on locally available nutrient input resources as is shown by the following characteristics (with proportionate uses between brackets). Crop production is characterised by crop rotation (over 90%), recycling of crop residues (78%), fallowing (51%) and negligible use of nutrient inputs such as cattle manures. The common types of crop residues available are cereal straws, and peelings of cassava and sweet potato. Households also reported that residues face other competitive uses as fodder (60%), fuel (51%), thatching materials (5%), mulching or are just burnt (57%). The remainder that is recycled is quantitatively small and qualitatively too poor to be used for soil fertility improvement. High labour requirements (41%), limited application skills (35%) and limited available quantities (32%) constrained widespread and efficient use of cattle manure whereas poverty (53%) and negative perceptions that inorganic fertiliser spoil soils (52%) constrained their use. These results are similar to those observed in other smallholder farming systems in low potential areas of sub-Saharan Africa (Hilhorst and Muchena, 2000; Nkonya et al., 2005).

Fertility management practices that include organic matter (cattle manure) cycling, crop rotation and nutrient conservation (sheet erosion control) have declined over time in the area. The available quantity of cattle manure, a major source of nutrients, is limited following the extensive rustling in the area. Tethering is now the common cattle management system as only few animals are kept. The result is that fields receive little manure input during stubble and dry season grazing. The option of increasing manure production by increasing cattle numbers now faces a great challenge as there are no adequate pastures.

Other management practices for improving productivity also face many challenges. Crop rotation was practiced mainly by farmers who had relatively large areas of land. The rotations were also not well designed to benefit the subsequent crops. In the 1950-60's, the management recommendation in this system was cropping for two years, followed by three to four years of fallowing designed in such a way to gradually cover the entire farm with time (Parsons, 1970). Legumes were a key component of the rotations (Uchendu and Anthony, 1975). During the fallow phases, manure deposition through livestock grazing also contributed to nutrient accumulation in such fields (Joblin, 1960). Nowadays, the fallow phase is so short; less than 6 months on 70% of

Table 9 Standardized regression coefficients for determinants of farm level nutrient and crop level balances and nutrient balance to stock ratios (BSR)

Parameter	B	TLU (No)	Crop yield (t ha^{-1})	LL ratio (ha ae^{-1})	Landscape position	Off-farm income	Adjusted R^2	Durbin -Watson Statistic
(a) Farm scale								
N balance	-17.50	0.68***	-0.06	-0.09	-0.05	0.14	0.45	1.92
P balance	-1.30	0.27***	-0.13	0.23[a]	-0.12	0.08	0.47	2.30
K balance	-3.52	3.08***	0.24	-0.09	0.24	0.07	0.58	2.01
N BSR	-0.02	0.64***	0.67***	0.21	0.13	0.78***	0.64	2.01
P BSR	0.00008	0.62***	-0.17	0.19	0.01	0.16	0.36	2.15
K BSR	-0.002	0.44**	-0.79***	0.13	0.31	0.89***	0.62	2.09

(b) Crop scale	B	TLU density (No ha^{-1})	Crop yield (t ha^{-1})	CL (ae ae^{-1})	Landscape position	Off-farm income	Adjusted R^2	Durbin Watson Statistic
N balance	-239	0.33**	-0.44**	0.64***	-0.095	0.29*	0.63	1.95
P balance	2.61	0.17	-0.58**	0.11	0.21	0.15	0.28	2.41
K balance	-97.9	-0.12	0.17	0.44*	0.26	0.17	0.17	1.97
N BSR	-0.09	0.06**	-2.59**	0.55	0.19	0.11	0.20	1.63
P BSR	0.011	0.18	-0.02**	0.07	0.28	0.12	0.12	2.15
K BSR	-0.01	0.05	-0.179	0.21	0.35*	0.38*	0.32	1.97

B = intercept

Sig: * $P<0.05$; ** $P<0.01$; *** $P<0.001$

Landscape position: 1 = upper, 2= middle

a.e. = Adult equivalent

TLU = Tropical livestock units, LL ratio = Land to labour ratio, CL = consumer to labour ratio the farms surveyed. Some farmers equate to resting a field with cassava as the last crop in the rotation cycle (cassava fallow) for 0.5 – 2 years; a practice also reported in the West African savannas (Kristjanson et al., 2002; Adjei-Nsiah et al., 2007). The '*cassava fallow'* is assumed to recycle nutrients through the large biomass produced by the early maturing varieties grown and the grass that grows in the fields during the 1 to 2 years of cropping. In reality, these high yielding cassava varieties remove substantial amounts of nutrients hence further degrading soils (Fermont et al., 2007).

Lack of implementation of land management policies contribute to degradation of soil fertility in smallholder farms. In the colonial times, the district by-laws and ordinances were implemented by chiefs and fines were attributed for failure to adhere (Kamugisha, 1993). In the lowlands of eastern Uganda that include Pallisa, grass bunds ('*amatuta'*) of 1 m between fields of 110 m x 65 m along contours were a requirement to control sheet erosion and bush burning was prohibited (Parsons, 1970). The grass bunds are now no longer effectively managed and explain the increased prevalence of sheet erosion during the rainy seasons. In summary, lack of input and output markets and lack of extension support are accelerating nutrient depletion in the system and hence the widespread negative nutrient balances reported in the system (Wortman and Kaizzi, 1998; Walaga et al., 2000; Nkonya et al., 2005).

2.3.7 Farm household determinants of farm sustainability

In Table 9, regressions between the characteristics across farm typologies and major nutrients showed that tropical livestock units (TLU) were the major determinant of balances and nutrient balance to stock ratios (NBSR) for all the major nutrients. For the NBSR however, crop yields and access to off farm income, especially for N and K, were also important. These results were expected because livestock is a major source of nutrient inflows to the farms through the grazing inflow. Farms with more livestock (LF) were expected to have better nutrient balances and NBSR due to accumulation of nutrients in manure from the cattle. In the case of NBSR, larger crop yields reduced the amounts of nutrients in the stocks as more nutrients were removed from the farm. Thus farms that produced more and sold produce (LF) had smaller NBSR's. Access to off farm incomes would probably reduce the farm area cultivated or investment in farming practices that would improve nutrient accumulation such as growing more legumes.

At the crop scale however, nutrient balances and NBSR were, next to TLU densities, largely dependent on crop yields. Larger crop yields made nutrient balances more negative as farmers did not apply any nutrients to crops. The contribution of the cattle was through free range grazing on the farms fields. Labour limited farms or farms with higher consumer to labour (CL) ratios, had less labour available for cultivation of land leading to less negative balances as only small crop yields were produced. Such farm households were food insecure. Observations in the field showed that the labour-limited farmers tried to plant as much cropland even if planting was late. Labour limitations affected weeding and its timing. Crops were lost or yields obtained were very small due to weed competition. The conditions of high CL ratios have been created because of the universal primary education policy which opened opportunities for many children to go to school. Previously, they formed the bulk of family labour. Without communal or group labour arrangements, cash is needed to buy in labour for farm operations which is a challenge for the poor households.

The scenario described here highlights a need for crop-livestock integration, particularly manure management to enhance crop production within farms in the case of farms with livestock. This would also boost the NBSR at the crop level and improve the systems sustainability. Improving opportunities for access to off farm income could relieve pressure from the land or help with purchase of nutrient inputs which in turn could assist in improving nutrient balances and NBSR.

2.4 Conclusions

Land use and productivity status in the Teso farming system changed during the four decades of analysis because of several factors rather than population growth alone, as commonly assumed to be the case for smallholder farming systems in sub-Saharan Africa. Important among these additional factors were political instability that increased insecurity, the lack of input and output markets and weakened land management and service delivery institutions. In response to these external shocks, smallholders diversified from millet and cotton to production of cassava, now the dominant crop for food security and cash, and rice and legumes such as groundnuts for cash. Rice cultivation expanded into the swamps faster as the cattle that used to graze there were depleted through rustling. Productivity of the farming system is poor as no external nutrient inputs are used and nutrient balances are negative at the crop scale because of reliance on nutrient mining. Sustainability of the farming system is determined by numbers of livestock, the amounts of crop production, labour ratios and access to off farm income.

The example of cotton-cereal farming system in southern Mali shows that improving soil fertility and productivity of farming systems hinges on how it is supported by stable policies and institutions over the long-term. Building institutional partnerships around profitable crops can be an entry point for improving soil fertility (Lesschen et al., 2004) but needs to focus on improving livelihood security of the smallholders to gain acceptance and to be sustained. Potential case-specific commercial commodities and viable partnerships for these systems therefore need to be identified and established.

For agronomic improvement of productivity, farmers with livestock need to use manure in crop production but also improve its management. Since labour can be a major constraint in use of manure, for example for transport and application on fields, labour saving approaches such as establishing kraals directly on fields so that manure accumulates on field that are later cultivated as in parts of Zambia (Penninkhoff, 1990) should be adopted by farmers rather than maintaining the kraals close to the homesteads. Creation of opportunities for off-farm income could help a majority of the farm households acquire nutrient inputs such as fertilisers to apply to the low fertility soils on their farms. However there is a need for complementary strategies as well as making fertilisers available. Opportunities also exist through growing of leguminous crops to improve soil fertility; especially increasing nitrogen supply through biological nitrogen fixation if other limitations like low P in soils are addressed (Vanlauwe and Giller, 2006). It is also possible to improve the farmer's strategy of matching crop production with soil fertility variations that have been created or reinforced on the farms over years (Carter and Murwira, 1995). This practice has been shown to lead to increased resource use efficiencies (labour and nutrient inputs) in some African farming systems (Zingore, 2006; Tittonell, 2007) and may aid development of context specific management recommendations that can lead to boosting productivity of smallholder systems - the best fits approach (Vanlauwe et al., 2007).

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Chapter 3

Characterisation of between- and within-farm heterogeneity in soil fertility in a low input farming system in Eastern Uganda[†]

[†] This chapter is submitted as: Ebanyat, P., Ridder, N. de, Majaliwa-Mwanjalolo, G., Oort, P. A. J., Delve, R.J., Tittonell, P., Giller, K.E. Characterisation of between- and within-farm heterogeneity in soil fertility in a low input farming system in Eastern Uganda. *Geoderma.*

Abstract

Heterogeneity in soil fertility is determined by inherent soil-landscape characteristics and historical human management. Understanding how this heterogeneity is constructed is vital to aid targeting of soil management practices. We characterised the nature and magnitude of variability in soil fertility through soil profile observations along toposequences of soil types and sampling of surface soils from fields on 33 farms in two villages exhibiting different geo-morphological features in Pallisa district, Eastern Uganda. Down the toposequences in Chelekura and Onamudian villages, soil pH, SOC, total N, Exch. Mg, Exch. Ca, Exch. K, CEC, sand and clay did not exhibit topographic-gradients. Extractable P was however 3 and 5 times higher in the top soils of the profiles in the valley bottoms than those in the upper landscape position of the toposequences in Chelekura and Onamudian respectively. Within the profiles of each local soil type, soil pH, SOC, total N, extractable P, exchangeable bases and sand decreased with depth except in the valley bottoms where Ca increased with depth. SOC and silt + clay are used to illustrate the spatial variability in soil fertility within-farms. Significant differences ($P<0.05$) were observed in average SOC concentrations in surface soil properties between landscape positions in both villages. Large and significant differences ($P<0.001$) in SOC were observed between field types. Fields classified as of good, medium and poor soil fertility by farmers had average SOC concentrations of, respectively 9.3 g kg^{-1}, 6.6 g kg^{-1}, 5.5 g kg^{-1} in Chelekura village and 15 g kg^{-1}, 11 g kg^{-1}, 7 g kg^{-1} in Onamudian village. In contrast with other studies in smallholder farming systems in sub-Saharan Africa, spatial analysis did not reveal a particular generalized pattern in variability in soil fertility (evaluated here using SOC as an indicator) across farms in each village. Within-farms, larger contents of SOC were associated with larger amounts of silt + clay and locations where cattle kraals had been sited in the past. The field scale, which is easily recognised by farmers, is an important entry point for targeting soil fertility management technologies since management decisions are at the farm scale.

Key words: *Sub-Saharan Africa; Spatial heterogeneity; Teso farming system; Smallholder farms*

3.0 Introduction

Productivity of smallholder farming systems in Sub-Saharan Africa (SSA) is constrained by poor soil fertility (Buresh et al., 1997; Smaling et al., 2002) yet efforts to improve soil productivity in these systems are challenged by the lack of robust recommendations that adequately consider heterogeneity in soil fertility at relevant scales. For example, fertilizer recommendations were made at agro-ecological scale assuming homogenous soil characteristics and climatic conditions and crop response (Smaling, 1993). The usefulness of such recommendations over time has been eroded because they do not account for management-induced changes in soil fertility status.

Inherent characteristics of soils are determined by the underlying geology and may guide land use decisions such as settlement, grazing, afforestation, and cultivation at larger spatial scales (Ogunkunle, 1993; Deckers, 2002). What is of importance to the farmer however, is the top soil where crop production is done. Assessing variability relevant for farmer management therefore should combine both topographic and surface soil characterisation because they are intertwined in determining the status of soil fertility.

Along toposequences, variability in soil fertility is related with the associated soil types on the landscape positions or soilscapes (Deckers, 2002). In many parts of Uganda, soils on the upper parts of the landscape are shallow and less fertile while those on the pediments are deeper and more fertile. This is due to processes of erosion and deposition down slope, creating gradients of increasingly fine soil texture that correspond with increasing soil fertility towards the lower positions of the landscape. Commonly, farmsteads are located on the uplands, in upper and middle landscape positions. Depending on settlement patterns and socially constructed patterns of land access, management imposed on the top soils along the toposequence may reinforce or overrule the toposequence-induced variability in soil fertility (Prudencio, 1993; Tittonell, 2007). This can create large differences in soil fertility over short distances within farms that influence crop productivity and may necessitate differential soil fertility management interventions. In several smallholder African farming systems, nutrient resource management practices have resulted in creation of soil fertility gradients in which soil fertility decreases away from homesteads (Giller et al., 2006; Tittonell et al., 2007a; Zingore et al., 2007a). Management induced soil fertility status strongly affects efficiency of added nutrients by crops (e.g. Vanlauwe et al., 2006; Wopereis et al., 2006; Zingore et al., 2007b; Tittonell et al., 2007b). Due to impacts of variability on crop productivity, targeting of management recommendations to heterogeneity in the diverse smallholder African farms is necessary. Soilscape (landscape) or fieldscape (field) scales have been suggested as appropriate scales for targeting soil fertility management practices for better nutrient management (Deckers, 2002). Appropriateness of these scales is farming system specific and need to be established.

This study focuses on the Teso farming system in eastern Uganda, where farmsteads have existed for several years and are randomly spread over toposequences (except in the valleys) with gentle slopes of <8%. Crop and soil management decisions are domains of individual households within the confines of farm boundaries. Our objective was to characterise the nature and magnitudes of variability in soil fertility within the Teso farming system, and thereby to determine whether toposequence variability and or within-farm variability are the most appropriate scale(s) for targeting of soil fertility management interventions. We focused on elucidating whether soil properties differ: (i) between delimited landscape positions on toposequences; (ii) between field types as classified by the farmers; (iii) between farm types differentiated by resource endowments; and (iv) systematically with distance from the homesteads.

3.1 Materials and methods

3.1.1 Site description

Pallisa district (1°09′ N, 33°48′ E) in eastern Uganda was selected for characterisation of the mixed crop-livestock Teso farming system which supports 5% of Uganda's population. Until recently, the millet cropping systems (that also extend to the Teso region of western Kenya) dominated and crops were produced with virtually no inorganic fertilisers (Ebanyat et al., 2008; Fermont et al., 2008). The district lies at an altitude of 1000-1100 masl with a landscape of a dissected peneplane of the Tanganyika surface (Chenery, 1960), characterised by wide gently convex interfluves separated by wide swampy valleys (Ollier et al., 1969). The toposequences are dominated by the Buruli or the Maizimasa complex of catena whose respective geology are a combination of lacustrine deposits and basement complex rocks (granitic-gneiss) or only basement complex rocks (Ollier and Harrop, 1960). The Buruli catena covers approximately 65% of the district land surface and the soils are light grey or pink sandy loam or loams. The Maizimasa catena has reddish brown sandy clay loams or brown clay loams. Rainfall is distributed in a bimodal pattern. The first rains are from March to June with a peak in April and the second rains are from August to October or November with a peak in September or October. The markedly dry periods are from November to March. Mean monthly temperatures range from 15°C to 36°C, with annual mean of 25°C (Yost and Eswaran, 1990).

3.1.2 Study sites

The sites selected for the study were Chelekura A village (hereafter referred to as Chelekura village) in Chelekura parish (1°17′N; 33°30′E) and Onamudian village in

Akadot parish (1°11´N; 33°43´E). There was an on-going research project on integrated nutrient management using a farmer field school approach (called 'Integrated nutrient management to attain sustainable productivity increases in East African farming systems'; INMASP) in these villages and this made it easier working with organised farmer groups to integrate farmer's local knowledge on soils. Chelekura represented the Buruli catena while Onamudian represented the Maizimasa complex catena. The study sites were within the same rainfall zone of 900 mm yr^{-1} and enabled focusing of studies on soil fertility heterogeneity. The sites however differed in population density, parent material from which soils are developed and distance to the main urban centre. Four main types of households, grouped by farm size, cattle and food security status were identified in the study sites (Table 1).

3.1.3 Participatory village transect mapping and farm surveys

Participatory transect mapping of soils was conducted with farmers from farmer field schools with already prior knowledge from village reconnaissance and village resource mapping including soils distribution documented under the INMASP project (Ebanyat et al., 2003). The mapping was done following transects and land surface coverage of the village with the local soil types noted in each village (Figure 1). The toposequences were divided into three positions on the basis of the dominant soils and changes in slope; the upper position (includes uplands in Onamudian village), middle position and the bottom position encompassing areas that are seasonally or permanently wet. Soil types were identified according to farmers' local knowledge, land use practices recorded, and the productivity constraints and potential of the local soil types identified and discussed with farmers during mapping. Profile pits were dug in each major local soil unit, morphological characteristics described and soil samples of each horizon taken for laboratory analysis (a total of 33 profile samples were collected). The location of each soil profile was geo-referenced with an Etrex Garmin global positioning system. The morphological descriptions of soil horizons and the results of soil analyses were used to classify the soils according to the FAO 1998 revised legend.

Farm surveys were conducted on the selected representative farms (i.e. larger farms (LF), medium farms (MF), small farms with cattle SF1, and small farms without cattle (SF2)) of farmers participating in the farmer field school project (Table 1). The farm types were derived by agglomerative cluster analysis using the cosine similarity index from rapid farm survey data collected from a total of 90 households (60 of which were non-farmer field school participating households) on data of farm resource endowments, production orientations and livelihood strategies (Tittonell et al., 2005). The main grouping variables were farm size, number of cattle, income sources, household food security, hire or sale of labour, types of crops grown, and

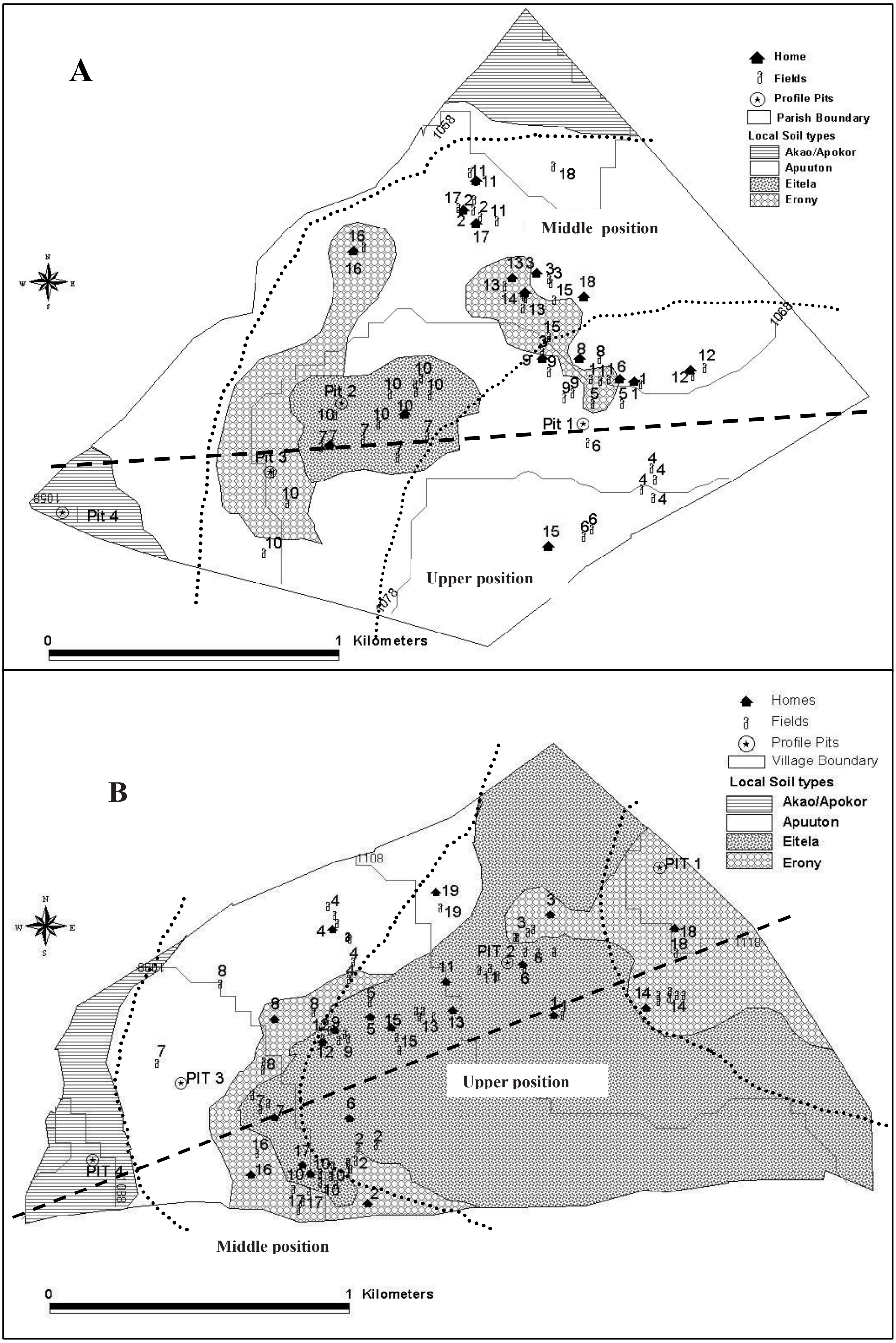


Figure 1 Locations of profile pits, farms and fields sampled by landscape positions in (A) Chelekura village and (B) Onamudian village, Pallisa District. Broken straight lines represent the transect paths; dotted curves are researcher delineated landscape position boundaries.

types of farm implements owned (Ebanyat et al., 2008). The sampling was done in 17 farms in Chelekura village and in 16 farms in Onamudian village. Sketches of farm maps were drawn with help of the farmers showing the fields. GPS coordinates of major corner boundaries of the farms were recorded and later used to compute farm sizes. Management history of the fields including cropping sequences over the previous four cropping seasons and soil fertility management practices were obtained through interviews with farm owners. Farmers were also asked to rate the fertility of individual fields of their farms and to indicate the main local soil unit to which each field was located.

3.1.4 *Surface soil sampling and sample preparation*

Soil samples were collected from 33 farms selected to represent the main farm types in the area (Table 1). Point grid sampling following 20 x 20 m grids laid on each of the fields of each farm was used and one sample collected from each grid point intersection at 0-20cm depth in February and March, 2005. Only fields of each farm on the upper and middle landscape positions were sampled because the study concentrated on these locations where a majority of crops are produced. Grid sampling is suitable for capturing variability especially when spatial structure in variability in fertility is not known (e.g. Flowers et al., 2005). The method resulted in collection of different number of soil samples from each of the farms so comparisons of soil properties between fields and farms were made using the weighted averages of samples collected per field in relation to total number of samples collected from a given farm. The mid-point locations of the homesteads and sampled fields (Figure 1) were geo-referenced using an Etrex Garmin GPS with an error of ± 7 m. A total of 1209 soil samples were collected, air-dried, crushed and sieved through 2 mm prior to analysis at the Soil and Plant Analysis Laboratory of the World Agroforestry Centre (ICRAF) in Nairobi, Kenya.

3.1.5 *Distance, bulk density, and slope computations*

Data of GPS recordings were processed in Arc GIS 9.1 to obtain mid-field distances from homestead using the square root of Euclidian distances algorithm. Bulk density was determined for each of the fields of each farm using an equation developed by multiple regression analysis between bulk density measurements determined by the core method (Anderson and Ingram, 1993) for 62 randomly selected fields in the two study villages and other soil properties. Bulk density was predicted from soil organic carbon (identified as the best predictor amongst other soil properties) using the equation below developed by regression analysis:

Table 1 Biophysical characteristics of study sites and resource endowments and livelihood strategies of household types in study sites, Pallisa District Uganda. Average values per household followed by the ranges observed between brackets

Characteristic	Chelekura parish	Chelekura A village				Akadot parish	Onamudian village			
		LF (n=2)	MF (n=5)	SF1(n=10)	SF2 (n=12)		LF (n=3)	MF (n=3)	SF1 (n= 9)	SF2 (n=12)
Rainfall (mm yr^{-1})	900					900				
Soil parent material §	Lake deposits and BC rocks					BC rocks				
Pop. Density † (Pers. km^{-2})	118					218				
No of households †	914					807				
Distance to urban market (km)	17					6				
Household size (no)	5	12 (7-17)	10 (6-15)	8 (4-12)	6 (2-17)	6	10 (5-14)	10 (7-12)	7 (4-11)	5 (1-14)
Age HH head (yr)		64 (62-67)	56 (30-78)	53(30-78)	43 (23-65)		57 (48-67)	44 (34-50)	41(29-68)	43 (23-69)
Age of farm (yr)		34 (30-37)	30(12-50)	27(9-62)	21(1-37)		25 (12-38)	22 (7-33)	15 (9-38)	15 (3-35)
Farm size (ha)		4.01(3.8-4.4)	2.01(0.7-4.0)	1.6(1-3.2)	0.98 (0.3-2.4)		8.5 (5.5-12)	2.7 (1.4-4.6)	1.4 (0.5-3.5)	0.5 (0.09-1.5)
Cultivated area (ha)		1.91(1.7-2.2)	1.47(0.4-2.5)	0.86 (0.2-1.5)	0.66 (0.2-1.6)		2.4 (1.3-2.4)	2.3 (1.33-2.4)	1.1(0.7-1.7)	0.18 (0.1-1)
Cattle (no)		15 (10-19)	2 (0-4)	2 (0-3)	0		8 (2-17)	4 (3-5)	1 (0-3)	0
Goats (no)		8 (4-11)	1 (0-4)	1(0-2)	1 (0-4)		3 (0-5)	3 (2-4)	1 (0-4)	1 (0-2)
Food insecure (no)		1 (0-2)	2 (0-4)	3 (0-6)	6 (1-8)		0.67(0-2)	2 (0-3)	2 (0-7)	4 (0-12)
Use of:										
(i)inorganic fertilisers		No	No	No	No		No	No	No	No
(ii) crop rotation		Yes	Yes	Yes	Yes		Yes	Yes	Yes	No/yes
(iii) crop residues		Yes	Yes	Yes	Yes/no		Yes	Yes	Yes	Yes
(iv) manure		Yes/no	Yes/no	No	No		No	No/Yes	No/yes	No
Sell labour		No	Yes/no	Yes/no	Yes		No	No/yes	No/yes	Yes
Buy labour		Yes	Yes	Yes/no	No		Yes	Yes	Yes/No	No
Income sources		Beer brewing, Crop sales, Part time employment	Beer brewing Gainful employment, Crop sales	Crop sales	Sell labour		Crop sale, small business, remittances	Formal employment, crop, sales, beer brewing	Crop sale Beer brewing	Crop sales, labour sale

LF = Larger farms; MF = medium farms; SF1 = Smaller farms with cattle; SF2 = smaller farms without cattle; HH= household head; BC = Basement complex rocks

$BD = -9.44 \times SOC + 1622$ ($R^2 = 0.08$; RMSE = 92 kg m^{-3})
(1)

Where: BD = bulk density (kg m^{-3}) and SOC is soil organic carbon (g kg^{-1}).
Slopes for each field were obtained from a slope map generated in GIS from a digital elevation model.

3.1.6 Spectral and chemical analysis of soil samples

The air-dry soil samples (<2 mm) were scanned at 350-2500 nm infrared region in Duran glass Petri-dishes using a FieldSpecTM FR spectroradiometer with optical set up as described by Shepherd et al. (2003). The relative reflectance data was reselected at every tenth nanometer value. The spectral data were then transformed using the first derivative in the Savtizky-Golay algorithm using the “The Unscrambler” software (CAMO, 2005) to minimize variations caused by grinding and optical set up. Wave bands in the ranges of 420-960, 1020-1770 and 1830-2480 nm having low signal to noise ratio were left out. The first two principal components explained 75% of the spectral variance (44% of which by the first PC and 31% by the second).

Fifteen percent of the total samples (n = 181) were randomly selected on the basis of the principal component model of the first derivative reflectance and subjected to wet chemistry analysis to determine pH, organic carbon, total nitrogen, extractable P, exchangeable bases (Mg, K and Ca) and particle size using methods described in Shepherd and Walsh (2002). Total organic C and total nitrogen were determined using a ThermoQuest EA 1112 elemental analyser.

A principal component analysis (PCA) model was developed using all the wet chemistry data (excluding two samples that were outliers) and the first two principal components were calibrated against the spectra. The first PC explained 57% of the total variance in the wet chemistry data while the second accounted for 19%. On the loading plot, information in PC1 was associated with variability in C, N, exchangeable bases Mg, Ca, silt and sand, while variability in extractable P, pH and clay was associated with PC2. The partial least square calibration model for spectra and the first PC from the wet chemistry PCA model was good with a cross-validation correlation coefficient of $r = 0.93$ and RMSE = 0.87, while for the second PC it was not as good as for PC1 ($r = 0.73$; RMSE = 0.96). The calibration models for extractable P, exchangeable K, exchangeable Ca and silt had a high correlation coefficient, $r < 0.9$. With the calibration models developed for each soil parameter, predictions were made for the other samples that were not subjected to wet chemistry analysis. Relationships between predicted and measured values for selected soil properties are in Figure 2.

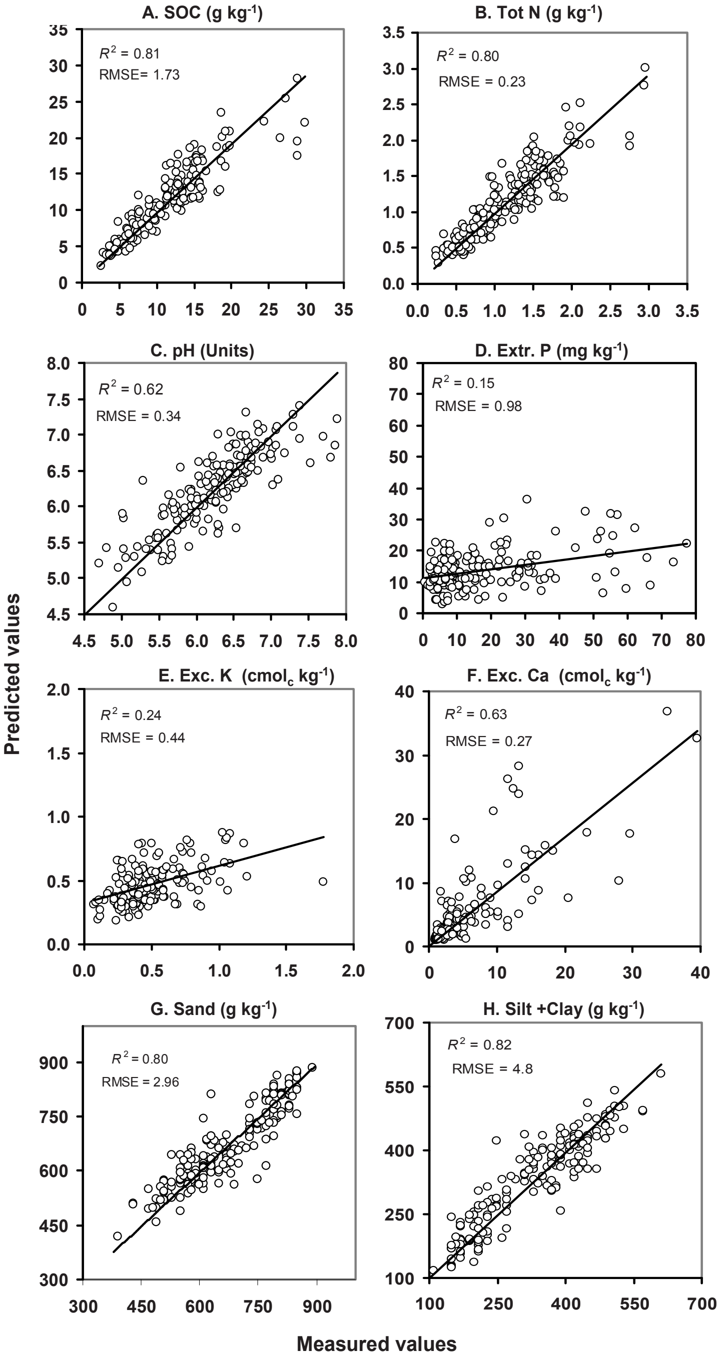


Figure 2 Relationship between predicted soil properties using near infrared spectroscopy and measured soil properties using standard wet chemistry methods (n =181).

3.1.7 Spatial variability of soil fertility within farms

Point maps were created in ILWIS for selected representative farms using the grid point data for only soil organic carbon and silt + clay and contour maps delineating zones of similar soil characteristics developed. These variables were chosen as recognised indicators of soil fertility status in tropical soils (Feller and Beare, 1997). The approach chosen to illustrate spatial variability in soil fertility within farms was adequate although we know that Geostatistics could have also been applied to generate continuous surfaces of soil variables.

3.1.8 Statistical analysis

Statistical analysis was performed using the mixed effects model (REML) in Genstat 11.1 with farm as a random factor. Soil properties; pH, SOC, total N, extractable P, exchangeable bases, particle size fractions and bulk density were evaluated for normal distribution. SOC was transformed to log and exchangeable bases to square root values, the rest of the variables were not transformed. Farm scale soil fertility status of each nutrient was calculated by weighted aggregation of soil parameter relative to the proportions of area of a given field relative to the farm total area (Tittonell, 2007). Total farm areas were adjusted for the areas occupied by the homestead, which are normally not used for production.

$$SF\overset{n}{\underset{i=1}{S}}(a) = \sum SF(a)i \times (FA/TFA) \qquad (2)$$

Where:

$SFS_{(a)}$ = Soil fertility status at farm scale for nutrient a

$SF_{(a)i}$ = Nutrient status for each field in the farm (1 to n fields)

FA_i = Area of each particular field (1 to n fields) in hectares

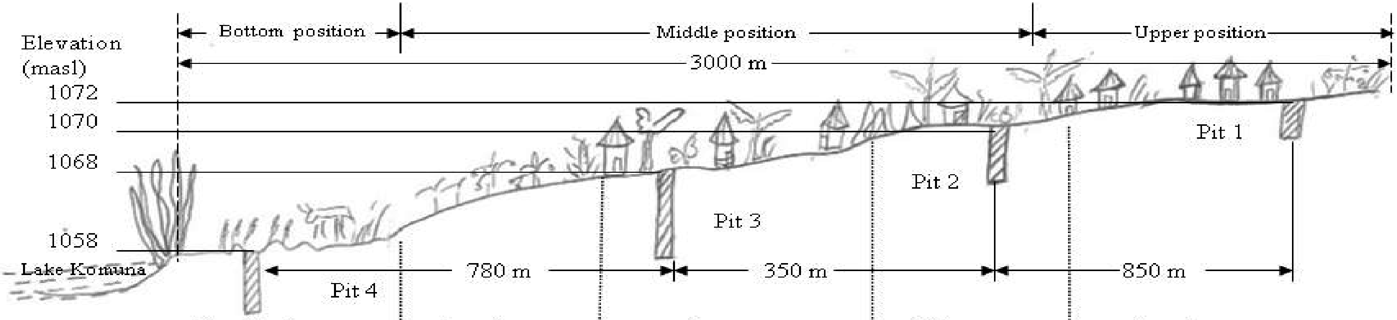
TFA = Total farm area in hectares.

3. 2 Results

3.2.1 Toposequences and soil profile description

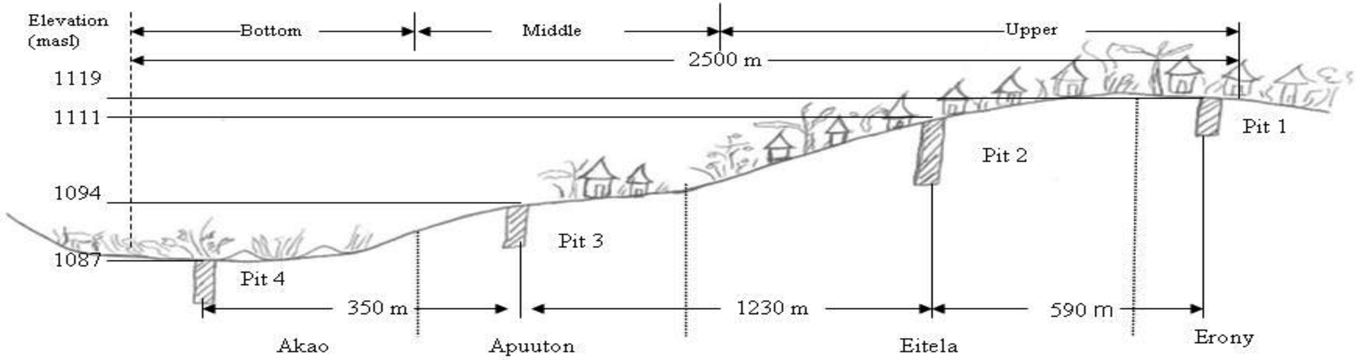
Local soil types and land use

Four major local soil types *Eitela, Apuuton, Erony*, and *Akao/Apokor* were identified in each of the study villages with the farmers. These soils were distinguished by the farmers on the basis of soil depth, colour, sticking properties and moisture retention ability. The local soil types *Apuuton* and *Eitela* dominated most of the Chelekura and



	Akao/Apokor	Apuuton	Erony	Eitela	Apuuton
Soil type	Dark gray Sandy clay	Light brown Sandy loam	Light brown Sandy loam/sandy clay loam	Dark reddish brown sandy loams	Light brown Sandy loams
Land use	Rice cultivation, sorghum and millet on termite mounds; Grazing; fishing, building sand mining, papyrus harvesting for craft making	Cultivation- millet sorghum, cassava, sweet potatoes, cotton; Grazing after cropping	Settlements; crop cultivation- groundnut, green grams, cowpea, cotton, cassava, fruit trees and bananas around home steads (oranges, papaws, jack fruit , millet sorghum; grazing after cropping	Settlements and cropping groundnut, green grams, cowpea, cotton, cassava, fruit trees around homesteads (oranges, papaws, jack fruit, millet sorghum	Settlements; and cropping groundnut, green grams, cowpea, cotton, cassava, fruit trees around homesteads (oranges, papaws, jack fruit) , millet sorghum, sweet potatoes; grazing after cropping
Soil fertility	Medium to high	Low	Medium, deep soils	Low	Low
Constraints	Flooding in rainy seasons, mono cropping with rice	Poor moisture retention, sheet erosion	Sheet erosion, over cultivation	Shallow soils , hard to till when dry	Poor moisture retention, leaching, sheet erosion; over cultivation without nutrient use
Potential interventions	drainage	Add manures and fertilizers	Add manures and fertilizers	Add manures and fertilizers	Add manures and fertilizers

Figure 3 Transect map showing soils identified on physiographic positions and their characteristics, locations of profile pits, and land use along a toposequence in Chelekura village, Pallisa district.



Soil type	Grayish brown sandy clay	Light brown sandy loams	Dark reddish brow sandy / sandy clay loams	Reddish brown sandy loams
Land use	Rice + maize intercrop, grazing in dry season, sorghum and millet on flanks	Very few settlements, cassava, sorghum, millet cowpeas, groundnuts, green gram, gazing after harvests	Many settlements; crop cultivation- groundnut, green grams, cowpea, cotton, cassava, fruit trees and bananas around homesteads (oranges, papaws, jack fruit , millet sorghum; grazing after cropping	Many settlements; crop cultivation- groundnut, green grams, cowpea, cotton, cassava, fruit trees and bananas around home steads (oranges, papaws, jack fruit , millet sorghum; grazing after cropping
Soil fertility	High	Low	Low to medium	poor
Constraints	Water logging, too sticky to cultivate when wet, mono cropping	Poor moisture retention, leaching, over cultivation, sheet erosion	Sheet erosion, deep but some portions have shallow soils with murrum, striga weeds	Shallow soils Too many weeds especially striga, over cultivation
Potential interventions	Drainage, cultivate at right time, rotations	Application of fertilizers and manures	Application of fertilizers and manures	Application of fertilizers and manures

Figure 4 Transect map showing soils identified on physiographic positions and their characteristics, locations of profile pits, and land use along a toposequence in Onamudian village, Pallisa district.

Table 2 Chemical and physical characteristics profiles classification of soils on the physiographic positions along toposequence in Chelekura village

Position/ Pit No/ Soil name	Horizon	depth	Colour[†]	structure‡	pH (H_20)	OC	Tot N	Extr. P	Exch. K	Exch. Ca	Exch. Mg	CEC	Sand	Clay	FAO Classification
		cm			units	---(g kg^{-1})----		(mg kg^{-1})	------------cmol$_c$ kg^{-1}-----------				---(g kg^{-1})----		
Upper	AP1	0-13	10YR4/2	w, f, cr	5.8	4.6	0.5	7.9	0.3	1.2	0.6	4.49	800	120	Haplic
Pit 1	AP2	13-23	10YR4/2	s, co, sa, bk	5.1	4.6	0.5	7.8	0.2	1.4	0.6	4.32	720	160	Ferralsol
(*Apuuton*)	B	23-60	7.5YR4/2	s, co, a, bk	4.1	4.4	0.5	8.5	0.1	1.0	0.5	4.37	660	240	
Middle	AP	0-10	2.5YR4/6	s, co, a, bk	4.5	6.2	0.7	6.0	0.2	1.0	0.5	5.38	560	370	Haplic
Pit 2	B1	10-30	2.5YR4/4	w, co, a, bk	4.6	8.3	0.9	8.4	0.3	1.0	0.7	6.56	570	350	Ferralsol
(*Eitela*)	B2	30-38	2.5YR4/4	w, co, a, bk	4.9	5.7	0.6	10.9	0.3	1.1	0.5	5.10	640	280	
Middle	AP	0-15	2.5YR3/2	m, co, a, bk	5.7	5.2	0.6	11.0	0.3	1.2	0.6	4.82	770	140	Haplic
Pit 3	A	15-22	5YR4/6	s, co, a, bk	5.2	5.5	0.6	12.4	0.3	1.4	0.6	4.99	710	180	Ferralsol
(*Erony*)	B1	22-54	5YR4/6	s, co, a, bk	4.3	4.5	0.6	6.9	0.1	1.1	0.5	4.43	590	320	
	B2	54-90	7.5YR4/6	s, co, a, bk	4.5	3.8	0.5	10.6	0.1	1.0	0.5	4.04	590	350	
Bottom	AP	0-14	10YR4/1	s, co, sa, bk	5.5	3.7	0.4	23.1	0.4	1	0.4	4.98	840	100	Dystric
Pit 4	A	14-41	10YR4/1	Ma	4.8	2.4	0.3	15.7	0.3	1.2	0.5	4.25	780	130	Fluvisol
(*Akao*)	B1	41-63	10YR4/2	Ma	3.7	1.7	0.2	14.0	0.1	1.2	0.4	3.86	710	200	
	B2	63-110	10YR4/6; 7.5YR4/6	s, co, pr	4.1	0.3	0.1	4.0	0.03	12.3	0.4	3.09	550	420	

†Colour when moist; ‡ Key: w = weak, s = strong, moderate; f = fine, co =coarse, me = medium; gr = granular, sa = subangular, a = angular; bk = blocky, ma = massive, pr = prismatic.

Onamudian villages respectively (Figure 1). The toposequences in both study villages were gently sloping (2-8%) and approximately 3 km and 2.5 km long in Chelekura village (Figure 3) and Onamudian village (Figure 4) respectively. In Chelekura, the toposequence was *Apuuton, Erony, Eitela* and *Akao/Apokor* while in Onamudian it was *Erony, Eitela, Apuuton, and Akao.* The pattern in Onamudian conformed to that generally expected, with reddish brown soils occurring on the upper positions with gradually coarse sandy soils towards the valley bottoms (Chenery, 1960).

Farmers' classification of soils was not consistent with the FAO classification in both villages except for soils on the valley bottoms because of different criteria used in classifications. The soils in Chelekura village were predominantly sandy (*Apuuton*) and the *Eitela* soils occurred in a small patch within the middle landscape position. The profiles of *Eitela* soils had marrum/ plinthite at depths of less than 40 cm and 70 cm in Chelekura and Onamudian villages respectively (See Appendix 3.1). *Erony* soils are an intergrade of *Apuuton* and *Eitela*. Textural characteristics of the soils in the uplands showed *Eitela* to have the largest proportions of clay followed by *Erony* and *Apuuton* (Table 2 and 3*)*.

In terms of land use, homesteads are located on the upper and middle positions (usually in the centre of farms) and most cropping is carried out on these positions. Crops grown on these landscape positions include grain legumes and root crops especially cassava. The valley bottoms are used for rice (*Oryza sativa* L.) cultivation and for grazing. Major constraints associated with the local soil units as indicated by farmers in both villages included over cultivation without use of soil nutrient inputs, sheet erosion, low moisture storage due to the sandy nature of the soils on the upper and middle landscape positions, and waterlogging in the valleys during the rainy seasons. The soils on the upper positions are also considered shallow and underlain by laterite or plinthite. These constraints have also been reported in other parts of Pallisa District (Ssali et al., 2002).

Pedological characteristics of the soil types

Morphological characteristics of the profiles are summarised in Table 2 (Chelekura village) and Table 3 (Onamudian village) and further details of the profile descriptions are provided in Appendix 3.1. Moist colours of the soils in the horizons ranged from dark reddish brown (10YR4/2), reddish brown (2.5YR4/4), dusky red (2.5YR3/2) on the upper and middle positions to dark gray (10YR4/1) in the valley bottoms in Chelekura village. For Onamudian village, colours varied from dusky red (2.5YR3/2), dark reddish grey (10YR3/1) in the upper and middle landscape positions to dark gray (10YR4/1) in the valley bottoms. Within the profiles in the valley bottoms, mottle colours, strong brown (7.5YR 4/6) were observed because of anaerobic conditions associated with seasonal moisture fluctuations. The soils in the

Table 3 Chemical and physical characteristics profiles classification of soils on the physiographic positions along toposequence in Onamudian village

Position / pit No/ soil name	Horizon	depth	Colour†	Structure ‡	pH (H_20)	OC	Tot N	Extr P	Exch . K	Exch. Ca	Exch . Mg	CEC	Sand	Clay	FAO Classification
		cm			units	----(g kg^{-1})---		(mg kg^{-1})	------------(cmol$_c$ kg^{-1})------------				---(g kg^{-1})----		
Upper	AP1	0-8	2.5YR3/2	w, f, gr	5.6	9.0	1.0	10.4	0.5	1.5	0.6	6.96	670	220	Humic
(Pit 1)	AP2	8-17	2.5YR3/3	s, co, a, bk	5.2	8.0	0.9	9.9	0.3	1.3	0.7	6.23	630	240	Ferralsol
(*Erony*)	B1	17-34	2.5YR3/4	s, m, a, bk	4.8	9.0	0.9	9.2	0.2	1.3	0.7	6.44	550	330	
	B2	34-58	2.5YR3/4	s, m, a, bk	4.4	7.0	0.8	5.7	0.1	1.0	0.6	5.38	520	400	
	B3	58-72	5YR4/4	w, m, a, bk	4.4	6.0	0.7	4.1	0.1	1.3	0.5	5.16	530	410	
Middle	AP1	0-6	2.5YR3/2	m, co, a, bk	5.6	12.0	1.2	10.2	0.4	1.9	0.8	8.64	620	250	Rhodic
Pit 2	AP2	6-16	2.5YR3/2	m, me, a, bk	5.2	9.0	1.2	5.5	0.3	1.3	0.7	6.01	500	410	Ferralsol
(*Eitela*)	B1	16-30	2.5YR4/4	s, co, a, bk	5.3	12.0	1.2	13.3	0.4	2.2	0.8	8.97	570	290	
	B2	30-42	2.5YR3/4	s, co, a, bk	5.0	8.0	0.9	4.6	0.2	1.0	0.6	5.8	490	450	
	C1	42-70	2.5YR4/6	s, me, a, bk	4.3	7.0	0.9	3.0	0.2	1.1	0.6	5.27	520	430	
Middle	AP	0-15	10YR3/1	w, co, a, bk	6.0	8.0	0.9	14.4	0.4	2.1	0.7	6.40	700	170	Humic
Pit 3	A	15-31	2.5YR3/2	m, me, a, bk	5.5	9.0	1.0	10.2	0.4	3.0	0.7	6.69	670	200	Ferralsol
(*Apuuton*)	B1	31-58	2.5YR2.5/2	s, co, a, bk	4.6	7.0	0.8	5.8	0.1	1.8	0.7	5.38	550	330	
	B2	58-85	5YR3/3	s, co, a, bk	4.3	5.0	0.6	5.0	0.1	1.0	0.5	4.17	580	320	
	B3	85-140	5YR4/4	w, me, a, bk	4.3	5.0	0.6	9.0	0.1	1.0	0.5	4.70	590	330	
Bottom	AP	0-10	10YR4/1	co, a, bk	6.5	13.0	1.3	49.2	1.2	8.9	0.9	9.21	700	150	Dystric
Pit 4	A	10-30	10YR4/1	Ma	5.5	6.0	0.6	24.3	0.7	1.4	0.6	5.27	760	120	Fluvisol
(*Akao*)	B1	30-80	10YR4/2	Ma	3.2	2.0	0.3	5.8	0.1	2.0	0.4	4.02	710	200	
	B2	80-100	10YR6/4; 7.5YR4/6	s, co, pr	5.9	1.0	0.1	8.1	0.1	10.0	0.5	3.64	470	500	

†Colour when moist; ‡ Key: w = weak, s = strong, moderate; f = fine, co =coarse, me = medium; gr = granular, a = angular; bk = blocky, ma = massive, pr = prismatic.

upper and middle positions were well drained and had well developed strong angular to subangular blocky structure in the B horizons. The A horizons were < 30cm with weak to moderate sub-angular blocky structure that easily broke into crumb structures. The profiles on the upper and middle positions in both villages were generally shallow and had laterite at < 70 cm. Profiles in the valley bottoms were deep probably due to long-term sediment deposition from surrounding uplands.

Variations in soil properties down the toposequences were not systematic in both villages (see also Appendix 3.2). Extractable P was however 3 and 5 times higher in the surface horizon of the profiles in the valley bottoms compared to those in the upper position in Chelekura and Onamudian respectively. SOC was lowest (3.7 g kg^{-1}) in the valley bottoms. Within the profiles of each local soil type, soil pH, SOC, total N, extractable P, exchangeable bases and sand decreased with depth except in the valley bottoms where Ca increased at depths greater than 80 cm. Clay increased with depth indicating a process of illuviation. The high clay content at depth in the valley-bottom soils form an impervious layer that restricts water percolation and explains why ponding occurs in the valley bottoms during rainy seasons, resulting in accumulation of adequate water for growing of rice.

Using the profile morphological and chemical characteristics, the soils were classified according to revised FAO (1998) legend as Ferralsols on the upper and landscape positions. The soils in the valley bottoms had an ochric A horizon, cambic B1 horizons, and Fluvic properties and were classified as Dystric Fluvisols.

3.2.2 Landscape and fieldscape variability in surface soil properties

Only SOC ($P< 0.05$) and total N ($P<0.001$) were significantly larger in the middle than upper landscape position (LP) but all the predicted soil properties were significantly ($P<0.001$) larger in the good than poor field types (FT) in Chelekura village (Table 4). In Onamudian village, silt + clay, SOC and Tot N significantly differed between LP and FT and there were significant ($P< 0.05$) LP × FT interactions of silt + clay, SOC and soil pH. In general, values of soil properties were higher in Onamudian village than Chelekura village and could be attributed to underlying geology from which the soils are developed.

At field scale, the highest values of these chemical properties were recorded on fields that were classified as ‘good’ and the lowest values in the ‘poor’ fields. These results show the farmers’ strong ability to judge between good and poor field types. In this study area, 28%, 43%, 29% and 63%, 24% and 13% of the fields were of good, medium and poor fertility in Chelekura and Onamudian respectively. Farmer’s judgment relates to crop productivity of fields relative to each other but it also differs between locations. For example, the mean SOC contents for good fields in

Table 4 Mean values of predicted surface soil properties by landscape position and field type in Chelekura village (n = 63 fields) and Onamudian village (n = 67 fields).

Village/field Type	Silt + Clay (g kg^{-1})		SOC (g kg^{-1})		Tot N (g kg^{-1})		Extr. P (mg kg^{-1})		Exc K (Cmol$_c$ kg^{-1})		Exc Ca (Cmol$_c$ kg^{-1})		Exc Mg (Cmol$_c$ kg^{-1})		pH) (units)	
	Upper	Middle	Upper	Middle	Upper	Middle	Upper	Middle	Upper	Middle	Upper	Middle	Upper	Middle	Upper	Middle
Chelekura																
Good	240	250	11.0	9.3	1.14	0.97	23	19	0.55	0.47	1.82	2.10	0.71	0.66	6.8	6.6
Medium	220	230	6.1	6.6	0.63	0.69	13	14	0.35	0.37	1.48	1.44	0.55	0.58	6.3	6.3
Poor	190	200	4.8	5.5	0.49	0.59	12	12	0.35	0.30	1.17	1.25	0.48	0.53	6.3	6.1
SED																
LP	20^{ns}		0.05^{*}		0.09^{*}		0.05^{ns}		0.05^{ns}		0.27^{ns}		0.04*		0.17^{ns}	
FT	25***		0.74***		0.10***		0.08***		0.04***		0.26***		0.04***		0.19***	
LP×FT	23^{ns}		0.06^{ns}		0.07^{ns}		0.06^{ns}		0.05^{ns}		0.26^{ns}		0.04^{ns}		0.18^{ns}	
Onamudian																
Good	390	370	15	15	1.59	1.57	15	16	0.55	0.55	9.5	10.0	0.83	0.85	6.4	6.5
Medium	430	340	14	11	1.53	1.05	14	13	0.54	0.44	8.3	4.1	0.84	0.82	6.3	5.9
Poor	390	240	12	7	1.34	0.79	14	12	0.52	0.43	7.4	3.2	0.74	0.54	6.1	5.7
SED																
LP	31*		1.76*		0.19*		0.05^{ns}		0.05^{ns}		0.49^{ns}		0.05^{ns}		0.2ns	
FT	32*		1.91***		0.22**		0.06^{ns}		0.05^{ns}		0.47^{ns}		0.05^{ns}		0.2ns	
LP × FT	32*		1.86*		0.21^{ns}		0.06^{ns}		0.05^{ns}		0.49^{ns}		0.05^{ns}		0.2*	

SED = Standard error of difference; LP = landscape position; FT =Field type
Significance: ns= not significant; * P<0.05; **P <0.01; *** P<0.001

Table 5 Weighted averages of soil properties at farm scale for different farm types in the study sites in Pallisa district.

Village/ Farm type	pH (units)	SOC (g kg^{-1})	Tot N (g kg^{-1})	Extr. P (mg kg^{-1})	Exc. K ($cmol_c$ kg^{-1})	Exc. Ca ($cmol_c$ kg^{-1})	Exc. Mg ($cmol_c$ kg^{-1})	Silt + Clay (g kg^{-1})	Bulk density (kg m^{-3})
Chelekura									
LF	6.5 (6.3)	7 (20)	0.71 (18)	14 (39)	0.39 (23)	3 (44)	0.58 (12)	210 (12)	1558 (1.0)
MF	6.2 (4.2)	7 (26)	0.69 (15)	14 (22)	0.37(19)	3 (54)	0.57 (14)	240 (17)	1553 (1.1)
SF1	7.1 (4.1)	8 (31)	0.79 (30)	14 (25)	0.42 (21)	4 (75)	0.62 (14)	240(14)	1716 (1.4)
SF2	5.9 (1.9)	8 (12)	0.59 (15)	15 (17)	0.32 (13)	2 (35)	0.55 (5)	200(8)	1447 (0.5)
SED	1.3 (2.6)	2 (12)	0.41(14)	4 (12)	0.08 (12)	3 (36)	0.12 (8)	5 (6)	305 (0.9)
Onamudian									
LF	5.5 (6.5)	13 (50)	1.34 (52)	14 (20)	0.45 (17)	24 (51)	0.72 (15)	300 (19)	1413 (0.5)
MF	5.9 (6.6)	13 (23)	1.43 (22)	12 (18)	0.47 (20)	6 (76)	0.81 (12)	390 (15)	1607 (0.5)
SF1	5.9 (3.6)	10 (10)	1.21 (19)	13 (12)	0.48 (14)	6 (46)	0.74 (10)	370 (14)	1357 (0.2)
SF2	6.2 (5.8)	15 (8)	1.63 (9)	13 (18)	0.54 (19)	9 (28)	0.84 (6)	410 (8)	1604 (0.2)
SED	0.8 (2.3)	2.5(14*)	0.24 (15)	2 (6)	0.08 (7)	9 (19)	0.12 (7)	70 (7)	160 (0.2)

Values in parentheses are coefficient of variation (%); LF = Larger farms; MF = Medium farms; SF1 = Small farms with cattle; SF2 = Small farms without cattle.
Significance: *, $P < 0.05$

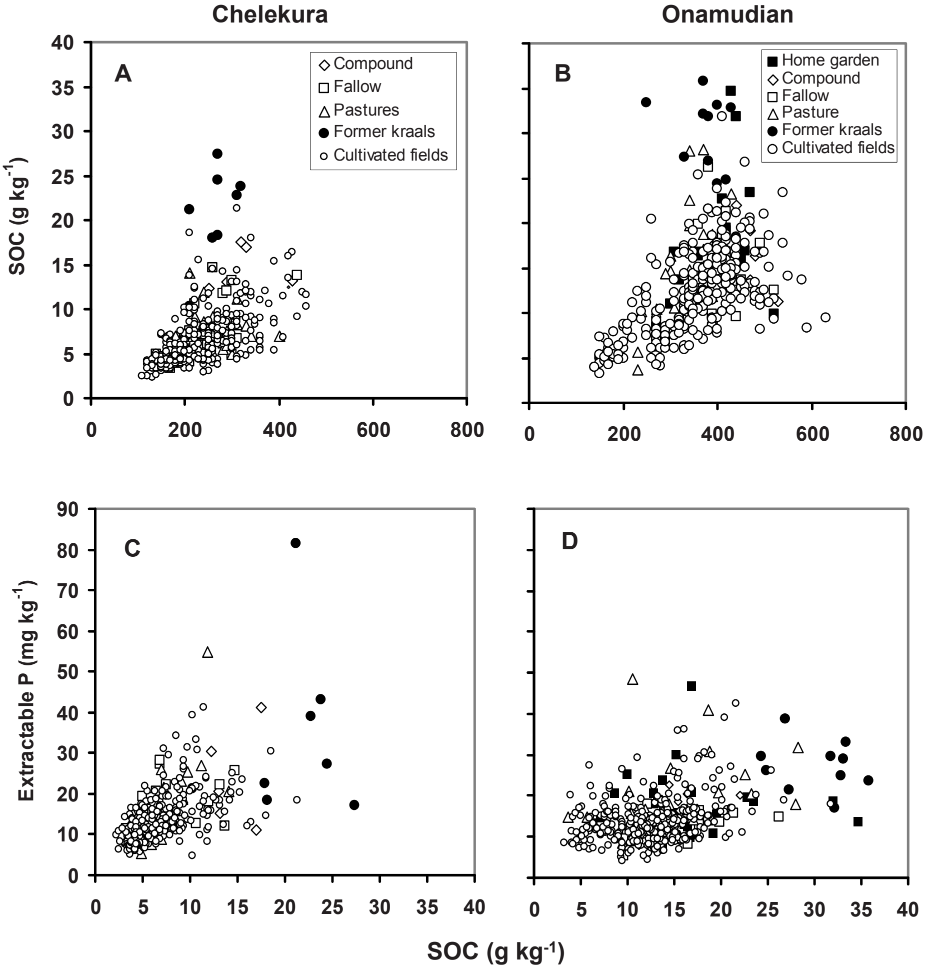


Figure 5 Relationship between SOC and silt + clay (A and B) and extractable P with SOC (C and D) respectively in Chelekura and Onamudian villages, Pallisa district).

Chelekura had an average of 9 g kg^{-1} which is similar to the fields of poor fertility (7 g kg^{-1} SOC) in Onamudian village.

3.2.3 Soil variability at farm-scale

Farm indices of soil properties and magnitude of variation

There were no significant differences in average farm weighted soil properties (soil fertility status) across farms in either of the study villages (Table 5). The status indices of SOC, the major indicator of soil fertility, in all the farms were less than 10 g kg^{-1} in Chelekura and >10 g kg^{-1} in Onamudian. Coefficients of variations across farm types were generally higher for exchangeable Ca ranging from about 28 to 76%. Although the weighted average of SOC did not differ across farm types in both villages, their

CVs on the other hand were highly significantly larger ($P<0.05$) between the LF (50 %) and the SF2 (8 %) and SF1 (10%) farm types in Onamudian village. This variation is related to livestock ownership and accumulation of manure on former kraals around the homesteads of the larger farms.

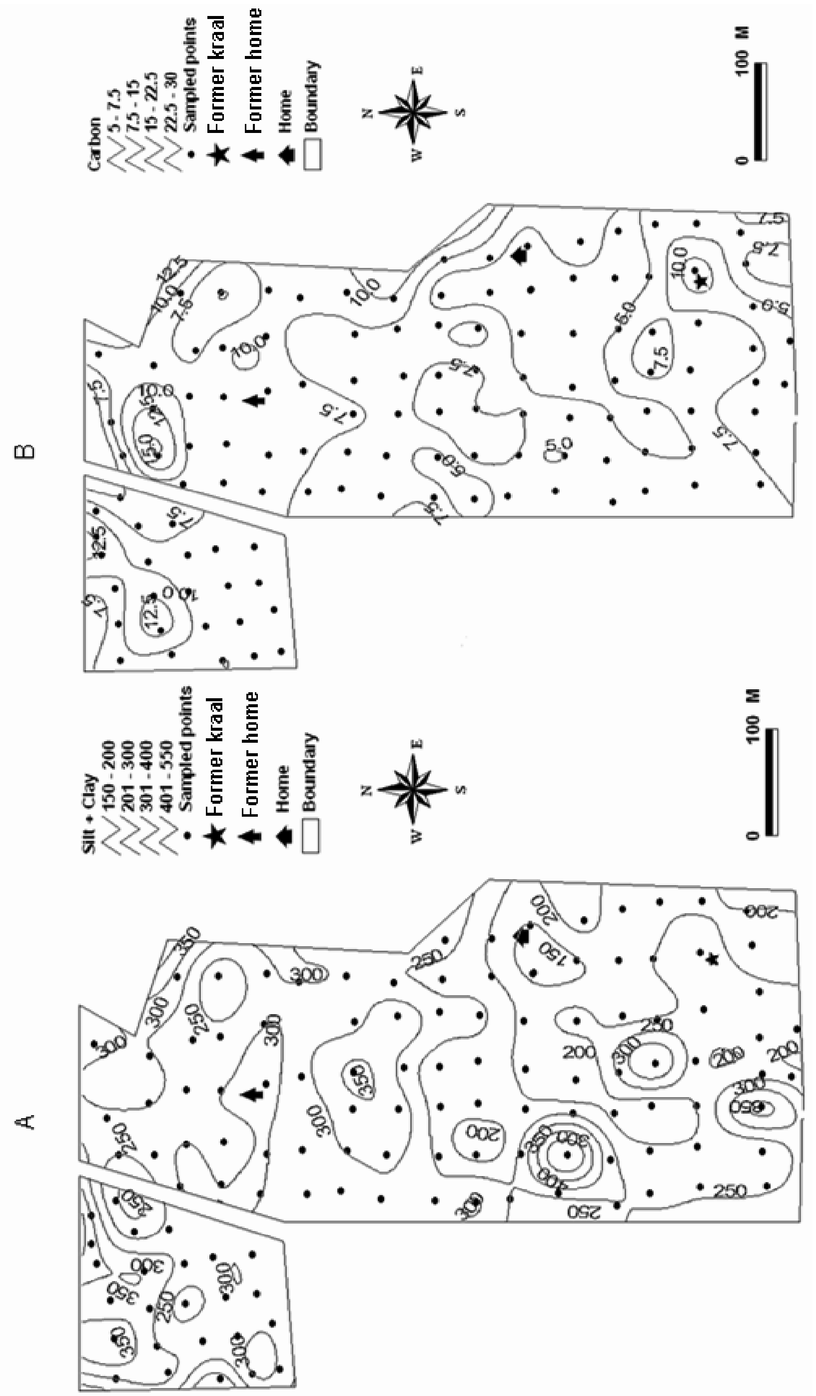
Relationships between SOC, texture and extractable P

Soil organic carbon increased with silt + clay across fields of farm types in Chelekura (Figure 5A) and Onamudian (Figure 5B), conforming to the pattern reported for tropical soils (Feller and Beare, 1997). There were no strong relationships between extractable P and SOC in Chelekura (Figure 5C) and Onamudian (Figure 5D).

3.2.4 Spatial variability in soil fertility within individual farms

Selected farms are used as examples to illustrate the nature and factors determining within-farm spatial variability in silt + clay and SOC in Chelekura (Figure 6) and Onamudian village (Figure 7). The distribution of silt + clay generally followed variations in slope and soil type within individual farms. The relationship between SOC and other measured soil properties as well with slope were weak (See Appendix 3.3). SOC distribution, although related to silt + clay, did not always exhibit the same pattern of distribution as silt + clay because of effects of past management. Where former kraals existed, the SOC was increased above that expected from the distribution of silt +clay within farms as illustrated in Figures 6B and 7B. There was no clear pattern of SOC with distance from the homesteads. In general, SOC contents were related to the intensity of management, the distribution of local soil types or the location of the farm on the landscape. With land fragmentation some of the farms are not contiguous and the farmers own fields on different soil types. Most of the farms characterized (60%) in Chelekura farms were fragmented compared with those in Onamudian village (20%). Mr. George Okodoi's farm (Figure 6A), had fields on the three local soil types; *Apuuton* with silt + clay ranging from 200 to 250 g kg^{-1}, *Erony* with silt + clay ranging from 200 to 300 g kg^{-1} and tiny portion of *Eitela* with silt + clay of 300 to 350 g kg^{-1}. Within the *Erony*, a patch with silt clay of 300-350 g kg^{-1} was a former homestead site and the increase in silt + clay was contributed by rubble of mud and wattle huts. The SOC distribution within the same farm related to the variations in silt and clay. However, the former kraal site had higher values of SOC (10 g kg^{-1}) for that part of the farm with silt + clay of 200 –250 g kg^{-1}.

Mr. Kupliano Oluka's farm was also spread along the slope on the middle landscape position in the Chelekura village respectively over three different soil units, *Eitela* (largest parcel), *Erony* (the intermediate parcel) and *Apuuton* (smallest parcel) silt + clay declining down the slope (Figure 6C). SOC was highest in *Eitela* (7 - 9 g kg^{-1}) and least in *Apuuton* (4 - 5 g kg^{-1}) (Figure 6D). In Onamudian, Mrs. Priscilla


A
B
Silt + Clay
150 - 200
201 - 300
301 - 400
401 - 550
Carbon
5 - 7.5
7.5 - 15
15 - 22.5
22.5 - 30
Sampled points
Former kraal
Former home
Home
Boundary
N
E
S
W
0
100 M

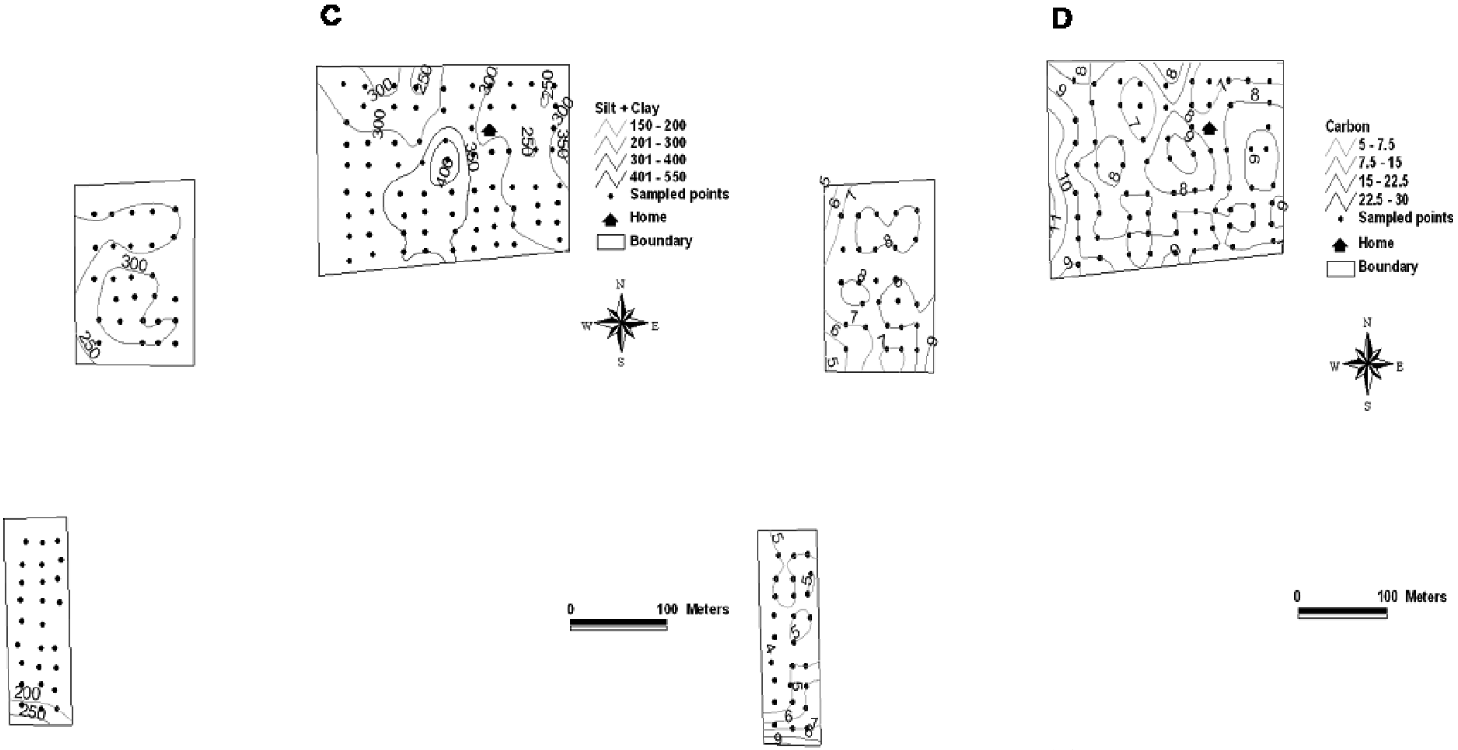
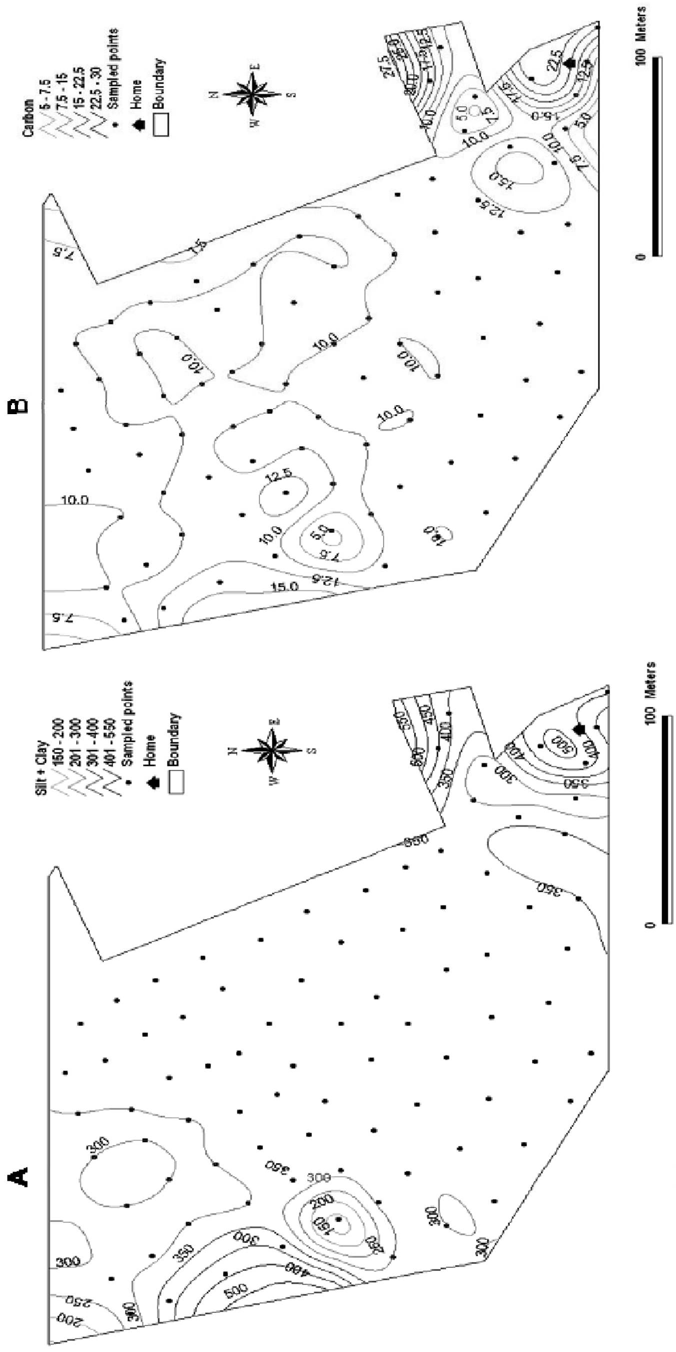


Figure 6 Contour maps of silt + clay and SOC (g kg –1) for selected farms in Chelekura village, Pallisa district. A and B are for silt + clay and SOC on Mr. George Okodoi’s farm and C and D are for silt +clay and SOC on Mr. Kupliano Oluka’s farm respectively.


A
Silt + Clay
150 - 200
201 - 300
301 - 400
401 - 550
Sampled points
Home
Boundary
N
E
S
W
0
100 Meters
200
250
300
350
400
500
150
B
Carbon
5 - 7.5
7.5 - 15
15 - 22.5
22.5 - 30
Sampled points
Home
Boundary
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100 Meters
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15.0
22.5
27.5

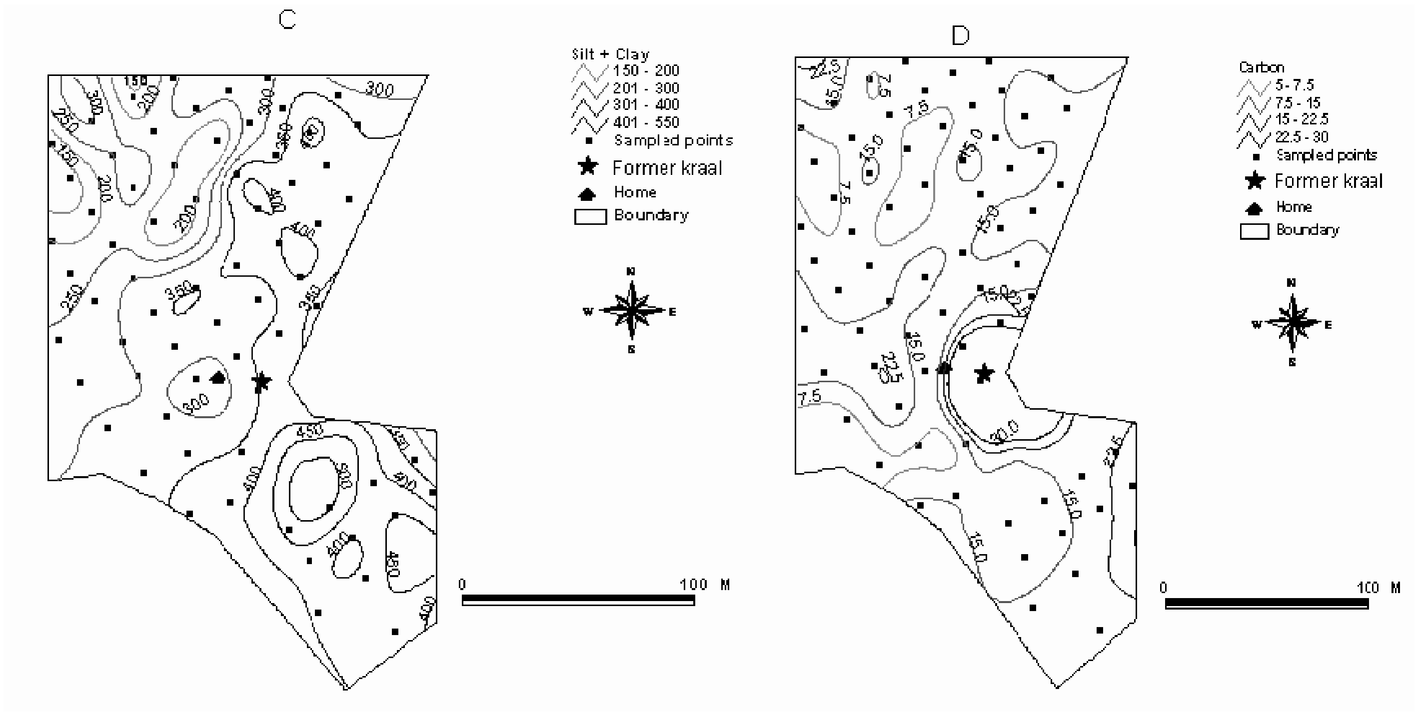

Figure 7 Contour maps of silt + clay and SOC (g kg –1) for selected farms in Onamudian village, Pallisa district. A and B are for silt + clay on Mrs. Priscilla Akol's farm and C and D are for silt +clay on Mr. Chrisostom Kakati's farm respectively.

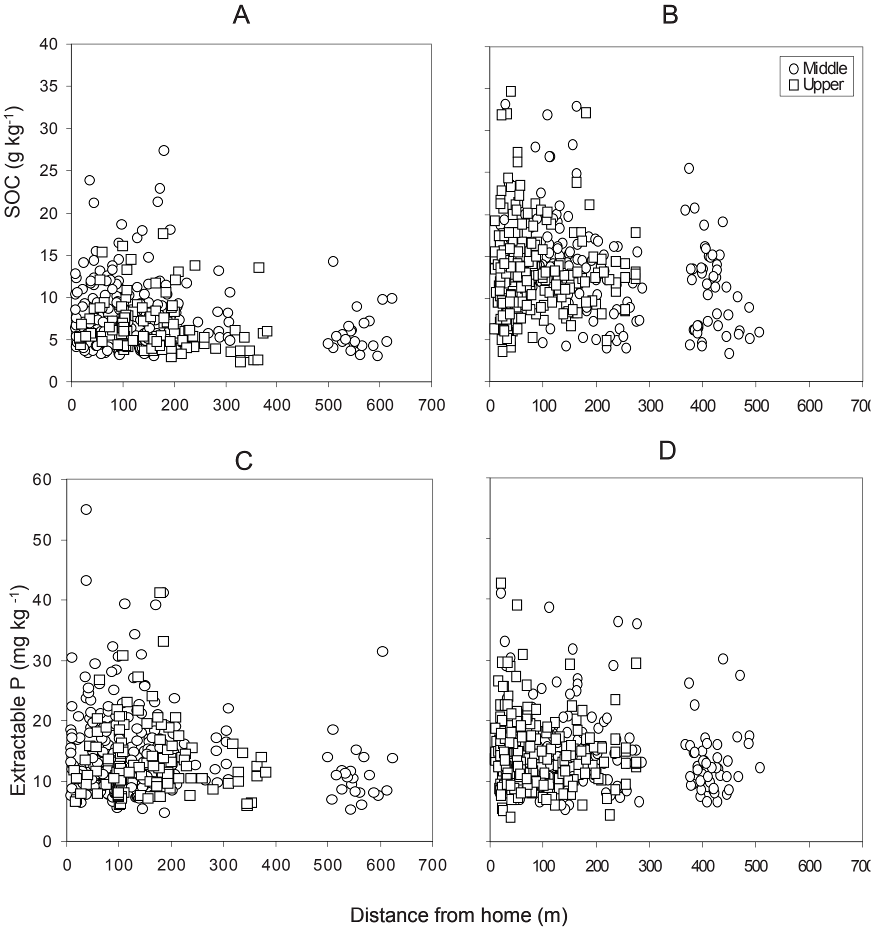

Figure 8 Variations of soil properties with distance from homestead by landscape position. A and B are for SOC (g kg^{-1}) and C and D for extractable P (mg kg^{-1}) respectively in Chelekura and Onamudian villages, Pallisa district.

Akol's farm was located on both upper and middle landscape positions. Silt + clay was highest in the upper positions with the soil type *Eitela* and was lowest in the soil type *Apuuton* in the middle landscape position (Figure 7A). The pattern in variability in SOC was similar to that of silt + clay on this farm (Figure 7B). These types of farms with contiguous land parcels from upper to bottom positions are rare in the study area. Mr. Kakati's farm located on the middle landscape position exhibited decreases in silt + clay fractions along the slopes towards the valley bottoms (Figure 7C). SOC distributions also followed similar patterns but the former kraals near the home had higher SOC (>30 g kg^{-1}) overruling the inherent effects of soil texture (Figure 7D).

No generalized systematic patterns in variations in SOC or extractable P with distance from homesteads across farms were observed in both Chelekura and Onamudian villages except that there was wide variability in fields that were closer (<200 m) to the homesteads (Figure 8). This differs from the common generalisation that SOC declines with distance from homesteads across smallholder African farms (Giller et al., 2006; Tittonell et al., 2005).

3.3 Discussion

3.3.1 Landscape variability

Variability along the toposequences is related to occurrence of soil types and slope effects on the soil forming process of erosion which influences the topsoil properties. The variability of soils in most parts of Uganda closely follows the toposequence position along a catenary sequence formed from same parent material (Milne, 1947). The soils of Pallisa belong to the Buruli catena and the Maizimasa complex catena and are characterised by shallow soils in the uplands and deeper soils in the valley bottoms (Chenery, 1960; Ollier and Harrop, 1960). The toposequences studied in both villages (Tables 2 and 3) were shallow at the upper positions (A horizon depths of 0-30 cm) with laterite at ≤70 cm and deeper in the valley bottoms (A horizon depths of 0-41 cm). The depth of the surface horizons is associated with the natural processes of erosion on the uplands and sediment deposition in the valley bottoms. In the AP horizon soil pH, SOC, and total N slightly increased along the toposequence in Chelekura but not in Onamudian village. The gradients in extractable P but not in other soil properties in the surface horizons were more prominent in both villages. Extractable P was 3 and 5 times higher in the AP horizons in the valley bottoms than upper landscape positions in Chelekura and Onamudian villages respectively and is associated with deposition of eroded soil sediments from the surrounding uplands.

Within the pedons the soil pH, SOC, total N and extractable P generally decreased with depth in the well-drained pedons in the upper and middle positions (Table 2 and 3). Decline in P with depth is attributed to fixation in such soils with high iron and aluminum oxide contents (Sanchez, 1976). The increase in clay content with depth is indicative of illuviation leading to formation of argillic subsurface horizons. In the valley bottoms, clay increased at (1 m) depth and could be related to clay formations *in situ* in moist subsoils in periodically wet soils in valley bottoms. Lower SOC contents in the valley bottoms in Chelekura (Table 2) were due to the periodic wetting and drying facilitating decomposition of organic matter in the sandy soils. Seasonal burning was also practiced in the area and could lead to reduction of

SOC in Chelekura. The gentle slopes of these peneplanes, with more or less a similar type of parent material (basement complex granite gneisses and lake deposits) and the random distribution of soil types could explain the lack of toposequence-related fertility gradients in these villages. Soilscapes are more applicable in gaining the local knowledge about soils distribution and general land use planning but can be limited for the special purpose of targeting nutrient management options (the object in this characterization) (Ogunkunle, 1993) and as such field scale becomes more relevant (Deckers, 2002).

Soil types are important in some systems for targeting production but this depends on settlement patterns, and relative distribution and household access to different local soil types. In Northern Namibia, farm households, on average, have access to three of the five indigenous local soil types and this influences the targeting of crop production (Hillyer et al., 2006). In Pallisa, farms are instead randomly distributed on the toposequences, mainly on the upper and middle landscape positions (Figure 3 and 4). Access to soil units is dependent on where a farm is located, and few farmers have access to all the local soil types. Targeting crop production to local soil types was clear only for lowland rice in the valley bottoms, although upland rice has recently been introduced into the system. Long-term crop production, relying on nutrient mining in this system may obscure differences in soil types.

3.3.2 Fieldscape variability in surface soil properties

Significant differences in soil properties between field types (Table 5) have also been reported elsewhere (Tittonell, 2007). The farmers' criteria for catergorisation are useful and have been gained from their long-tem experience cultivating their farms (Mairura et al., 2008). The farms characterised had been cultivated for periods ranging from 15 to 34 years (Table 1). Farmers' categorisation was based on local indicators including crop yield, amongst others (Barrios et al., 2001; Maruge et al., 2000). Soil fertility variations between field types are more explicit for farmers and could be a better entry point for targeting management practices for soil fertility maintenance or soil restoration; aspects that integrate best fitting of integrated soil fertility management technologies to local variability (Vanlauwe et al., 2006). Farmers' local knowledge cannot however be easily translated into quantitative thresholds for gauging the soil quality of the various field types. At best soil tests will remain important. Keulen (2001) asserted that it is difficult to develop acceptable thresholds for organic matter in tropical soils. We found in this study also that in Chelekura village, the quality of fields considered to be of good fertility has similar soil chemical fertility status to poor fields in Onamudian village (Table 5) and this reiterates the need for site specific interventions.

3.3.3 Farm scale and with-farm variability in soil fertility

Farm level indices of soil properties were similar across farm types classified on basis of resource endowments (Table 5) because of lack of contrasts in use intensity of nutrient inputs between farmers. Soil fertility at farm scale is determined by inherent characteristics due to soil types. The spatial variability in soil fertility differs between farms depending on the location of farm on the toposequence (and hence soil type the farm is endowed with) and historical management related to presence of former kraals and former homesteads within farms. These factors largely determine the variability in SOC in farms within and between the study villages. Compared with Chelekura village, SOC is high in farms across Onamudian village due to the finer texture leading to more physical protection of organic carbon (Six et al., 2002).

Historical management in which manure accumulates in former kraals results in larger concentrations of SOC consequently overruling the effects of texture. Long-term effects of former kraals (up to 4 decades) on soil fertility have been reported elsewhere in east Africa (Augustine, 2003). For some of the homesteads the former kraals were over 15 years old. The larger amounts of SOC on these sites may be due to presence of unprotected particulate organic carbon not necessarily associated with silt + clay fractions (Plante et al., 2006). Because farmers continually rotate the kraals and also move their homesteads this results in seemingly random patterns with isolated patches of high fertility within the farms.

Besides very few nutrient inputs are used in the Teso farming, the random settlement patterns of homesteads on the toposequences, and the lack of contiguous fields within the farms along entire toposequences contrasts with other smallholder African farming systems previously described. Elsewhere in western Kenya for example, farms tend to be sited on the hill crests or pediments and farms have consolidated strips of land extending from uplands to valley bottoms (≤300 m). They also practice intensive nutrient management close to the homesteads creating inverse soil fertility gradients overruling the effects of topography (Tittonell et al., 2005; Tittonell et al., 2007a). Similarly in the ring management systems of western Africa, settlements are communal and fields are located on rings of decreasing management intensities from the village creates inverse soil fertility gradients (Prudencio, 1993). Soil fertility gradients within farms in Zimbabwe have also been reported to be generated due to targeted application of inorganic fertilisers and organic materials to fields close to homesteads (Mtambanengwe and Mapfumo, 2005; Zingore et al., 2007b).

Strong slope effects combined with cultivation practices account for gradients of increasing soil fertility along slopes within bench terraces and along entire hill slopes in highlands of southwestern Uganda (Siriri et al., 2005) and can be a basis for determining targeting of soil fertility management interventions. In the Teso farming system, the slopes are gentle and together with rather individual farm management approach make it difficult to guide targeting of soil fertility management practices according to landscape position. It might be useful to target according the recognisable differences in soil fertility between field types within farms to enhance soil productivity.

3.4 Conclusions

Profile characterisation revealed that variations in soil properties were not systematic down the toposequences in the top soils found in both villages. However extractable P accumulated more in the valley bottoms compared to the upper and middle landscape positions due topography mediated effects of erosion and deposition. Surface soil properties significantly differed between the delineated landscape positions for SOC and total N (Chelekura) and silt + clay, SOC and Total N (Onamudian); they were usually being associated with the dominant soil types in the landscape positions. These variations were however not as and large as those between field types as categorised by farmers. All the selected soil properties were significantly larger between field types in Chelekura village but only SOC, total N, silt + clay, in Onamudian village. There were no significant differences in status of soil properties between farms types reflecting the lack of differences in intensity in soil fertility management in the farming system. Within farms, the spatial heterogeneity in the soil fertility indicator, SOC, is due to inherent soil characteristics (silt + clay), and historical management related to former homesteads and former kraals. Spatial analysis did not reveal a particular generalised pattern in variability in soil fertility across farms in each village. Referring to our objective, we conclude that field and not landscape position or farm is the most suitable scale for targeting soil fertility management interventions in the Teso farming system.

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Chapter 4

Impacts of heterogeneity in soil fertility on legume-finger millet productivity, farmers targeting and economic benefits[†]

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Abstract

Targeting of integrated management practices for smallholder agriculture in sub-Saharan Africa is necessary due to the great heterogeneity in soil fertility. Experiments were conducted to evaluate the impacts of landscape position and field type on the biomass yield, N accumulation and N_2-fixation by six legumes (cowpea, green gram, groundnut, mucuna, pigeonpea and soyabean) established with and without P during the short rain season of 2005. Residual effects of the legumes on the productivity of finger millet were assessed for two subsequent seasons in 2006 in two villages, Chelekura and Onamudian, in Pallisa district, eastern Uganda. Legume biomass and N accumulation differed significantly ($P<0.001$) between villages, landscape position, field type and P application rate. Mucuna accumulated the most biomass (4.8-10.9 Mg ha^{-1}) and groundnut the least (1.0-3.4 Mg ha^{-1}) on both good and poor fields in the upper and middle landscape positions. N accumulation and amounts of N_2-fixed by the legumes followed a similar trend as biomass, and was increased significantly by application of P. Grain yields of finger millet were significantly ($P<0.001$) higher in the first season after incorporation of legume biomass than in the second season after incorporation. Finger millet also produced significantly more grain in good fields (0.62-2.15 Mg ha^{-1}) compared with poor fields (0.29-1.49 Mg ha^{-1}) across the two villages. Participatory evaluation of options showed that farmers preferred growing groundnut and were not interested in growing pigeonpea and mucuna. They preferentially targeted grain legumes to good fields except for mucuna and pigeonpea which they said they would grow only in poor fields. Benefit-cost ratios indicated that legume-millet rotations without P application were only profitable on good fields in both villages. We suggest that green grams, cowpea and soyabean without P can be targeted to good fields on both upper and middle landscape positions in both villages but mucuna without P to poor fields on the middle landscape position in Chelekura village and cowpea without P to poor fields on the upper landscape position in Onamudian village.

***Key words*:** *Landscape position; Field type; Legume biomass productivity; N_2-fixation; P application; Farmers acceptance; Benefit-cost ratios; sub-Saharan Africa*

4.0 Introduction

Heterogeneity in soil fertility is a common feature of smallholder farming systems in sub-Saharan Africa (SSA) that results from the interactions between inherent soil characteristics, and historical and current human management (Tittonell et al., 2005; Zingore et al., 2007a). Heterogeneity in soil fertility has largely been ignored in development of soil fertility management recommendations there is evidence that it strongly affects agronomic performance of soil management technologies (Vanlauwe et al., 2006; Tittonell et al., 2007). As such, blanket fertiliser recommendations for agroecological zones are of little value. Due to this, research in smallholder farming systems in SSA now emphasises the need for site specific management (Deckers, 2002; Zingore et al., 2007b). Soil fertility improvement technologies should be targeted to socio-ecological niches within farming systems (Ojiem et al., 2006) recognising differences among landscapes (*soilscapes*) or fields (*fieldscapes*) within farms (Deckers, 2002). This approach will increase efficiency in resource use, guide the design of management strategies to maintain or replenish soil fertility and enhance sustainable use of soil improvement technologies if proven agronomically effective, socially acceptable and economically viable: the key principles of integrated soil fertility management (Vanlauwe et al., 2002; Vanlauwe et al., 2009).

In most smallholder farming systems in SSA, N and P are the major nutrients limiting crop productivity (Sanchez et al., 1997). Mineral fertilisers could be used to address these limitations but their scarcity, high costs and poor profitability have curtailed their wider use (Morris et al., 2007). Legumes can provide substantial amounts of N through N_2-fixation, and contribute N to subsequent crops in rotation in low input farming systems (Giller, 2001). They also can improve other soil chemical and biological properties creating better growth conditions for subsequent crops (Yusuf et al., 2009). Many studies report cereal yield increases after legumes in smallholder African farming systems (e.g. Osunde et al., 2003; Ncube, 2007; Ojiem et al., 2007). To realise such benefits however, constraints to legume growth such as soil acidity and poor phosphorus availability have to be ameliorated through application of lime and inorganic P fertilisers (Vanlauwe and Giller, 2006).

Legume effectiveness to improve crop productivity in smallholder farming systems has largely been assessed on large spatial scales, covering agro-ecological units (Baijukya, 2004; Kaizzi et al., 2006; Ojiem et al., 2007). Comprehensive evaluations of the impacts of between and within-farm variability on the contribution of legumes to the productivity of subsequent cereal crops in rotation are scarce (Ojiem et al., 2007). Our focus was therefore to identify the most appropriate niches for different legumes within the Teso farming system of eastern Uganda. We explored potential

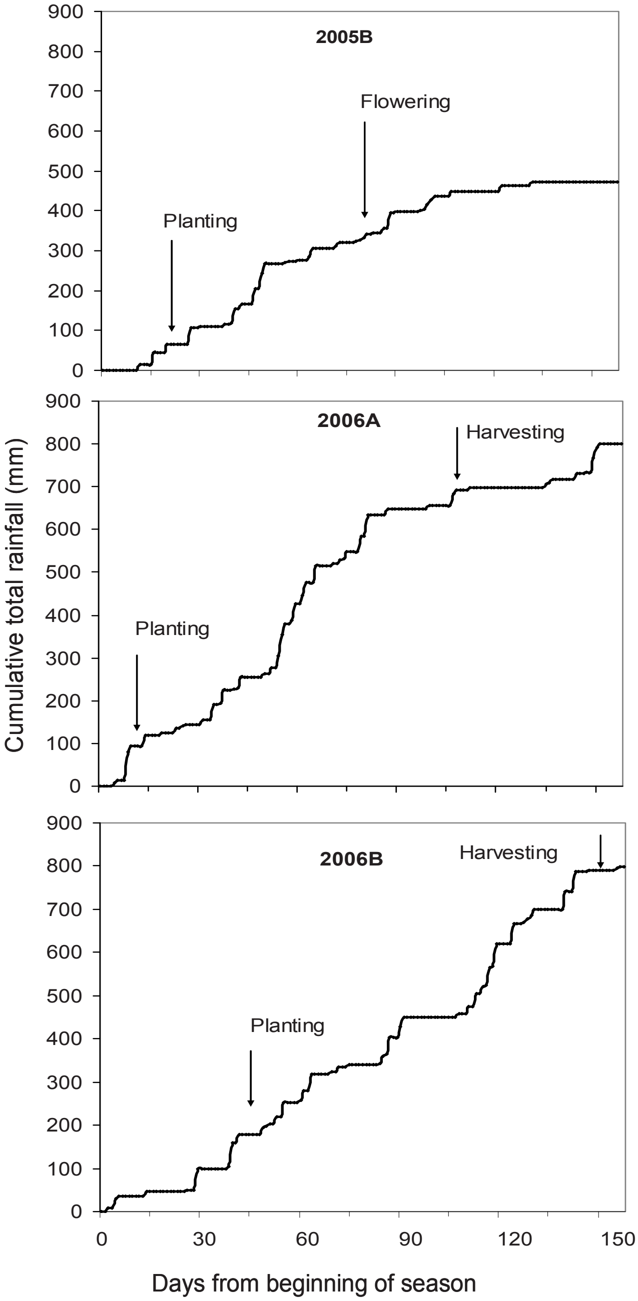

Figure 1 Cumulative total rainfall during the experimentation seasons in the study area. Legumes were grown in the short rains (2005B) of 2005 followed by finger millet in the long (2006A) and short rains (2006B). Note that in 2005B no grains were harvested due to drought.

landscape positions and field types to target production of legume species with or without P application, and their residual effects on production of finger millet (*Eleusine coracana* [L.] Gaertn), the major staple cereal crop. The Teso farming system is characterised by poor crop productivity due to little nutrient input use, and with N and P being the major limiting nutrients (Wortmann and Eledu, 1999). The specific objectives of the study were to evaluate the impacts of heterogeneity in soil fertility: (i) on biomass production and the contribution of biological nitrogen fixation to N accumulation by the legume species; (ii) on grain yield response and N use efficiency by finger millet crop following incorporation of legume biomass; (iii) to assess farmers preference and targeting of legumes to different types of fields; and (iv) to determine economic benefits of legume–finger millet rotations.

4.1 Materials and Methods

4.1.1 Study sites

The study was conducted in Chelekura (1°24′ N; 33°30′ E) and Onamudian (1°11′ N; 33°43′ E) villages in Pallisa district (1°13′ N; 31°42′ E), eastern Uganda. These sites represented the low input crop-livestock Teso farming system, supporting 5% of Uganda’s population. Finger millet is the second important cereal after maize in Uganda, mainly grown in the Teso farming system. It is a food security crop and major source of income for smallholders through its use for local brewing (NAARO/SAARI, 1991).

The study area is situated between 1000 and 1100 masl and is characterised by gently sloping toposequences on broad, rounded and flat-topped uplands. Mean annual rainfall (950-1100 mm) is distributed in a bimodal pattern, with the long rains from March to June (550-600 mm) and the short rains from September to October/ November (400-500 mm), and a marked dry period from December to February. During the experimentation period, cumulative daily total rainfall received in the short rains of 2005 in the study villages (500 mm) was poorly distributed, but above normal in both seasons in 2006 (ca. 1600 mm annual total) (Figure 1). Heterogeneity in soil fertility along toposequences and between field types within farms in the study villages is large and the soils on the raised lands and valley bottoms are generally classified as Ferralsols and Fluvisols respectively (Ebanyat et al., 2009)

4.1.2 Field selection, soil sampling and preparation

Fields of good and poor fertility located on the upper and middle landscape positions that had been cultivated with finger millet prior to experimentation were selected based on farmers’ long-term knowledge of fertility status of their fields. Field selection was restricted to these landscape positions as legumes are not grown in the lower landscape positions that are prone to flooding. In total, 56 fields were selected (7 each for good and poor fields in the upper and middle landscape positions in each village). Soil samples were randomly taken in each field at a depth of 0-20 cm from five spots, to obtain composite samples of approximately 0.5 kg. The composite samples were air-dried, ground and sieved through 2 mm.

4.1.3 Establishment of researcher-managed experiments

Field experiments were conducted for three seasons; short rains of 2005 (2005B), long rains of 2006 (2006A) and short rains of 2006 (2006B). Selected fields were ox-ploughed twice and plots of 5 × 5 m demarcated prior to establishment of the legume experiments in 2005B. Six legume species were planted using recommended spacing: soyabean (*Glycine max* [L.] Merr.), variety TGX 1740-2F or SB 19 (0.75 × 0.10 m); cowpea (*Vigna unguiculata* [L.] Walp.), variety SEKO 1 (0.6 × 0.15 m); green gram (*Vigna radiata* [L.] R. Wilczek), local variety (0.6 × 0.15 m); groundnut (*Arachis hypogaea* L.), variety SERENUT 3R (0.45 × 0.10 m); pigeonpea (*Cajanas cajan* [L.] Millsp.), variety SEPI 1(0.75 × 0.30 m); and mucuna (*Mucuna pruriens* [L.] DC.) (0.75 × 0.6 m). All legumes were improved varieties, except green gram. A weedy fallow and finger millet variety U15 or SEREMI 2 (0.45 × 0.05 m) treatment were also included. The legumes were planted between 22nd and 27th August 2005 (season 2005B). Each legume species was established with and without basal application of 30 kg P ha^{-1} supplied as single super phosphate (SSP) while the continuous finger millet and weedy fallow treatments received no basal fertiliser. Legumes were maintained at 2 plants per hill except for soyabean and groundnut (1 plant per hill). Millet was thinned to 0.05 m within rows at first weeding i.e. 14 days after planting (DAP). Further weed control was by hand hoeing at 28 DAP. In the 2005B season, the legumes and finger millet did not produce grain due to drought at pod initiation and grain filling (Figure 1). Total rainfall received during the legume growth was 410 mm. After legumes, the same finger millet variety (SEREMI 2) was planted between 15th and 22nd March 2006 (season 2006A) and between 15th and 19th September 2006 (season 2006B) on all the plots, thus the overall crop sequence was legume-millet-millet. Weeding was done twice in each season. Total rainfall received during the growing period of millet was 580 mm (2006A) and 615 mm (2006B).

4.1.4 Plant sampling and preparation

At 50% flowering of the legume species, biomass samples were obtained from two locations along three middle rows using 1 m^2 quadrats for determination of dry matter accumulation, N_2-fixation and N uptake. Millet and weedy fallow treatments were also sampled at 120 DAP and biomass determined. Millet samples were obtained from within the three middle rows of each plot, and randomly within plot centres of the weedy fallow treatments. At maturity, the millet heads were harvested using small knives, and the straw cut at 0.05 m above ground level. All plant samples were oven dried at 65^{o}C for 72 hr and dry weights obtained. Millet heads were threshed in special cloth bags to minimise losses of the husks and the respective grain weights obtained. The grain and biomass samples were ground to pass through a 1 mm sieve prior to laboratory analysis.

4.1.5 Soil and plant analysis

Soil and plant samples were analysed at the World Agroforestry Centre (ICRAF), Nairobi, Kenya. Diffuse reflectance spectra were recorded for the soil and plant samples using a Field Spec FR Spectroradiometer (Analytical Spectral Devices Inc, Boulder CO) at wavelengths from 0.35 to 2.5 μm with a spectral sampling interval of 1nm. The optical set up for soil analysis procedures are described in detail by Shepherd and Walsh (2002) and for plant analysis by Shepherd et al. (2003).

Soil chemical properties (pH, Olsen P, Exchangeable Ca, Mg and K, CEC) and soil particle composition (sand, silt and clay) were determined using standard methods for tropical soils (Anderson and Ingram, 1993) while total organic C and nitrogen were determined using a ThermoQuest EA 1112 elemental analyser on 20 (i.e. approximately one- third) randomly selected samples from the total number of soil samples. Total N in legume and N and P in millet samples were determined from micro-Kjeldahl digests with H_2SO_4 and H_2O_2 by steam distillation and titration with HCl for N and by colorimetry (molybdenum- blue) for P.

Partial Least Squares Regressions (PLSR) were used to relate spectral reflectance to measured soils or plants properties and calibration models for each property developed on a random two-thirds of samples (20 soil samples and 300 plant samples) analysed by wet chemistry. Cross-validation was applied to prevent over-fitting of the models. The prediction performance of the models was evaluated on predicted and measured values of soil and plant attributes using the coefficient of determination (R^2) and root mean square error (RMSE).

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum (x_i - y_i)^2} \qquad \text{(Equation 1)}$$

Where $(x_i - y_i)$ is the difference between the measured value by chemical analysis and predicted value by PLSR, n is the total number of samples in the test (Naes et al., 2002). The analysis was performed using OPUS version 6.5 (copyright © Bruker Optik GmbH 1997-2007). The models for prediction of soil properties were good for:

SOC, total N, CEC, total P and silt (R^2 = 0.90-0.96; RMSE = 0.11-0.75); for exchangeable Ca, sand and clay (R^2=0.85-0.87; RMSE = 0.04-1.69); and, soil pH, exchangeable K and exchangeable Mg (R^2=0.72-0.75; RMSE = 0.22-0.39). However, prediction of extractable P was less reliable and consequently, all samples were analysed for extractable P using the modified Olsen method (Anderson and Ingram, 1993) at Kawanda National Agricultural Laboratories Research Institute and these data are subsequently used. The models were good for N in both millet (R^2= 0.8, RMSE = 0.08) and legume (R^2 = 0.59, RMSE = 1.57) samples.

4.1.6 Determination of N_2-fixation

Nitrogen fixed from the atmosphere was computed by the N-difference method that assumes both the legume and the non-leguminous reference crop derive the same amount of N from the soil. The method works reasonably well for soils with low capacity to supply N and when the reference crop accumulates less N than the legume test plants (Unkovich et al., 2008), conditions that held in Pallisa. Two fields in Onamudian village, where the reference crop accumulated substantially higher N than the legume treatments were excluded from the computations. The proportion of N_2-fixed was calculated as:

$$\% \ N_2\text{-fixed} = 100 \times [\text{TotN}_{\text{legume}} - \text{TotN}_{\text{non legume}}] / \text{TotN}_{\text{legume}} \qquad \text{(Equation 2)}$$

The non-fixing crop used for reference was finger millet. The amount of N_2-fixed by the legume was calculated as:

$$N_2\text{-fixed (kg ha}^{-1}) = [\% \text{ N derived from } N_2\text{-fixation} /100] \times \text{total N in legume biomass} \qquad \text{(Equation 3)}$$

Legume and reference samples were analysed for $\delta^{15}N$ with the intention of calculating inputs from N_2-fixation using the ^{15}N natural abundance method, but legume samples had highly variable ^{15}N-enrichment, often greater than that in the reference millet samples (data not presented), which precluded calculation of N_2-fixation. Below-ground N contributions of legumes are not considered in this paper but root N contributions of legumes are estimated to be roughly 30% of total N_2-fixed (McNeill et al., 1998).

4.1.7 Nitrogen use efficiency

Nitrogen use efficiencies of N derived from legume residue in finger millet following incorporation of legume biomass was determined using average yields of millet for the two seasons and the amounts of legume N as:

$$\text{NUE} = \frac{GY_{treatment} - GY_{millet}}{LN_{treatment}} \qquad \text{(Equation 4)}$$

Where: *NUE* is N use efficiency, *GY* is grain yield (kg ha^{-1}) and *LN* is the legume N (kg ha^{-1}) incorporated.

4.1.8 Farmers' preference and targeting of legumes

Farmers' preferences for legume species and targeting to soil fertility heterogeneity were assessed using the direct matrix ranking methodology (Theis and Grady, 1991). Farmer field school participants evaluated the performance of the legume species at the end of the season after visiting the field experiments within their respective villages. Twenty seven and 24 farmers participated in Chelekura and Onamudian villages respectively. Important characteristics used for evaluation were mainly related to soil fertility (biomass production, drought tolerance, pest and disease resistance, and weed suppression, improvement of yields of subsequent crops), and additional benefits such as household nutrition and income source (grouped as others). Each farmer ranked the legume attributes on the scale: 1 = poor, 2 = fair, 3 = good, 4 = very good and 5 = excellent. Each farmer also gave a score of 1 to a preferred field type for production of a given legume and a reason for the preference. The scores were tabulated and total frequencies converted to percentages.

4.1.9 Economic Analysis

Benefit cost ratio analysis (CIMMYT, 1988) was conducted to assess the profitability (i.e. > 2 is profitable) of legume-millet rotations. Total yields of finger millet for two seasons were used to compute total benefits. Production costs for both legumes and millet were included in the calculation of the benefits. The total variable costs for legume biomass production included; seed, single superphosphate (SSP) fertiliser at the farm gate, labour (cost of ploughing, planting, weeding, chopping and incorporation). For finger millet, the variable cost for each season included seed and labour for land preparation, planting, weeding, harvesting, drying and threshing. The labour costs were obtained from farms within the study sites and for mucuna from two progressive farmers of a Conservation Agriculture project who were producing mucuna seed for sale but also practicing fallowing to improve fertility of their farms. Since pigeonpea was not native to this system, production costs could not be obtained. We assumed the costs to be similar to those of mucuna since it also required cutting and chopping biomass before incorporation. The farm gate millet price was 400 Ush kg^{-1} as observed during the experimentation seasons and was used to calculate the gross value of production. No grain was obtained from the legumes and therefore was

Table 1 Initial soil characteristics for fields selected for field experimentation on the upper and middle landscape positions in Chelekura and Onamudian village.

Village/ landscape position	pH (H_20)	SOC (%)	Tot N (%)	Extr. P (mg kg^{-1})	Exc. K (cmol $_{(c)}$ kg^{-1})	Exc. Ca (cmol $_{(c)}$ kg^{-1})	Exc. Mg (cmol $_{(c)}$ kg^{-1})	CEC (cmol $_{(c)}$ kg^{-1})	Tot P (%)	Sand (%)	Clay (%)	Silt (%)
Chelekura												
Upper												
Good	7.2	0.89	0.09	9.50	0.79	1.81	0.89	6.9	0.03	69	23	8
Poor	6.5	0.67	0.08	4.50	0.55	2.70	0.66	5.4	0.02	68	25	7
SED	0.55	0.20	0.01	5.90	0.16	0.66	0.15	1.1	0.01	3.8	2.4	1.7
Middle												
Good	7.2	0.87	0.10	21.0	0.59	4.5	1.33	7.1	0.03	68	22	10
Poor	6.2	0.63	0.07	9.10	0.34	2.4	0.75	3.8	0.01	67	24	9
SED	0.19	0.09*	0.01**	5.2*	0.07*	0.56**	0.09***	1.1**	0.004**	2.0	1.8	1.0
Onamudian												
Upper												
Good	6.5	1.24	0.13	8.20	0.74	4.80	1.50	9.76	0.04	63	25	12
Poor	5.7	0.95	0.11	5.6	0.58	1.93	0.87	9.05	0.04	60	26	14
SED	0.34*	0.10**	0.01	3.6	0.05**	0.58***	0.16**	0.57	0.003	1.7	1.5	1.4
Middle												
Good	6.4	1.19	0.13	19.0	0.59	4.57	1.44	9.23	0.04	63	23	14
Poor	6.0	1.02	0.11	3.80	0.39	2.95	1.41	8.35	0.03	65	22	13
SED	0.25	0.20	0.01	7.80	0.15	0.98	0.28	1.60	0.01	4.7	3.3	4.6

Significance: * $P<0.05$; ** $P<0.01$; *** $P<0.001$

not included in the computation of gross value. The benefit cost ratio (BCR) was calculated as:

$$BCR = \frac{GVT - TVCT}{TVCT} \qquad \text{(Equation 5)}$$

Where: GVT = Gross value treatment and TVCT = Total variable cost of treatment.

4.1.10 Statistical analysis

Analysis of farmer's acceptance of legume species

Farmers' acceptance of legume species was assessed by quantitative analysis of ranking data of legumes through computation of probabilities and logit regression analysis using the logistic preference ranking analysis tool (Hernández-Romero, 2000). The analytical approach allows for separation of species to those that are likely to be accepted.

Analysis of legume biomass and millet yield responses

Legume biomass, N accumulation and amounts of N_2-fixed, and millet grain yield data were analysed with the Restricted Maximum Likelihood (RELM) mixed effects model in Genstat 11.1. The fixed model terms included landscape, field type, legume species, phosphorus application and seasons, and their interactions and the random terms included farm, field and plot.

4.2 Results

4.2.1 Initial soil conditions of experimental fields

The soils from the experimental fields in Chelekura were weakly acidic to basic, with low organic carbon and CEC. Soils from the fields in Onamudian village were moderately to weakly acidic and with moderate organic carbon and CEC (Table 1). Fields of both sites had small concentrations of extractable P (< 10 mg kg^{-1}) with the exception of good fields on the middle landscape position. Exchangeable bases were high but higher in Onamudian than in Chelekura. Though not always significantly different, measured soil properties in a village were in general better in the good than the poor fields (farmer's classification). Significantly ($P<0.01$) better soil properties were found in good than poor fields in the middle landscape position except the soil particle size fractions and soil pH in Chelekura village. Significant better soil pH, SOC, exchangeable bases were found in good than poor fields located in the upper landscape position in Onamudian village. Our results agree with findings in central Kenya that farmer's local knowledge can be used to categorise fertility of fields within their farms (Mairura et al., 2008). This farmer categorisation is, however,

Table 2 Performance of legumes (a) biomass productivity (Mg ha^{-1}), (b) biomass N (kg ha^{-1}) and (c) N_2-fixed ((kg ha^{-1}) without or with 30 kg P ha^{-1}, weedy fallow and millet grown on good and poor fields on the upper and middle landscape positions in Chelekura and Onamudian villages (2005B).

(a) Biomass productivity (Mg ha^{-1})

	Upper						Middle					
	Good			Poor			Good			Poor		
Treatment/village	P_0	P_{30}	ΔP	P_0	P_{30}	ΔP	P_0	P_{30}	ΔP	P_0	P_{30}	ΔP
Chelekura												
Cowpea	4.8	6.0	25	3.4	3.8	13	4.8	6.1	26	3.8	3.9	3
Green gram	3.2	3.7	18	2.0	2.6	30	4.2	5.3	25	2.7	2.7	0
Groundnut	1.8	1.5	-16	1.0	1.4	37	1.5	1.4	0	1.2	1.3	8
Mucuna	6.5	5.3	-18	3.9	4.1	4	6.1	6.0	-2	5.3	4.7	-11
Pigeonpea	2.2	2.1	-1	1.2	1.1	-9	2.5	2.6	6	1.8	1.8	0
Soyabean	1.1	1.2	7	0.9	0.9	7	1.0	1.9	86	0.9	1.3	45
Weedy Fallow	2.2			1.7			1.9			1.3		
Continuous millet	1.1			1.0			1.9			1.1		
Onamudian												
Cowpea	4.3	5.2	21	3.2	4.1	28	5.6	7.6	35	3.7	4.9	30
Green gram	3.3	4.3	32	2.6	3.3	27	4.3	4.2	-3	3.1	3.9	24
Groundnut	1.2	1.5	17	1.2	1.3	6	2.7	3.4	25	2.5	2.6	5
Mucuna	5.1	4.8	-6	4.2	3.8	-10	7.6	10.9	44	5.9	8.9	52
Pigeonpea	2.2	2.4	9	1.6	1.8	13	4.9	4.0	-19	3.6	3.9	10
Soyabean	1.8	1.9	10	1.0	1.3	32	3.7	4.2	15	2.9	2.7	-8
Weedy fallow	1.8	-		1.5	-		3.2	-		1.7	-	
Continuous millet	2.0	-		1.8	-		2.8	-		3.4	-	

SED villages = 0.090***

SED Chelekura village: LP = 0.093ns; FT = 0.101***; Legume = 0.104***; Phosphorus = 0.103*; LP × legume = 0.06*

SED Onamudian village: LP = 0.078***; FT = 0.076**; Legume = 0.078***; Phosphorus = 0.078***; LP × Legume = 0.054***; FT × Legume =0.050*

Table 2 continued….

(b) Biomass N (kg ha^{-1})												
Chelekura												
Cowpea	136	204	50	108	109	1	128	141	10	97	111	14
Green gram	100	114	14	58	73	26	115	174	51	74	86	16
Groundnut	56	42	-25	27	45	62	44	40	-11	36	40	13
Mucuna	148	180	22	92	95	4	177	175	-1	144	104	-28
Pigeonpea	72	73	1	41	35	-15	79	89	13	57	54	-6
Soyabean	32	39	21	23	26	11	26	48	82	25	35	42
Weedy fallow	22	-		15	-		20	-		11	-	
Continuous millet	13	-		11	-		21	-		14	-	
Onamudian												
Cowpea	133	167	26	96	134	39	165	296	79	121	147	22
Green gram	99	117	17	80	91	13	153	151	-2	78	132	70
Groundnut	45	53	18	43	48	11	108	119	9	87	92	6
Mucuna	119	140	17	127	103	-19	217	281	29	191	216	14
Pigeonpea	80	73	-9	57	72	26	173	143	-18	115	121	5
Soyabean	56	56	-1	32	51	58	129	134	4	95	80	-16
Weedy fallow	17	-		14	-		33	-		15	-	
Continuous millet	23	-		29	-		33	-		47	-	

SED villages = 0.094***

SED Chelekura village: LP = 0.093ns; FT = 0.102***; Legume = 0.103***; Phosphorus = 0.103*; LP × legume = 0.08*

SED Onamudian village: LP = 0.076***; FT = 0.076**; Legume = 0.079***; Phosphorus = 0.078***; LP × Legume = 0.048***; FT × Legume =0.064*

Table 2 continued…….

(c) N_2-fixed (kg ha^{-1})												
Chelekura												
Cowpea	119	185	55	95	95	0	105	113	7	83	97	17
Green gram	77	97	26	45	57	27	88	144	64	58	70	21
Groundnut	41	24	-40	14	31	126	23	19	-18	18	25	39
Mucuna	127	173	36	78	81	4	147	146	-1	126	91	-27
Pigeonpea	53	50	-6	26	21	-21	54	63	18	41	37	-9
Soyabean	18	24	30	14	10	-26	7	24	235	11	10	-13
Weedy fallow	-	-		-	-		-	-		-		
Continuous millet	-	-		-	-		-	-		-		
Onamudian												
Cowpea	108	137	27	54	81	51	138	266	93	70	94	34
Green gram	72	91	26	51	44	-12	117	116	-1	41	77	88
Groundnut	19	23	21	10	11	7	71	81	13	21	42	97
Mucuna	95	110	16	90	68	-24	179	253	41	145	165	14
Pigeonpea	54	46	-15	21	31	44	141	110	-22	64	52	-19
Soyabean	30	30	2	10	12	12	92	97	5	50	36	-29
Weedy fallow	-	-		-	-		-	-		-		
Continuous millet	-	-		-	-		-	-		-		

SED villages = 0.16ns

SED Chelekura village: LP = 0.156ns; FT = 0.152**; Legume = 0.154***; Phosphorus = 0.153[a]; LP × Legume = 0.09[a]

SED Onamudian village: LP = 0.14**; FT = 0.141**; Legume = 0.153***; Phosphorus = 0.150*; LP × Legume = 0.08**; FT × Legume = 0.077*

Statistical analysis done on log transformed data.

P_0 and P_{30} are 0 and 30 kg P ha^{-1} respectively; ΔP = respectively percentage apparent P effects on biomass production, N accumulation and N_2-fixed calculated as (P30-P0)/P0 × 100

SED= Standard error of difference of the means; LP = Landscape position (Upper and Middle); FT = field type (Good and Poor)

P significance: ns = not significant; ** $P<0.01$; ***$P<0.001$; [a] $P<0.1$

relative to the specific context: good fields in Chelekura are similar to poor fields in Onamudian (Table 1).

4.2.2 Heterogeneity and P effects on legume productivity

Biomass productivity

Biomass productivity differed strongly (P<0.001) between the study villages, with larger yields generally in Onamudian (Table 2a). Field type, legume species (P<0.001) and phosphorus and landscape position × legume interaction significantly (P<0.05) affected biomass yield in Chelekura village. Biomass yield was generally larger on good compared with poor fields on each of the landscape positions for all the legumes. This effect remained when P was applied although the effect of P was mixed and sometimes negative. Biomass productivity followed the order: mucuna (3.9-6.5 Mg ha^{-1}) > cowpea (3.4-6.1 Mg ha^{-1}) > green gram (2.0-5.3 Mg ha^{-1}) > pigeonpea (1.1-2.6 Mg ha^{-1}> groundnut (1.0-1.8 t ha^{-1}) ≈ soyabean (0.9-1.9 Mg ha^{-1}). The trend in biomass production in Onamudian village was similar to that of Chelekura except that soyabean performed better than groundnuts. The largest biomass (10.9 Mg ha^{-1}) was obtained in this village from mucuna. Application of phosphorus consistently increased biomass yield of cowpea on both good and poor fields on both landscape positions in each study site. This increase in biomass with P application ranged from 3-25 % in Chelekura and 21-35% in Onamudian. P increased groundnut biomass on all fields and landscape positions in Onamudian (5-25%) with apparent overall P effects ranging from -18 to 86%. The strongest effects of P application were obtained with soyabean (86%) on good fields in the middle landscape position in Chelekura and with mucuna on poor fields in the middle position (52%) in Onamudian village.

Biomass N accumulation

Legume biomass N accumulation significantly (P<0.001) differed between villages (Table 2b). The effect of landscape position was significant in only Onamudian village. Groundnut and soyabean accumulated comparatively small amounts of N on both good and poor fields and landscape positions in Chelekura and Onamudian villages. The ranges for groundnut were 27-56 kg N ha^{-1} and 43-119 kg N ha^{-}1, and for soyabean 23-48 kg N ha^{-1} and 32-126 kg N ha^{-1} in Chelekura and Onamudian villages, respectively. Cowpea and mucuna accumulated the largest amounts of N in good fields on the middle landscape positions in both villages. In general, N accumulated increased with biomass accumulated.

The apparent effects of P on biomass N accumulation varied with legume species, field type, landscape position and P application. The strongest increase was obtained with cowpea on good fields (79%) and green gram on poor fields (70%) both on middle landscape position in Onamudian village. In Chelekura village, the strongest apparent effects of P were from soyabean (82%) and green gram (51%) on good fields and poor fields respectively on the middle landscape position and from groundnut (62%) on poor fields in the upper landscape position.

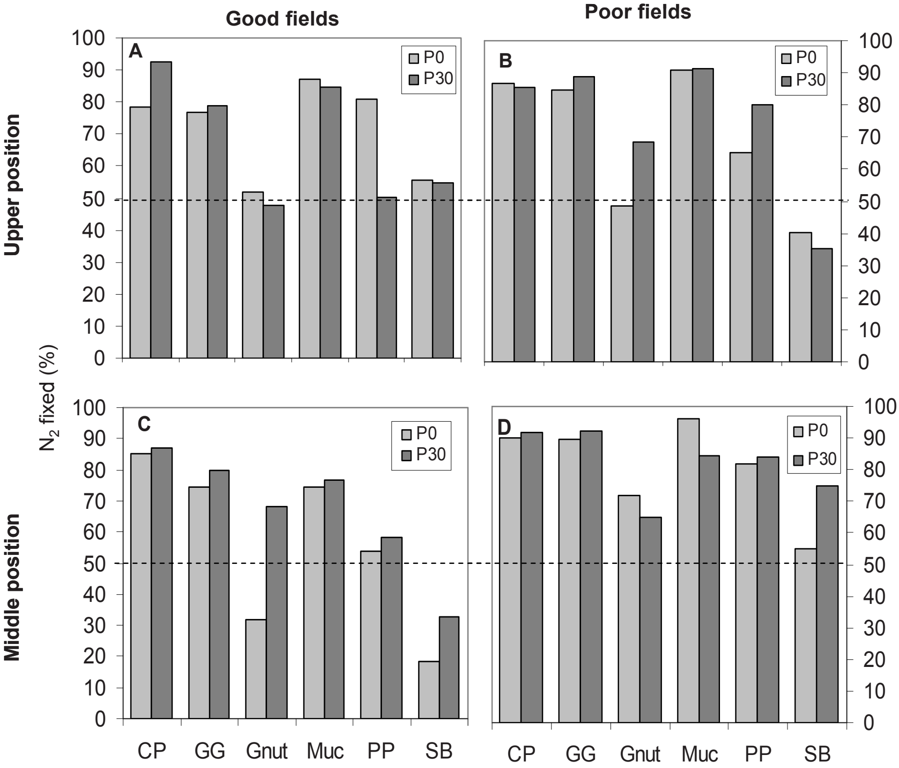

Figure 2a Percentage of N_2-fixed from atmosphere by legume species without (P0) and with 30 kg P ha^{-1} (P30) on good and poor fields in Chelekura village during the short rainy season (2005B). A and B are respectively good and poor fields on upper landscape position. C and D are good and poor fields respectively on the middle landscape position. CP= cowpea; GG = greengram; Gnut = groundnut; Muc = mucuna; PP = pigeonpea and SB = soyabean.

Nitrogen fixation

In Chelekura village, the majority of the legumes fixed more than 50% of their N with or without P application in both landscape positions (Figure 2a). Soyabean derived the smallest %N from N_2-fixation on the good fields in the middle landscape position and on poor fields on the upper landscape position even when P was applied, probably because of soyabean rust. The highest increase in the proportion of N_2-fixed when P was applied was obtained with groundnut on the good fields (38%) followed by soyabean (16%) on the poor fields of the middle landscape position (Figure 2a, C). Application of P increased N_2-fixed by groundnuts by 19% on the poor fields on upper landscape position and 10% by soyabean on the good fields on the middle landscape position. The proportions of N_2-fixed from the atmosphere were generally higher in Chelekura (Figure 2a) than in Onamudian village (Figure 2b). In the latter village, only mucuna, cowpea and pigeonpea fixed more than 50% of their N when

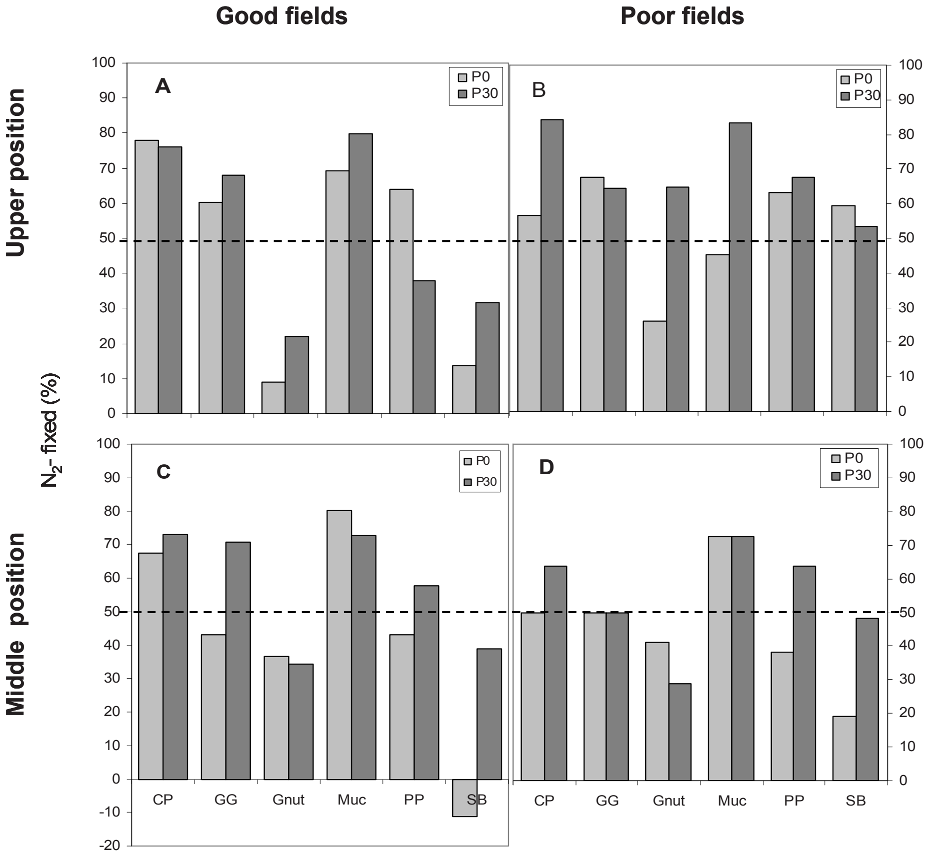

Figure 2b Percentage of N_2-fixed from atmosphere by legume species without (P0) and with 30 kg P ha^{-1} (P30) on good and poor fields in Onamudian village during the short rainy season (2005B). A and B are respectively good and poor fields on upper landscape position. C and D are good and poor fields respectively on the middle landscape position. CP= cowpea; GG = greengram; Gnut = groundnut; Muc = mucuna; PP = pigeonpea and SB = soyabean.

combined with P on the poor fields on the middle landscape position (Figure 2b, D). The largest increments in N_2-fixed were obtained with groundnut (40%) and mucuna (42%) grown on poor fields with P at the upper landscape position. On poor fields at the middle landscape position, increases of 15, 26 and 20% with P application were obtained for cowpea, pigeonpea and soyabean respectively. Without P, no N_2–fixation by soyabean was detected on the good fields of the middle landscape positions but there was a 50% increase in N_2-fixation when P was applied. Application of P resulted in a 26% increase in N_2-fixation by green gram on the good fields on the middle landscape position.

The amounts of N_2-fixed by legume species, by field types and by landscape position were generally larger for each legume species when established with P (Table 2c). Field type and legume effects were significant ($P<0.001$) in Chelekura village. In Onamudian, landscape position × legume and field type × legume interactions were also significant in addition to the main effects of landscape position, field type, legume and phosphorus. Considering both villages, cowpea and mucuna respectively fixed 83-266 kg ha^{-1} and 68-253 kg ha^{-1} which were the highest amounts in both field types in the upper and middle landscape positions. The amounts fixed were usually larger in the middle compared with the upper landscape positions in both villages. The range of N_2-fixed by soyabean was small (7-97 kg ha^{-1}) because of the generally small amounts of biomass accumulated.

Finger millet grain yield performance after legumes

In Chelekura village, millet grain yield significantly differed between seasons ($P<0.001$), field type ($P<0.01$) and legume species ($P<0.05$) (Table 3a). The yield was greater in 2006A compared with 2006B due to the immediate beneficial effects of biomass incorporation. In 2006A, legume biomass without P increased millet yield from -0.12 to 1.02 Mg ha^{-1} (good fields) and 0.14 to 0.85 Mg ha^{-1} (poor fields) on the upper landscape position. Yield increases ranged from 0.42 to 0.78 Mg ha^{-1} (good fields) and from -0.05 to 0.23 Mg ha^{-1} (poor fields) in the middle landscape position. The residual effect of the legume biomass in season 2006B was small, resulting in yield increases above the continuous millet treatment of -0.14 to 0.39 Mg ha^{-1} in both good and poor fields in the upper landscape position and from -0.02 to 0.31 Mg ha^{-1} in the middle landscape position.

Table 3 Grain yield of finger millet (Mg ha^{-1}) following incorporation of biomass legumes established with or without P, weedy fallow and continuous millet treatments on good and poor fertility fields located on the upper and middle landscape positions (LP) in (a) Chelekura village and (b) Onamudian meaned across the 2006A and 2006B seasons.

(a) Chelekura village

Season/treatment	Upper						Middle					
	Good			Poor			Good			Poor		
	P0	P30	ΔP	P0	P30	ΔP	P0	P30	ΔP	P0	P30	ΔP
2006A												
Cowpea	1.47	1.30	-12	1.29	1.31	2	1.74	1.66	-5	1.08	1.23	14
Green gram	2.04	1.36	-33	1.33	1.53	15	1.81	1.79	-1	0.92	1.16	26
Groundnut	1.28	1.40	9	1.45	1.5	3	1.45	1.63	12	0.87	0.77	-11
Mucuna	1.28	1.48	16	1.23	1.19	-3	1.76	1.74	-1	0.85	1.03	21
Pigeonpea	0.80	1.25	56	1.02	1.31	28	1.58	1.39	-12	0.80	0.94	18
Soyabean	1.13	1.12	-1	0.74	1.15	55	1.58	1.57	-1	0.86	0.95	10
Weedy fallow	0.91	-		0.79	-		1.04	-		0.59	-	
Continuous millet	1.02	-		0.60	-		1.03	-		0.85	-	
2006B												
Cowpea	0.71	0.94	32	0.53	0.67	26	0.80	0.78	-3	0.78	0.85	9
Green gram	0.70	0.83	19	0.38	0.60	58	0.77	0.79	3	0.76	0.60	-21
Groundnut	0.65	0.96	48	0.50	0.51	2	0.81	0.79	-2	0.45	0.58	29
Mucuna	0.79	0.77	-3	0.82	0.55	-33	0.64	0.77	20	0.74	0.79	7
Pigeonpea	0.73	0.85	16	0.68	0.76	12	0.77	0.89	16	0.59	0.69	17
Soyabean	0.63	0.73	16	0.29	0.25	-14	0.76	0.71	-7	0.59	0.57	-3
Weedy fallow	0.78	-		0.39	-		0.62	-		0.43	-	
Continuous millet	0.69	-		0.43	-		0.63	-		0.47	-	
SED Season	0.269***											
SED LP	0.261ns											
SED Field type	0.265**											
SED Legume	0.271***											
SED Phosphorus	0.270ns											

Table 3 continued …

(b) Onamudian village

2006A												
Cowpea	1.87	2.01	7	1.09	0.88	-19	1.83	1.73	-5	1.29	1.18	-9
Green gram	1.81	2.10	16	0.88	0.68	-23	2.15	1.88	-13	0.89	1.00	12
Groundnut	1.54	1.74	13	0.68	0.91	34	1.63	1.95	20	0.96	1.08	13
Mucuna	1.98	1.90	-4	0.92	0.93	1	1.88	1.76	-6	1.16	1.25	8
Pigeon pea	1.90	1.89	-1	0.99	0.87	-12	1.70	1.87	10	0.87	1.18	36
Soyabean	1.76	2.03	15	0.61	0.74	21	1.70	2.08	22	1.05	1.12	7
Weedy fallow	1.69	-		0.84	-		1.85	-		0.65	-	
Continuous millet	1.67	-		0.98	-		1.63	-		0.58	-	
2006B												
Cowpea	0.72	1.21	68	0.63	0.67	6	1.06	1.23	16	0.75	0.74	-1
Green gram	0.65	0.83	28	0.51	0.59	16	1.18	1.34	14	0.74	0.90	22
Groundnut	0.62	1.13	82	0.55	0.5	-9	0.77	0.74	-4	0.57	0.76	33
Mucuna	0.80	0.93	16	0.76	0.71	-7	0.76	0.92	21	0.76	0.90	18
Pigeonpea	0.80	1.07	34	0.69	0.71	3	0.70	0.77	10	0.92	0.93	1
Soyabean	0.81	0.92	14	0.46	0.37	-20	0.69	0.81	17	0.59	0.68	15
Weedy fallow	0.69	-		0.52	-		0.71	-		0.76	-	
Continuous millet	0.52	-		0.48	-		0.74	-		0.57	-	
SED Season	0.212***											
SED LP	0.209*											
SED Field type	0.208***											
SED Legume	0.213***											
SED Phosphorus	0.212***											

SED = Standard error of difference; Significance, * $P< 0.05$; *** $P < 0.001$;ΔP Apparent effect of phosphorus = $(P_{30}-P_0)/P_0 \times 100$

Yield responses were consistent with inherent variability in soil fertility. Usually stronger responses were found in the good compared with the poor fertility fields in both seasons. On average, yields on the good fields were higher than those on poor fields in 2006A and the difference was even larger in the 2006B season as a result of decline in residual effectiveness of legumes biomass. Millet grain yields did not differ significantly on establishment of legumes with P.

The general trends in millet grain responses to legume biomass incorporation in Onamudian village were similar to those in Chelekura village except that responses to landscape positions ($P<0.05$) and P ($P<0.001$) were also significant (Table 3b). In addition, the apparent effects of P were stronger in the good fields than the poor fields and millet yielded more in the middle landscape position for both field types and seasons.

Average additional grain yield of finger millet above continuous millet for the two seasons showed a positive contribution of the legumes to millet production (Figure 3). The added yields only significantly ($P<0.001$) differed between legumes species in Chelekura village. In Onamudian village, the added yields significantly ($P<0.001$) differed with legumes and application of phosphorus and interaction between landscape position × legume ($P<0.05$). Amounts of added grain yield were on average 0.2-0.3 Mg ha^{-1} in poor and good fields located on the upper landscape position in Chelekura and 0.15- 0.2 Mg ha^{-1} in Onamudian village. Millet responses were larger for all legumes with P except for cowpea and green gram in good fields (upper landscape position) in Chelekura village. Generally P application on legumes benefited millet in the poor fields more than in the good fields.

Biomass NUE by finger millet

NUE was in general low and only in few cases approached 25 kg grain kg^{-1} N taken up. P application gave increased NUE in each of the field types and landscape positions in both Chelekura and Onamudian village (Table 4). NUEs were higher on poor than on good fields in the upper landscape position with the largest NUE obtained with groundnut residues (18.2 kg grain kg^{-1} N). With P, the NUE after pigeonpea doubled from 7.1 to 14.3 kg grain kg^{-1} N. In Onamudian village higher NUE's were found on the good fields ranging from 0.87 to almost 25 kg grain kg^{-1} N.

Grain yield and N uptake

Overall relationships between grain yield with N uptake following biomass incorporation across the treatments in each village were relatively weaker in

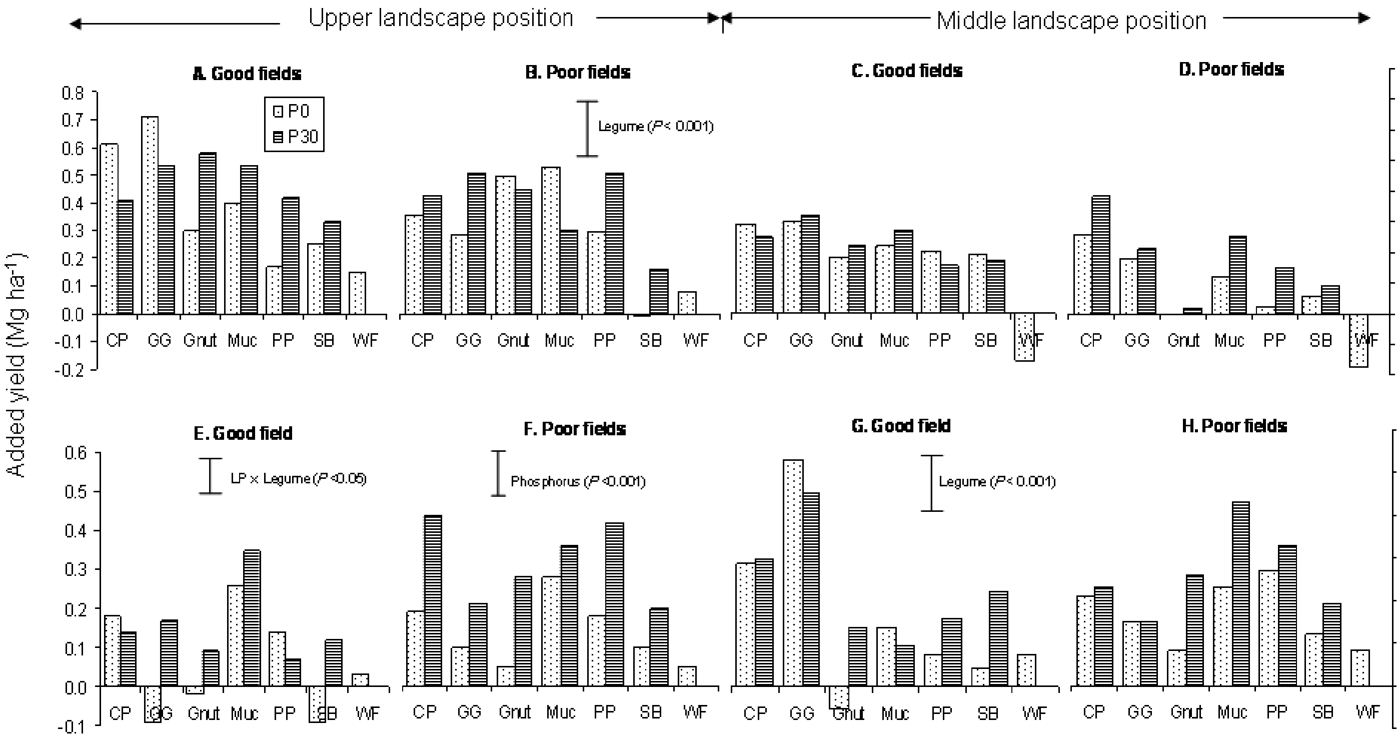

Figure 3 Average additional grain yield of finger millet (Mg ha^{-1}) above continuous millet following legumes grown with or without P fertiliser and weedy fallow on good and poor fields located on the upper and middle landscape positions in Chelekura (upper) and Onamudian (below) for 2 seasons. Respective grain yields for continuous millet treatment in Chelekura village, A-D: 0.85, 0.47, 1.00 and 0.76 Mg ha^{-1}; and for Onamudian village, E-H: 1.22, 0.51, 1.23 and 0.54 Mg ha^{-1}. CP= cowpea; GG = green gram; Gnut = groundnut; Muc = mucuna; PP = pigeonpea; SB = soyabean and WF = weedy fallow.

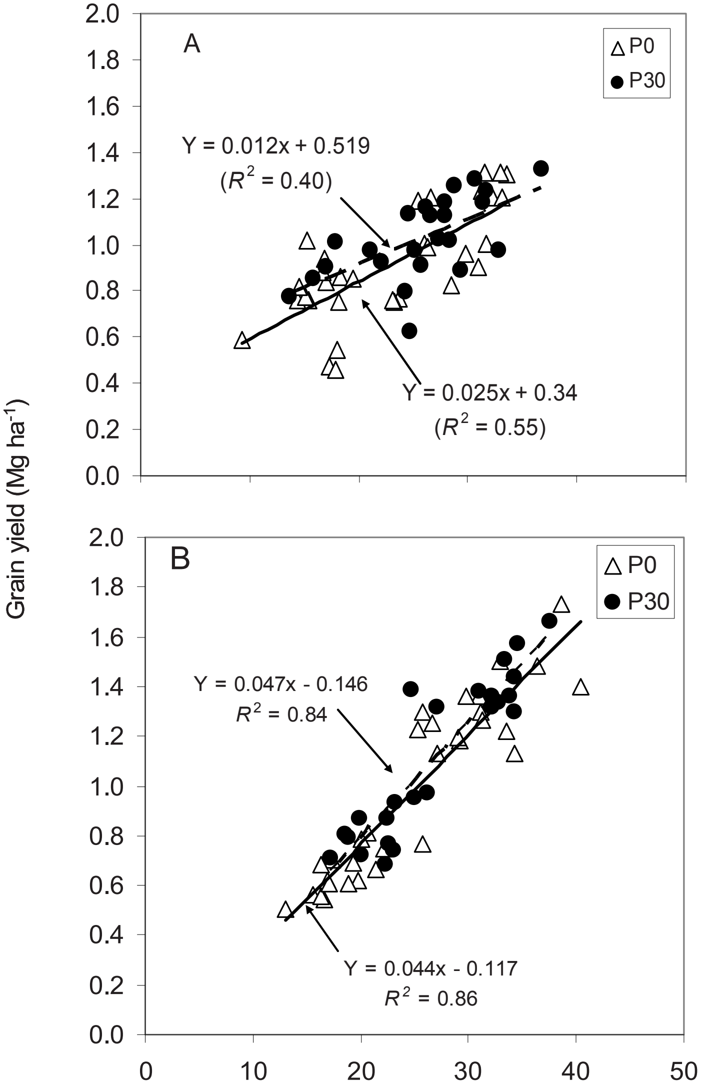

Figure 4 Finger millet grain yield relationships with total N uptake in Pallisa district, 2006. A= Chelekura and B=Onamudian village. Open triangles are treatments without P and filled circles are treatments with 30 kg P ha^{-1} on preceding legume crops.

Table 4 Nitrogen use efficiencies (kg grain kg^{-1} N uptake) in finger millet following incorporation of biomass of legumes grown with or without P fertiliser, weedy fallow on good and poor fertility fields located on the upper and middle landscape positions in Chelekura and Onamudian villages (averaged across 2 seasons).

Village/legume	Upper				Middle			
	Good		Poor		Good		Poor	
	P0	P30	P0	P30	P0	P30	P0	P30
Chelekura								
Cowpea	2.57	0.77	3.25	3.84	2.35	1.81	2.71	3.42
Green gram	4.55	2.37	4.82	6.89	2.69	1.87	2.42	2.51
Groundnut	0.76	7.75	18.28	9.75	4.20	5.71	0.09	0.48
Mucuna	0.98	1.49	5.63	3.43	1.29	1.60	0.87	2.42
Pigeonpea	-1.23	2.29	7.10	14.34	2.56	1.76	0.34	2.76
Soyabean	-0.12	1.79	-0.33	6.01	7.63	3.75	2.48	2.78
Weedy fallow Millet	-4.85		5.19		-8.23		-15.26	
Onamudian								
Cowpea	1.38	0.87	2.02	3.31	1.64	0.94	1.70	1.54
Green gram	-0.87	11.84	1.26	2.34	3.29	2.86	1.86	1.08
Groundnut	-0.51	24.79	1.33	5.92	-0.44	1.13	0.86	2.88
Mucuna	2.21	11.24	2.21	3.53	0.61	0.32	1.18	1.99
Pigeonpea	1.81	17.73	3.14	5.89	0.40	1.08	2.33	2.72
Soyabean	-1.52	23.89	3.22	4.04	0.29	1.57	1.27	2.50
Weedy fallow Millet	1.94		3.64		2.12		4.93	

Chelekura (R^2=0.52) than in Onamudian (R^2= 0.85) and slopes of the lines are lower in the first village compared with the latter. The relationship was also weaker with P application in Chelekura (R^2=0.40) but not different between with and without P application in Onamudian village (Figure 4). The latter could be due to the somewhat higher extractable P in the soils in Chelekura (Table 1). In both villages, increasing grain yield with N-uptake are low perhaps because other nutrients are limiting response. This is more distinct in Chelekura (lower R^2) than in Onamudian (higher R^2) which is supported by the fact that soil fertility in the latter village is somewhat better in particular in CEC (Table 1).

4.2.3 Socio-economic evaluation

Legume acceptance and preferential targeting by farmers

Groundnut had the highest probabilities of being ranked first in Chelekura (60%) and Onamudian (75%) villages (Figure 5). It was followed by cowpea and green gram in

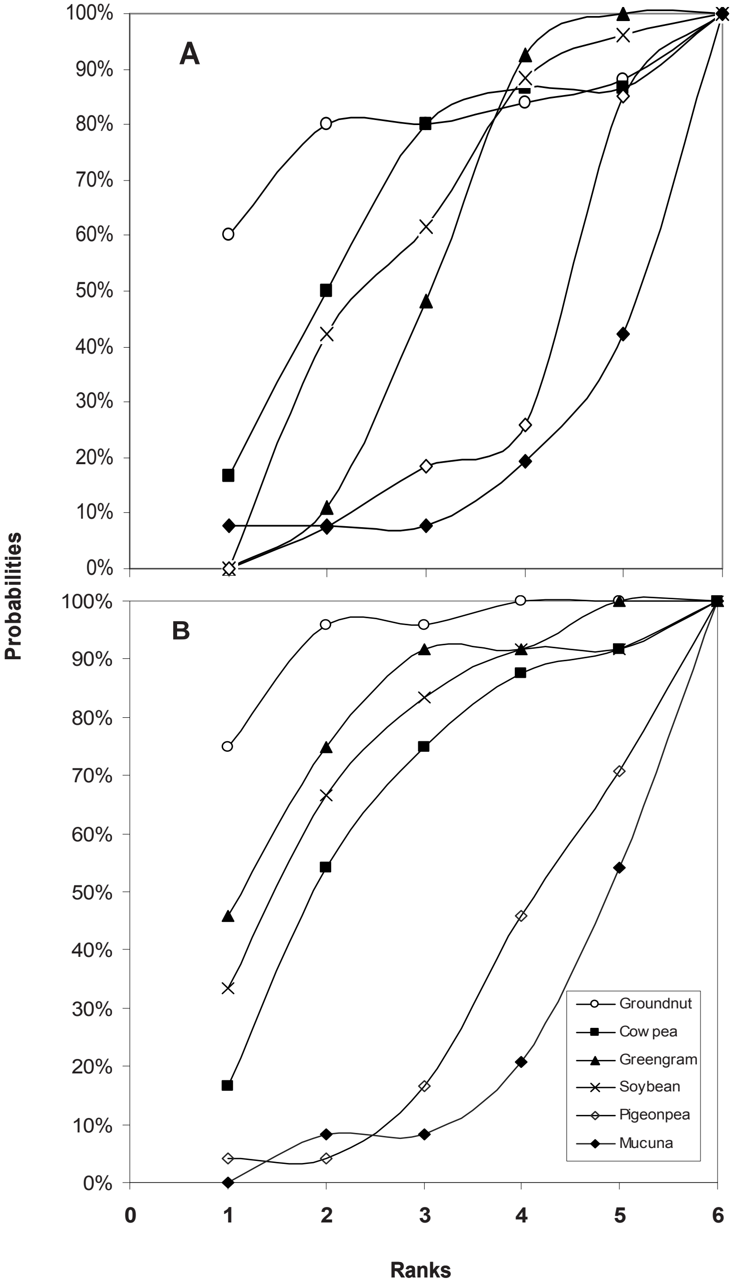

Figure 5 Comparison of acceptance of legume species by participants in the farmer field schools in A: Chelekura (n= 27) and B: Onamudian (n= 24) villages, Pallisa District.

Table 5 Millet grain yield (Mg ha^{-1}), gross value and total variable costs (both in Ush ha^{-1}) and benefit cost ratios (in bold BCR>2.0) for rotations with legumes grown with or without P fertiliser, weedy fallow and continuous millet cropping systems grown on good and poor fields located on upper and middle landscape positions in (a) Chelekura village and (b) Onamudian village.

(a) Chelekura village

Treatment/position	Good fields								Poor fields							
	Po				P30				Po				P30			
	GY	GV	TVC	BCR	GY	GV	TVC	BCR	GY	GV	TVC	BCR	GY	GV	TVC	BCR
Upper																
Cowpea	2.18	872	395	**2.21**	2.24	896	746	1.20	1.86	744	395	1.88	2.08	832	746	1.12
Green gram	2.74	1096	363	**3.02**	2.19	876	714	1.23	1.68	672	363	1.85	1.76	704	714	0.99
Groundnut	1.93	772	590	1.31	2.36	944	941	1.00	1.32	528	590	0.89	1.35	540	941	0.57
Mucuna	2.07	828	398	**2.08**	2.25	900	749	1.20	1.59	636	398	1.60	1.82	728	749	0.97
Pigeonpea	1.53	612	412	1.49	2.1	840	763	1.10	1.39	556	412	1.35	1.63	652	763	0.85
Soyabean	1.76	704	410	1.72	1.85	740	761	0.97	1.45	580	410	1.41	1.52	608	761	0.80
Weedy fallow	1.69	676	330	**2.05**					1.02	408	330	1.24				
Continuous millet	1.71	684	373	1.83					1.32	528	373	1.42				
Middle																
Cowpea	2.54	1016	395	**2.57**	2.44	976	746	1.31	1.82	728	395	1.84	1.98	792	746	1.06
Green gram	2.58	1032	363	**2.84**	2.58	1032	714	1.45	1.71	684	363	1.88	2.13	852	714	1.19
Groundnut	2.26	904	590	1.53	2.42	968	941	1.03	1.95	780	590	1.32	2.01	804	941	0.85
Mucuna	2.4	960	398	**2.41**	2.51	1004	749	1.34	2.05	820	398	**2.06**	1.74	696	749	0.93
Pigeonpea	2.35	940	412	**2.28**	2.28	912	763	1.20	1.7	680	412	1.65	2.07	828	763	1.09
Soyabean	2.34	936	410	**2.28**	2.28	912	761	1.20	1.03	412	410	1.00	1.40	560	761	0.74
Weedy fallow	1.66	664	330	**2.01**					1.18	472	330	1.43				
Continuous millet	1.66	664	373	1.78					1.03	412	373	1.10				

Table 5 continued…

(b) Onamudian village

Upper																
Cowpea	2.89	1156	395	**2.93**	2.96	1184	746	1.59	2.04	816	395	**2.07**	1.92	768	746	1.03
Green gram	3.33	1332	363	**3.67**	3.22	1288	714	1.80	1.63	652	363	1.80	1.90	760	714	1.06
Groundnut	2.4	960	590	1.63	2.69	1076	941	1.14	1.53	612	590	1.04	1.84	736	941	0.78
Mucuna	2.64	1056	398	**2.65**	2.68	1072	749	1.43	1.92	768	398	1.93	2.15	860	749	1.15
Pigeonpea	2.4	960	412	**2.33**	2.64	1056	763	1.38	1.79	716	412	1.74	2.11	844	763	1.11
Soyabean	2.39	956	410	**2.33**	2.89	1156	761	1.52	1.64	656	410	1.60	1.80	720	761	0.95
Weedy fallow	2.56	1024	330	**3.10**					1.41	564	330	1.71				
Continuous millet	2.37	948	373	2.54					1.15	460	373	1.23				
Middle																
Cowpea	2.59	1036	395	**2.62**	3.22	1288	746	1.73	1.39	556	395	1.41	1.27	508	746	0.68
Green gram	2.46	984	363	**2.71**	2.93	1172	714	1.64	1.23	492	363	1.36	1.41	564	714	0.79
Groundnut	2.16	864	590	1.46	2.87	1148	941	1.22	1.68	672	590	1.14	1.64	656	941	0.70
Mucuna	2.78	1112	398	**2.79**	2.83	1132	749	1.51	1.68	672	398	1.69	1.58	632	749	0.84
Pigeonpea	2.7	1080	412	**2.62**	2.96	1184	763	1.55	1.07	428	412	1.04	1.11	444	763	0.58
Soyabean	2.57	1028	410	**2.51**	2.95	1180	761	1.55	1.36	544	410	1.33	1.27	508	761	0.67
Weedy fallow	2.38	952	330	**2.88**					1.46	584	330	1.77				
Continuous millet	2.19	876	373	2.35					1.39	556	373	1.49				

GY = Total grain yield (Mg ha^{-1}) for 2 seasons; GV = Gross value in ‘000 Ush (GY × price of millet); TVC = Total variable costs in ‘000s Ush; BCR = Benefit cost ratio computed from (GV–TVC)/TVC; price of finger millet = 400 Ush kg^{-1}; Conversion: 1730 Ush = 1US$

Chelekura and Onamudian, respectively. The slopes of regression lines of cumulative frequencies of farmers ranking of groundnut were 0.07 and 0.04, with positive and significant probabilities from zero of 0.59 and 0.80 in Chelekura and Onamudian respectively indicating a strong likelihood of acceptance by farmers. In both sites, probabilities were not significantly different for mucuna and the intercepts were negative. In the case of pigeonpea, the intercepts were negative although the probabilities were significant. The results indicated that mucuna and pigeonpea are unlikely to be accepted by farmers.

Farmers preferred to target grain legumes with or without P application to fields of good fertility as indicated by 35-96 % of the respondents and pigeonpea and mucuna to fields of poor fertility (70-100%) in both villages. The farmers indicated that they would grow cowpea in both good (35-38%) and poor (45-63%) fertility field types which tallies with the good agronomic performance of cowpea across field types, and the response to P application. Farmers targeted grain legumes more to the good (26-93%) than poor fields mainly to avoid yield losses. Pigeonpea and mucuna were targeted to fields of poor fertility because of their biomass production potential and accompanying benefits of weed suppression and tolerance of poor soil fertility (63-92%).

Economic benefits

Benefits from millet following legumes were greater than from continuous millet treatment in both field types and landscape positions in the study villages (Table 5). Legumes without P application were profitable only on good fields in both villages. In Chelekura, profitable legumes (BCRs > 2) included green gram, cowpea and mucuna on good fields in the upper position and all the legumes except groundnut on good fields in the middle position. On poor fields only mucuna was profitable in the middle position. With the exception of groundnut, all the legumes without P application and weedy fallow and continuous millet cropping had BCRs > 2 on good fields on both upper and middle landscape positions in Onamudian village. However, only cowpea without P application was profitable on poor fields in the upper position.

4.3 Discussion

Heterogeneity in soil fertility influenced productivity of legumes established without and with P (Table 2) and the subsequent millet yields (Table 3). Biomass production, N accumulation and N_2-fixation of the legumes were within ranges reported elsewhere in sub-Saharan Africa (Hauser and Nolte, 2002; Baijukya, 2004; Kaizzi et al., 2006; Ncube, 2007; Ojiem et al., 2007). Greater N availability in soils is known to inhibit N_2

fixation (Giller, 2001) which explains why the proportions of N_2-fixed were larger in Chelekura village with fields of lower total N than in Onamudian village (Table 1). Application of P increased the amounts of N_2-fixed (Table 2b) rather than the proportions fixed (Figure 2) and had stronger effects in the poor fertility fields which were often P deficient (Table 1).

Millet yields increased following legumes, as is commonly found in legume cereal cropping systems (Osunde et al., 2003; Ncube, 2007; Franke et al., 2008). The yield responses were larger when larger amounts of legume biomass were incorporated. Residual effectiveness of the legumes was however short lived as the yields in season 2006B were significantly less than those of 2006A season due to a decrease in N availability. Legume residues release large amounts of N rapidly once incorporated in soil rendering it susceptible to leaching losses (Dawson et al., 2008). This could have been more likely as more than normal rainfall was received in 2006B season (Figure 1). Millet straw has high C: N ratio and because the straw of the previous season was incorporated into the plots, N immobilisation could have also compounded the low yields in 2006B season.

Heterogeneity in soil fertility mediated the millet yield responses. The larger millet yield responses observed in good than poor fields following legumes imply that other factors than N restricted millet growth. Larger relative responses of millet to P applied to the previous legume crop on poor fields showed a residual benefit of P application as reported earlier from legume-cereal rotations (Kihara et al., 2007). This is advantageous as it could cut costs of P application and also has cumulative benefits to all the crops in the rotation sequence because of increasing P recovery with time (Janssen and Wolf, 1988)

Yield responses are also influenced by nutrient recoveries and use efficiencies as modified by heterogeneity in soil fertility. The agronomic N use efficiencies of legume biomass N in this study were stronger when P was applied to both good and poor fields (Table 4) a similar response to that observed with maize across different field types (Tittonell et al., 2007; Zingore et al., 2007a). The N use efficiencies were however smaller on less fertile fields. Zingore et al. (2007b) demonstrated that poor N use efficiencies on infertile fields were due to multiple nutrient limitations including deficiencies of micronutrients. To realise improved N use efficiencies and benefit from use of legumes, a better understanding of factors influencing N dynamics after legumes is needed, especially after straw incorporation. Other factors that interact to limit millet production in poor fertility fields need to be explored, such as deficiencies of other nutrients.

Although mucuna and pigeonpea resulted in significantly higher millet yield increases compared with continuous millet, farmers would not accept them to be planted on good fertility fields demonstrating a mismatch between agronomic performance and farmers preferences. Farmers were unfamiliar with pigeonpea which is a crop of the northern farming system in Uganda. They neither knew the crop as a food crop nor the potential marketability of its grain. For the case of mucuna, it was not popular with farmers because it has no direct food benefit to the farmers, although it produced large amounts of N-rich biomass, demonstrating that improving soil fertility is a secondary goal of farmers. Lack of acceptance of mucuna is also linked to substantial amounts of labour required for incorporation, and the fact that land is used without producing food (Nyende and Delve, 2004). In Chelekura, soyabean did not establish well and was attacked by rust, which influenced the farmers ranking (Figure 5). Onamudian is close to the main market in Pallisa and green gram and soyabean are marketable and used in making snacks, and farmers preferred growing them. Their biomass performance also was better in this village. Overall, farmers' evaluation could have been biased by the lack of grain yield due to the poor rainfall received during the 2005B season (Figure 1). Groundnut was highly preferred by farmers because it contributes to household food needs and is highly marketable despite its poorest economic performance on good fields where almost all legumes were potential to be targeted (Table 5).

Farmers' targeting of legumes to field types often did not reflect the agronomic or economic performance of the legumes. For example, farmers do not grow groundnut on high fertility fields as it produces a lot of biomass but the haulm yields are poor. Unpublished survey data from the same villages showed that groundnut was grown on fields of poor to moderate fertility yet farmers said they would target it to good fertility fields. Furthermore, our experimental results showed that in general all legumes produced more biomass on good fields than poor fertility fields (Table 2 (a)). Economic analysis indicated high returns on incorporation of legume biomass with or without P application because of the increased yield of the subsequent millet crop (Tables 5a and b). However growing legumes without P was most profitable (BCR > 2) on good fertility fields in both landscape positions in the study villages. With the current yields and prices, use of P fertilisers is not attractive for farmers. At current yields a 15–20% increase in the value of the produce or a 30–40% reduction in the price of P fertiliser would be needed to make all of the legume technologies profitable. Integration of agronomic performance and farmers' production objectives and economic benefits is needed to best fit legumes to socio-ecological environments (Ojiem et al., 2006).

From agronomic and economic viewpoint, green gram, cowpea, and mucuna established without P could be targeted to good fields (upper landscape position) and all the legumes except groundnuts (middle position) in Chelekura village. Only mucuna without P was suitable for poor fields in the middle landscape positions in this village. In Onamudian village, all the legumes (except groundnuts) could be targeted to good fields and only cowpea to poor fields on upper position. A BCR > 2 is often used as an economic threshold to identify soil fertility management technologies that can attract reinvestment and in turn may lead to their sustainable use. Millet however is grown for other social benefits (e.g. social functions/ ceremonies like marriages) to which it is difficult to attach a direct economic value. Therefore legumes (especially without P application) that result in BCRs greater than those from continuous millet could be attractive to farmers for growing in both good and poor fields for social sustainability. The wider perceptions of multiple benefits that farmers attach to a technology explain why groundnut was prioritised in both sites although it did not contribute significantly to higher yields of the subsequent millet. The high cost of the seed for the variety used and weak residual effect on millet yield explained its lack of profitability. Due to the poor rainfall, no grain of the legumes was produced, but in better seasons all the legumes including groundnuts may be profitable. Much as the economic analysis indicated that pigeonpea and mucuna were profitable on the good fields, the opportunity cost of missing out on food production means they are unlikely to be accepted by farmers, except for growing in the poor fields where their use was not profitable. Integrating the agronomic, social and economic factors in the targeting of legume species therefore draws as to suggest that green gram, cowpea and soyabean should be targeted on good fields in both villages, mucuna to poor fields in the middle landscape position in Chelekura village and cowpea to poor fields on the upper position in Onamudian village.

4.4 Conclusions

Variability in soil fertility strongly influenced the productivity of legumes and their contribution to subsequent crops of finger millet. Legumes increased millet productivity on both good and poor fields. P is necessary for establishment of legumes and accumulation of N in poor fertility fields. Farmers preferred targeting legumes with perceived multiple benefits to good fertility fields and legumes with no immediate contribution to household food requirement to poor fields but not because of a greater impact on fertility. Economic benefits were affected by heterogeneity between field types and, with current millet yields and prices, legume-millet rotations without P fertiliser were more profitable on good fields. Our results challenge the generalised recommendation that legumes are suitable for improving the productivity of low input farming systems. From our experiments, we suggest that green gram and cowpea without P be targeted to good fields on both upper and middle landscape positions in both villages, mucuna without P to poor fields in the middle landscape position in Chelekura village, and cowpea to poor fields on upper position in Onamudian village. Thus, niches for different legume species need to be identified in the low input farming systems to derive maximum benefit from legumes.

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Chapter 5

Evaluation of efficacy of nutrient management options to improve millet production on degraded fields in smallholder African farms using former kraals as a benchmark [†]

[†] This chapter is submitted as: Ebanyat, P., Ridder, N. de, Bekunda, M.A., Delve R.J., Giller, K.E. Evaluation of efficacy of nutrient management options to improve miller production on degraded fields in smallholder African farms using former kraals as a benchmark. *Experimental Agriculture*

Abstract

Nutrient additions are required to increase crop production on degraded fields. Field experiments were conducted for three seasons to evaluate the effectiveness of inorganic fertilisers and kraal manure to improve the productivity of finger millet on nutrient-depleted fields on smallholder farms in Pallisa district, eastern Uganda. N, P fertilisers alone (0, 30, 60, 90 kg ha^{-1}), N+P at equal rates of single application, and manure (3 t ha^{-1}) supplemented with N (0, 30, 60 and 90 kg ha^{-1}) were applied to degraded fields located in upper and middle landscape positions in Chelekura and Onamudian villages. A second control treatment of millet grown on soils of former kraals (high fertility niches) was included as a benchmark. Average grain yield ranged from 404 kg ha^{-1} to 2026 kg ha^{-1} and differed significantly ($P<0.001$) between villages and seasons in 2006. Significant effects ($P<0.05$) of landscape position on grain yield were observed only in Onamudian village. The treatments significantly increased millet yields on degraded fields but could not eliminate the yield differences between degraded fields and former kraals. The largest grain yields on degraded fields were obtained with application of N+P with average yields of 800 kg ha^{-1} in Chelekura village and 1171 kg ha^{-1} in Onamudian village. These yield responses closed the yield difference between the former kraal fields and degraded fields by 24% and 43 % compared with yields obtained on former kraal fields in Chelekura and Onamudian respectively. The physiological efficiencies, agronomic efficiencies and apparent recoveries of N and P were poor; often less than 25%. Pot experiments conducted in a greenhouse showed that S also limited millet growth in Chelekura and K was a limiting nutrient in Onamudian which partly explains the large yield gaps of finger millet between fertilized fields and former kraals in the smallholder farming systems.

Key words: *Heterogeneity in soil fertility; Integrated nutrient management; Nutrient use efficiencies; Fertiliser recoveries; Finger millet, Sub-Saharan Africa, Limiting nutrients.*

5.0 Introduction

Poor soil fertility is a major problem constraining crop productivity in smallholder farms of sub-Saharan Africa (SSA) due to inadequate replenishment of nutrients removed (Buresh et al., 1997). The magnitudes of nutrient depletion vary across the continent and are amongst the highest in Uganda: 20-40, 3.5-6.6 and 17-33 kg ha^{-1} yr^{-1} for N, P and K respectively (Smaling et al., 1997). Although negative nutrient balances are prevalent throughout SSA, areas of nutrient accumulation are created through management and resulting in heterogeneity in soil fertility and crop productivity within farms (eg Rowe et al., 2006; Tittonell et al., 2007; Zingore et al., 2007). Continued depletion of nutrients results in degraded patches of soil within farms.

The area covered by poor fertility fields in smallholder African farms is substantial and will increase if no action is taken to replenish and sustain soil fertility. Tittonell (2007) found the proportion of poor fertility fields according to farmers' categorisation to account for approximately 30% of total farm fields in six farming systems in western and central Kenya and eastern Uganda. In two villages in Pallisa district the degraded fields covered 13-29 % of the land area (Ebanyat et al., 2009). Together with reducing farm size this threatens the food security of smallholders who rely on farming for their livelihood. Thus deliberate measures to increase crop production on degraded fields are necessary.

Potential options to restore soil fertility include the use of inorganic fertilisers or locally-available organic inputs. The use of inorganic fertilisers is constrained by high costs and inaccessibility, and a lack of economic returns (Morris et al., 2007). At the same time the limited amounts of organic resources available on smallholder farms and their poor nutrient quality constrain their use and effectiveness in soil fertility management (Ridder et al., 2004). Combined use of organic and inorganic fertilizers in integrated nutrient management is a potential approach to ameliorate soil fertility because of their complementary benefits (Vanlauwe et al., 2002).

Strategies for fertility regeneration in smallholder farming systems can best be designed with the knowledge of field responsiveness to nutrient management interventions. Vanlauwe et al. (2009) propose a stepwise approach in targeting and adapting nutrient management interventions and germplasm to local variations as a way to moving towards integrated soil fertility management. The stepwise approach requires recognisable benchmarks against which to evaluate efficacy of the intervention strategies and the beginning point we suggest is identifying such benchmarks within the farming system. In the Teso farming system in eastern Uganda where this study was conducted, areas where manure accumulated over years of night corralling (former kraals) are fertile, give good yields of finger millet and are readily observed by smallholders. We used these former kraal sites as benchmarks to assess within-farm differences in millet yield and to evaluate responsiveness of

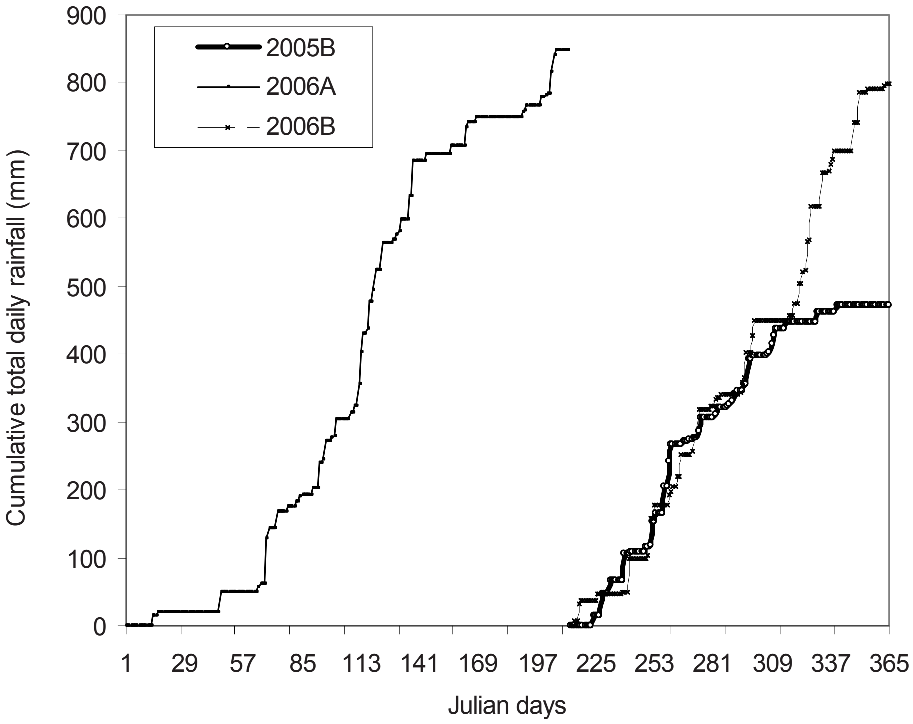

Figure 1 Cumulative daily rainfall received in the study area during field experimentation for three subsequent seasons 2005B, 2006A and 2006B.

degraded fields to nutrient interventions in two study sites in Pallisa district. N and P are the major nutrients limiting millet production in the low input farming systems in eastern Uganda (Tenywa et al., 1999). We tested the hypothesis that differences in finger millet yield between the former kraals and degraded fields can be eliminated by application of appropriate rates of N and P of organic and inorganic origin on degraded fields. The specific objectives of the study were: (i) to determine finger millet yield response to applied nutrients of organic and inorganic origin on degraded fields and assess the extent to which yield differences between benchmark sites and degraded fields amended with nutrient inputs are reduced; (iii) to determine nutrient use efficiencies by finger millet; and (iii) to identify other nutrients limiting finger millet production in degraded fields.

5.1 Materials and methods

5.1.1 The study sites

Field experiments were conducted in two villages: Chelekura in Chelekura parish (1°24′N; 33°30′E) and Onamudian in Akadot parish (1°11′N; 33°43′E) in Pallisa district (1°09′ N, 33°48′ E) representative of the Teso farming system of eastern Uganda. Soils of Chelekura are formed from lake deposits and those of Onamudian from basement complex rocks (granitic gneisses) (Harrop, 1970). The landscape is characterized by wide gently convex interfluves separated by wide swampy valleys (Ollier et al., 1969). The toposequence can be divided into three sub-zones; the upland zone at the summits (upper landscape positions), the midland zones located on pediments (middle landscape positions) and the valleys which may be seasonally or permanently wet (lower landscape positions). In both villages, soils are Ferralsols and Dystric Fluvisols in the uplands and valley bottoms respectively (Ebanyat et al., 2009).

Mean annual rainfall ranges from 900 to 1200 mm and is distributed in a bimodal pattern. The first rains are from March to June and the second rains from August to October or November. A dry spell stretches from November to March. Both study sites were within the same rainfall zone of 900 mm yr^{-1}. Monthly temperature ranges from 15°C to 36°C, with an annual mean of 25°C (Yost and Eswaran, 1990). Cumulative total rainfall during the growing period of short rain season in 2005B was low (≈400 mm) but was above normal in 2006B (Figure 1). Millet (*Eleusine coracana* L.) is an important staple and income crop in the study area.

5.1.2 Field experiments

Field selection and soil and manure characterization

Ten degraded fields (5 on upper and 5 on middle landscape positions) based on farmers perceptions of fertility status and five former kraal sites last used for night corralling five years prior to this study were selected for experimentation in each of two study villages of Chelekura and Onamudian. Five soil sub-samples were taken from each field from 0-20 cm, thoroughly mixed and by quarter sampling composite samples were obtained. Manure was collected from 2 (Chelekura) and 3 kraals (Onamudian) and subsamples taken for oven drying at 65°C for 48 hr to obtain the average moisture content. Air-dried composite samples of soil (<2 mm) and manure samples were subjected to physico-chemical analysis at the World Agroforestry Centre (ICRAF) following spectral and standard wet chemistry analysis procedures (Shepherd and Walsh, 2002). Extractable P was determined at Kawanda National Agricultural Laboratories Research Institute in Uganda using the modified Olsen method (Anderson and Ingram, 1993).

Field preparation and experiment establishment

The fields were ox-ploughed twice and plots of 3 × 3 m demarcated and kraal manure, N (urea) and P as triple super phosphate (TSP) were applied as single replicates per farm and landscape position as follows: Control (with no nutrient inputs), N and P alone at rates of 30, 60 and 90 kg ha^{-1} and combinations of N and P each at equal rates (i.e. 30N+30P, 60N+60P and 90N+90P), kraal manure at 3 t ha^{-1} and kraal manure 3 t ha^{-1} with N at 30, 60 and 90 kg ha^{-1} (i.e. M+30N, M+60N and M+90N). Manure and TSP fertilizer were basal applied by spreading and worked into soil with a hand hoe. Finger millet variety SEREMI 2 was planted during the short rains of 2005 (2005B) at a spacing of 0.3 m between rows and thinned to 0.05 m within rows at 2 weeks after planting (WAP). Nitrogen was applied in two equal splits at first weeding (2 WAP) and second weeding (4 WAP). In the subsequent seasons of 2006A and 2006B, land preparation was done on a plot basis using a hand hoe. The experiments were replanted in the same plots without any nutrient input additions in the long rainy season (2006A), but with nutrient inputs at the same rates during the short rainy season (2006B). All other agronomic operations were carried in the same way across the seasons.

Millet sample collection, preparation and analysis

In 2005B, only straw was harvested because of poorly distributed rains (Figure 1) that did not allow panicle filling. In 2006, millet panicles were harvested by cutting with thumb knives (farmers practice) and straw cut at 0.05 m above the ground surface from two quadrats of 1 m^2 along the 3 middle rows of each plot. The panicles and straw samples were oven dried at Makerere University's Soil and Plant analytical laboratories at 65°C for 72 hours. Panicles were threshed and weights of grains and husks, and straw were obtained before they were ground to pass through a 1 mm sieve. The samples were analysed at the World Agroforestry Centre (ICRAF), Nairobi, Kenya for total N using of spectral and wet chemistry procedures as detailed in Shepherd et al. (2003). Total P was determined using the wet chemistry procedure as detailed by Anderson and Ingram (1993) for plant materials at Kawanda National Agricultural Laboratories Research Institute in Uganda.

5.1.3 Greenhouse pot experiment

Bulk soils were collected from 5 locations within the degraded fields used for experiments at 0-20cm; three each from upper and middle landscape positions of each village. The samples were bulked and mixed using a manually rotated drum. The mixed soils of each village were weighed into pots to provide a rooting volume of 2000 cm^3 i.e. 3.48 kg and 3.10 kg for degraded soils, and 2.84 and 2.78 kg for former kraal soils from respectively Chelekura and Onamudian villages. Treatments applied constituted macro and micro nutrients: N, N+P, N+P+K, N+P+K+S, N+P+K+S+Ca, N+P+K+S+Ca+Mg, N+P+K+S+ micro-nutrients and N+P+K+S+Ca+Mg + micro-nutrients. The source and amount of each nutrient applied (g pot^{-1}) to soils from Chelekura and Onamudian village were: N (NH_4NO_3; 0.2429, 0.2214), P (NaH_2PO_4; 0.1974, 0.1800), K (K_2O; 0.0410, 0.0374), S ($(NH_4)_2SO_4$; 0.2104, 0.1918), Ca (CaO; 0.2380, 0.2170), Mg (MgO; 0.1133, 0.1033), Mo(Na_2MoO_4; 0.0010, 0.0009), Mn ($MnSO_4$; 0.0200, 0.0183), Cu ($CuSO_4$; 0.0150, 0.0137), Zn ($ZnSO_4$; 0.0150, 0.0137), Bo

($Na_2B_4O_7$; 0.0010, 0.0009) and Co ($CoCl_2$; 0.0025, 0.0023). The nutrients were dissolved in the amounts of distilled, deionised water required to bring the soils in pots to field capacity. The pots were left to stand for 2 days and then planted with 0.5 g of finger millet seed (variety SEREMI 2). The experiment design was a complete randomized block with three replicates. At 2 weeks after emergence only 20 plants were maintained per plot. Water was added after every 2 days to maintain moisture content of the pots at 70% of field capacity during the experiment period. Millet shoots were cut at 0.05 m from the soil surface at 8 WAP and oven dried at 65°C for 48 hr to obtain shoot dry weights. Roots were recovered by washing soil from each pot through a 2 mm sieve. The roots were then oven dried to obtain root dry weights. Total biomass was a total of recovered roots and shoot biomass.

5.1.4 Data calculations and analysis

Total nutrient uptake in straw and grain was determined as a product of straw or grain yield with mass respective percentage total N or total P and the nutrient physiological or internal nutrient efficiencies for N and P computed using the equation of Witt et al. (1999):

$$PhE = GYT/UNT \qquad \text{(Equation 1)}$$

Where:

PhE is physiological nutrient efficiency (kg kg^{-1}); GYT = Grain yield for treatment (kg ha^{-1}) and UNT is the total uptake of nutrient (kg ha^{-1}).

Agronomic efficiency and apparent nutrient recovery fractions of nutrients applied to degraded fields were computed from the following equations:

$$AE = (GYT - GYC)/RN \qquad \text{(Equation 2)}$$

Where:

AE is agronomic efficiency (kg kg^{-1}); GYT = grain yield of treatment (kg ha^{-1}) and GYC is grain yield of control treatment (kg ha^{-1}) and RN is rate of applied nutrient (kg ha^{-1}), and

$$ARN = (UT - UC)/RN \qquad \text{(Equation 3)}$$

Where:

ARN is apparent recovery of nutrient (kg kg^{-1}); UT = total uptake of nutrient in straw and grain (kg ha^{-1}); UC is total uptake in straw and grain in the control treatment (kg ha^{-1}); RN is the rate of applied nutrient (kg ha^{-1}).

Table 1 Initial soil properties of degraded fields compared with poor fields and former kraals used for experimentation by landscape positions in the study villages[a].

Village/ landscape position	pH (H_20)	SOC	Tot N	Ext. P	Exc.K	Exc. Ca	Exc. Mg	CEC	Tot P	Sand	Clay	Silt
		(%)	(%)	(mg kg^{-1})	($cmol_c$ kg^{-1})					(%)		
Chelekura												
Degraded fields (*n* =10)												
Upper	6.2	0.59	0.06	4.7	0.30	2.5	0.7	3.2	0.01	69	20	11
Middle	6.1	0.55	0.06	6.2	0.26	2.4	0.6	3.9	0.01	70	18	12
SED	0.29	0.08	0.01	1.7	0.07	0.7	0.1	0.9	0.002	3	3	1
Poor fields (n=14)												
Upper	***6.5***	***0.67***	***0.08***	***4.5***	***0.55***	***2.7***	***0.66***	***5.4***	***0.02***	***68***	***25***	***7***
Middle	***6.2***	***0.63***	***0.07***	***9.10***	***0.34***	***2.4***	***0.75***	***3.8***	***0.01***	***67***	***24***	***9***
Degraded fields (*n* =10)												
Onamudian												
Upper	5.3	0.90	0.11	4.56	0.30	2.04	0.86	8.6	0.03	60	27	13
Middle	6.3	0.81	0.09	7.13	0.41	2.74	1.19	6.6	0.02	69	20	11
SED	0.3	0.21	0.02	1.01	0.15	0.64	0.32	1.6	0.01	5	4	2
Poor fields (n=14)												
Upper	***5.7***	***0.95***	***0.11***	***5.6***	***0.58***	***1.93***	***0.87***	***9.05***	***0.04***	***60***	***26***	***14***
Middle	***6.0***	***1.02***	***0.11***	***3.8***	***0.39***	***2.95***	***1.41***	***8.35***	***0.03***	***65***	***22***	***13***
SED (Village)	0.21*	0.11*	0.01*	1.00	0.08	0.48	0.17***	0.98**	0.003*	3	3	1
Former kraals (*n* = 10)												
Chelekura												
Upper	7.2	1.7	0.15	14	0.8	4.5	1.2	7.5	0.03	67	22	10
Middle	7.3	1.6	0.16	18	1.1	5.2	1.3	8.4	0.04	65	23	11
SED	0.32	0.39	0.03	3.9	0.2	0.9	0.11	1.3	0.01	3.8	3.1	1
Onamudian												
Upper	6.6	2.1	0.20	24	0.7	5.4	2.0	12.0	0.06	59	26	15
Middle	6.7	2.4	0.23	21	0.8	5.1	1.70	11.2	0.05	66	25	9
SED	0.4	0.34	0.04	6.2	0.16	1.6	0.22	1.40	0.02	2.6*	1.95	1.5
SED (Village)	0.24*	0.25*	0.03*	3.5	0.13	0.88	0.13***	0.89**	0.01*	2.5	1.71	1.4

[a] Poor fields were also identified by farmers (Ebanyat et al., 2009); Significance: * $P<0.05$; ** $P<0.01$; ***$P<0.001$

Statistical analysis was performed using the linear mixed effects models of the Genstat 11.1 statistical package for field experiments with the fixed model term: Constant + Landscape position + Treatment + Season + Landscape position × Treatment + Landscape position × Season + Treatment × Season + Landscape position × Treatment × Season, and the random term: Farm + Farm × Plot. Analysis was only conducted on data from 16 of the 20 farms because several plots were destroyed by livestock. Only data for the two seasons of 2006 are used in the analysis. For the greenhouse limiting-nutrient pot experiment, a two way analysis of variance was conducted on millet biomass and the factors compared were soils and nutrient application.

5.2 Results

5.2.1 Soil and manure quality

Initial soil quality of degraded fields selected by farmers differed significantly in pH, SOC, total N, exchangeable Mg, CEC and total P between sites but not between landscape positions (Table 1). In both sites, the fields were moderately acidic and poor in extractable P (<10 mg kg^{-1}). Compared with poor fields, the degraded fields generally had a lower pH and contained less SOC, total N, Exc. K, Exc. Mg, and CEC in both villages. The silt fraction in degraded fields was larger than in poor fields in Chelekura village, and caused surface crusting. The former kraals differed significantly between sites in pH, SOC, total N, exchangeable Mg, CEC and total P, but were richer reflecting niches of good soil fertility. Manure quality varied between sites and seasons, and was poor in carbon (Table 2). The narrow C: N ratio (8-11) implies that manure used in both study sites was well-decomposed.

5.2.2 Finger millet yield, nutrient uptake and nutrient use efficiencies

Analysis of yield, nutrient uptake and physiological efficiencies data showed significant ($P<0.001$) differences between sites thus further analysis was conducted by site to assess landscape position, treatment, season and their interaction effects.

Seasonal variations

The relationship between inherent soil fertility, rates of fertilizer and yield was investigated with the aid of three-quadrant diagrams (Wit, 1992). With this procedure fertiliser application and yield responses (quadrant i) are split into the relationships between total nutrient uptake and yield (quadrant ii) and between fertiliser rates and total nutrient uptake (quadrant iii), for N (Figure 2) and P (Figure 3). These relationships were plotted for the grain yield of finger millet for treatments applied to degraded fields during seasons 2006A and 2006B by landscape position. Yield responses are related to nutrient uptake, which was influenced by

Table 2 Chemical properties of cattle manure used in the experiments.

Site/Season	pH	Tot C (%)	Tot N (%)	Total P (%)	Total K (%)	Total Ca (%)	Total Mg (%)	C/N ratio
Chelekura								
2005B	8.0	5.24	0.55	0.15	0.57	0.56	0.14	10
2006B	9.5	7.99	0.71	0.26	0.94	0.62	0.19	11
Onamudian								
2005B	7.5	8.31	1.09	0.39	0.85	1.24	0.49	8
2006B	7.0	5.61	0.70	0.28	0.52	0.60	0.17	8

the apparent nutrient recovery. Apparent nutrient recoveries were also determined by the indigenous nutrient supply by the soils and varied between seasons.

The indigenous supply of N was larger in both seasons in the upper than middle position with 19 kg N ha^{-1} and 13 kg N ha^{-1} (2006A) and 15 kg N ha^{-1} and 8 kg N ha^{-1} (2006B) in Chelekura village. In Onamudian, the indigenous supply of N was larger in the upper landscape position (21 kg N ha^{-1}) than the middle position (13 kg N ha^{-1}) in 2006A. Indigenous supply of N however declined in the upper landscape position (11 kg N ha^{-1}) but remained the same in the middle landscape position (13 kg N ha^{-1}) in the 2006B season. Apparent N recoveries (ANR) were less than 25 % for both the N-only treatments and manure +N treatments on both landscape positions in Chelekura village in each of the seasons. In Onamudian only a few cases did it approach 40%. These low recoveries contributed to small total N uptake which in turn determined the generally rather flat yield response curves in both villages (Quadrant (i)). The responses in 2006A are due to nutrient application in 2005B and those for 2006B are due to nutrient application that season, plus any residual effect of P that was applied earlier. Application of manure with N occasionally gave slight increases in ANR, which was reflected in responses in N uptake and yield signifying an additive benefit from manure application, especially in the 2006A season.

The indigenous P supply was higher in 2006A than 2006B season for both landscape positions (Figure 3). In Chelekura village, indigenous P supply in the upper position (1.79 kg P ha^{-1}) was larger than in the middle position (1.59 kg P ha^{-1}) in 2006A and 1.61 kg P ha^{-1} in the upper position and 1.34 kg P ha^{-1} in the middle position in 2006B. Because of larger total P reserves, indigenous P supply in Onamudian village was larger than in Chelekura village: 1.93 kg P ha^{-1} (upper position) and 1.58 kg P ha^{-1} (middle position) in 2006A and 1.67 kg P ha^{-1} (upper position) and 1.70 kg P ha^{-1} (middle position) in 2006B. Apparent P recoveries (APR) were also small and usually less than 25% for both the P only and N+P treatments. P uptake was higher in N+P treatments than sole application of P in both study villages, implying that N and P were limiting in both sites. Yield responses were higher in 2006A than 2006B.

Across season analysis

Average straw and grain yield significantly differed between treatments but not between landscape positions in Chelekura village (Table 3). Yield ranged from 1024 kg ha^{-1} to 2322 kg ha^{-1}and 400 to 1069 kg ha^{-1} for straw and grain respectively. N uptake was significantly (*P*<0.05) larger on the upper than middle landscape position. It also differed significantly (*P*<0.001) between treatments with the greatest uptake usually obtained from the N+P treatments. The average N uptake ranged from 10 to 27 kg ha^{-1}. Average P uptake also differed significantly (*P*<0.001) between treatments. Treatments that received P fertiliser generally resulted in significantly larger P uptake compared with the control. Only physiological P efficiencies differed significantly (*P*<0.001) between treatments and by treatment × landscape position and ranged from 181 to 285 kg kg^{-1}.

Trends in average responses of yield, uptake and physiological efficiencies in Onamudian village (Table 4) were similar to those in Chelekura with some minor differences. Grain yield was significantly (*P*<0.05) larger on the upper than the middle landscape position. The yields in Onamudian village were greater than those in Chelekura village. N uptake was not significantly different between landscape positions but physiological N efficiencies differed significantly (*P*<0.001) between treatments and ranged from 32 to 58 kg ha^{-1}. Agronomic efficiencies (AE), apparent N recovery fractions (ANR) and apparent P recovery fractions (APR) of N, P and manure +N applied to degraded fields were generally poor (Table 5). In Chelekura village AE ranged from -0.23 to 5.94 kg grain yield per kg of N, and 1.72 to 8.27 kg grain yield per kg of P. The range for ANR was 0.03- 0.26 kg kg^{-1} and for APR from 0.01 to 0.22 kg kg^{-1}. The values for these indices were comparatively higher in Onamudian village: AE ranged from 1.4 to 14 kg grain yield per kg of N, and 2.6 to 19.4 kg grain yield per kg of P. Ranges for ANR and APR were 0.10- 0.41 and 0.02- 0.09 kg kg^{-1} respectively

Within-farm yield differences

Across application rates, grain yield responses to application of N, P, manure, manure +N, and N + P treatments on degraded fields were variable but yields were increased above the control treatment (Figure 4). Responses were larger in Onamudian than Chelekura village although in both villages yields obtained with fertilizers were always less than those on the former kraal sites. In Chelekura village all treatments produced yields less than 1000 kg ha^{-1} and in Onamudian village, only manure +N (1036 kg ha^{-1}) and N+P (1171 kg ha^{-1}) produced yields greater than 1000 kg ha^{-1}. The trend in yield responses relative to the control were: manure (0.21) < P (0.45) < N (0.47) < manure +N (0.62) < N+P (0.88) in Chelekura and (0.43) < N (0.64) < P (0.70) < manure +N (0.87) < N+P (1.11) in Onamudian village. Treatment application to degraded fields resulted in closing of gaps in grain yields between former kraals and the control treatment (1532 kg ha^{-1}) by 6 % (manure) to 24% (N+P) in Chelekura village and in Onamudian village (1442 kg ha^{-1}) by 16% (manure) to 43% (N+P).

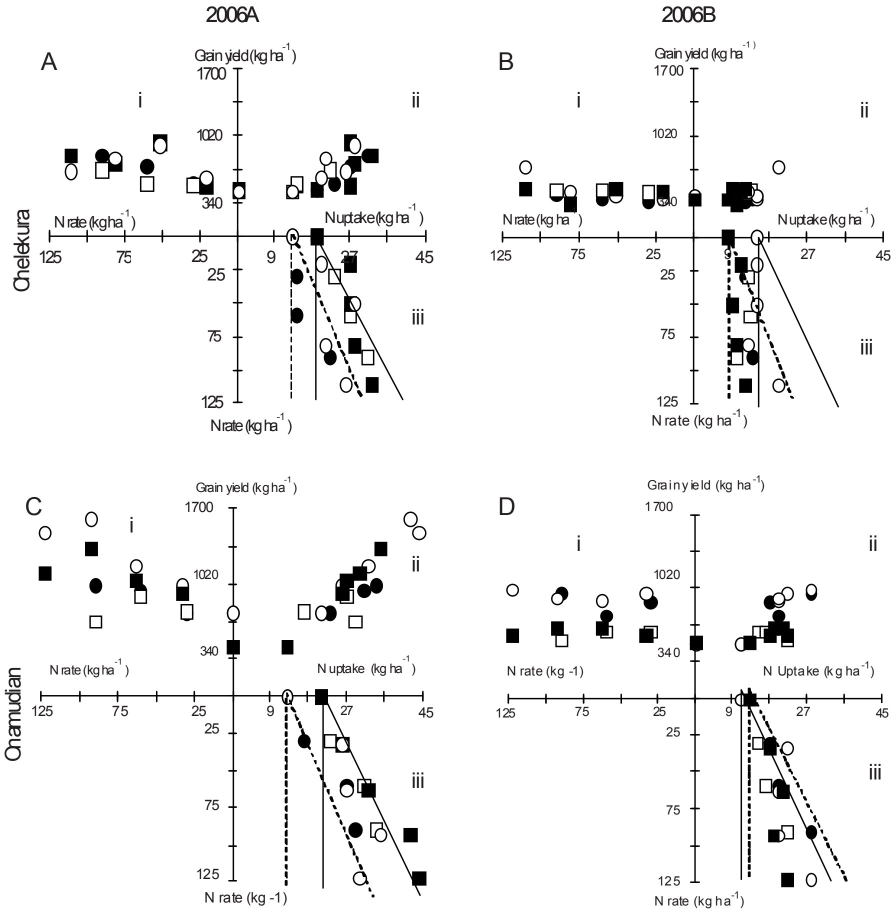

Figure 2 Three-quadrant diagrams showing relationships between N application, N uptake and grain yield of finger millet; (i) Yield against fertiliser rate (fertiliser use efficiency), (ii) Yield against N uptake (Physiological N use efficiency), (iii) N uptake against fertiliser application rate (Fertilizer Recovery) in degraded fields located on the upper and middle landscape positions in Chelekura (A and B) and Onamudian (C and D) village during seasons 2006A (A and C) and 2006B (B and D).(□) = N alone, upper landscape position; (■) = manure (3 t ha^{-1}) + N, upper landscape position; (●) = Nitrogen alone, middle landscape position; and (○) = manure (3 t ha^{-1}) + N, middle landscape position. Areas under bold (   ) and dotted lines (------) respectively represent ANR under 25% in the upper and middle landscape positions respectively.

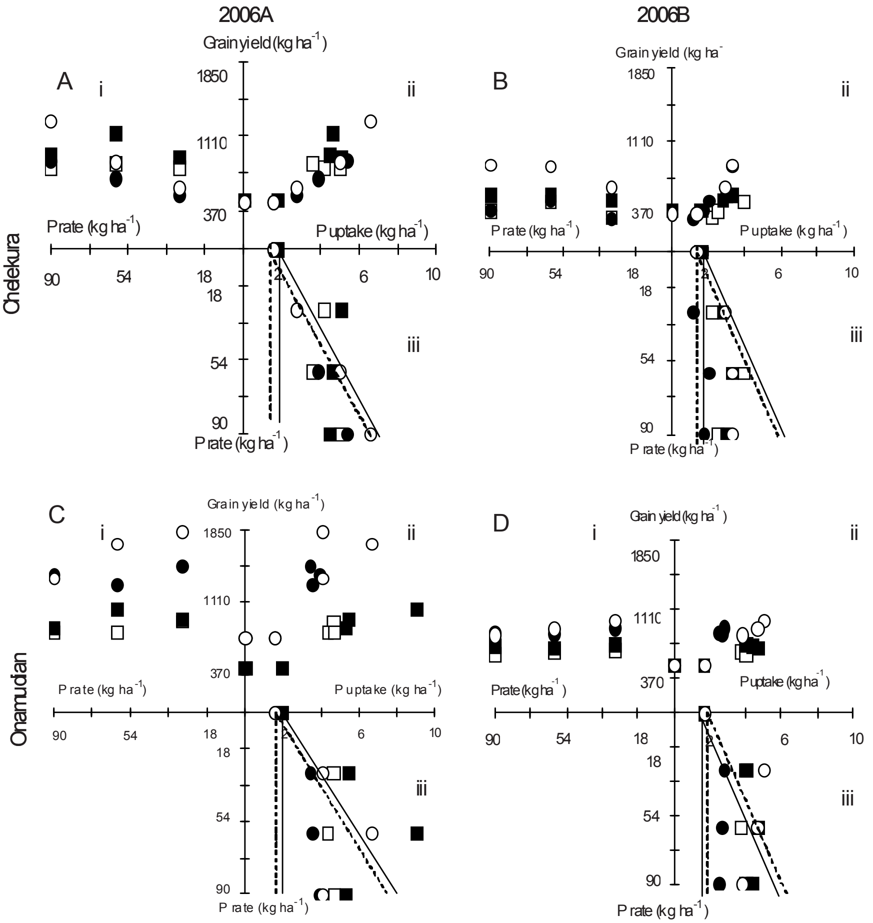

Figure 3 Three-quadrant diagrams showing relationships between P application, P uptake and grain yield of finger millet; (i) Yield against fertiliser P rate (fertiliser use efficiency), (ii) Yield against P uptake (Physiological P use efficiency), (iii) P uptake against fertiliser application rate (Fertilizer Recovery) in degraded fields located on the upper and middle landscape positions in Chelekura (A and B) and Onamudian (C and D) village during seasons 2006A (A and C) and 2006B (B and D). (□) = P alone, upper landscape position; (■) = N+P, upper landscape position; (●) = Nitrogen alone, middle landscape position; and (○) = N + P, middle landscape position. Areas under bold (   ) and dotted lines (-----) respectively represent ANR under 25% in the upper and middle landscape positions respectively.

Table 3 Average straw yield, grain yield, total nutrient uptake and internal nutrient use efficiencies of finger millet as affected by application of nutrient inputs to degraded fields on the upper and middle landscape positions in Chelekura village, 2 seasons of 2006.

	Upper						Middle					
	Straw	Grain	N Uptake	P uptake	PhE*N*	PhE*P*	Straw	Grain	N Uptake	P uptake	PhE*N*	PhE*P*
Treatment	kg ha^{-1}				kg kg^{-1}		kg ha^{-1}				kg kg^{-1}	
Control	1043	443	17	1.7	28	276	1024	418	10	1.5	43	285
30N	1305	441	18	2.6	26	194	1147	493	13	2.1	37	254
60N	1341	550	21	2.4	28	251	1193	404	14	1.5	35	263
90N	1649	625	23	3.0	28	228	1172	576	16	2.4	42	265
30P	1212	571	16	3.2	33	205	1425	679	18	3.5	42	234
60P	1268	668	15	3.4	52	223	1185	600	17	2.9	37	217
90P	1251	598	18	3.6	33	192	1408	646	18	3.5	35	202
Manure	1255	552	21	3.5	36	251	1065	462	15	2.8	30	239
M+30N	1510	685	21	3.4	33	235	1175	709	19	3.5	45	223
M+60N	1650	783	23	2.6	28	237	1536	628	17	2.1	37	229
M+90N	2012	766	26	4.1	33	240	1850	569	23	2.2	24	256
30N+30P	1516	715	21	3.9	34	211	1240	625	16	3.6	40	181
60N+60P	2109	854	27	4.0	33	252	1633	858	23	4.1	38	217
90N+90P	2322	749	25	3.7	34	228	1846	1069	26	4.9	40	227
SED												
LP	330ns	156ns	3.2*	0.8ns	7ns	6ns						
TRT	427***	201**	3.3***	1.1***	9ns	29***						
LP*TRT	380ns	180ns	3.2ns	0.9ns	8ns	18***						

PhE*N* = physiological efficiency of nitrogen; PhE*P* = physiological efficiency of phosphorus
SED = Standard error of difference; LP = Landscape position; TRT = Treatment;
Significance: ns = not significant; * $P<0.05$; ** $P<0.01$*** $P<0.001$

Table 4 Average straw yield, grain yield, total nutrient uptake and internal nutrient use efficiencies of finger millet as affected by application of nutrient inputs to degraded fields on the upper and middle landscape positions in Onamudian village, 2 seasons of 2006.

	Upper						Middle					
	Straw	Grain	N Uptake	P uptake	PhE*N*	PhE*P*	Straw	Grain	N Uptake	P uptake	PhE*N*	PhE*P*
Treatment	kg ha^{-1}				kg kg^{-1}		kg ha^{-1}				kg kg^{-1}	
Control	1055	620	15	1.8	44	262	823	482	13	1.6	39	250
30N	1381	826	20	3.0	41	217	889	695	16	2.9	44	211
60N	1639	867	26	3.2	34	198	1524	766	22	3.5	37	156
90N	1863	987	31	3.6	32	200	2044	605	26	2.5	24	118
30P	1658	1202	23	4.4	53	235	1174	798	19	3.1	45	214
60P	1938	1077	23	4.0	50	200	2044	734	23	3.1	34	154
90P	2053	1131	27	4.3	44	190	1387	717	20	3.2	38	167
Manure	1598	993	24	3.7	42	230	1417	790	24	3.7	34	159
M+30N	1564	1037	26	3.7	41	233	1778	820	26	4.1	39	188
M+60N	2107	1293	31	5.4	45	198	1413	858	22	4.1	36	150
M+90N	2374	1241	36	5.8	35	154	1776	1001	26	4.4	32	121
30N+30P	2154	1405	27	4.7	57	231	1544	839	17	4.7	57	128
60N+60P	2527	1889	37	8.2	56	157	2023	1051	21	8.2	56	124
90N+90P	2803	1102	32	4.4	39	151	1776	793	21	4.4	46	122
SED												
LP	347ns	153*	3.8 ns	0.59ns	4.0ns	25**						
TRT	453***	195***	4.5***	0.76***	4.3***	26***						
LP*TRT	401ns	175ns	4.2ns	0.68*	4.29ns	26ns						

PhE*N* = physiological nitrogen efficiency; PhE*P* = physiological phosphorus efficiency
SED= Standard error of difference of means; LP = Landscape position; TRT = Treatment
Significance: ns = not significant; * $P<0.05$; ** $P<0.01$;*** $P<0.001$

Table 5 Average grain yield, N and P uptake, agronomic efficiencies (AE), apparent N recovery (ANR) and apparent P recovery fractions (APR) for different treatments on the upper and middle landscape positions in the study villages [1].

Village/treatment	Upper						Middle					
	Grain yield	N uptake	P uptake	AE	ANR	APR	Grain yield	N uptake	P uptake	AE	ANR	APR
	(kg ha^{-1})			kg kg^{-1}			(kg ha^{-1})			kg kg^{-1}		
Chelekura												
Control	443	17	1.7				418	10	1.5			
30N	441	18	2.6	-0.07	0.03	-	493	13	2.1	2.50	0.10	-
60N	550	21	2.4	1.78	0.07	-	404	14	1.5	-0.23	0.07	-
90N	625	23	3	2.02	0.07	-	576	16	2.4	1.76	0.07	-
30P	571	16	3.2	4.27	-	0.05	679	18	3.5	8.70	-	0.07
60P	668	15	3.4	3.75	-	0.03	600	17	2.9	3.03	-	0.02
90P	598	18	3.6	1.72	-	0.02	646	18	3.5	2.53	-	0.02
Manure	552	21	3.5	5.74	0.21	0.30	462	15	2.8	2.32	0.26	0.22
M+30N	685	21	3.4	4.94	0.08	0.05	709	19	3.5	5.94	0.18	0.06
M+60N	783	23	2.6	4.30	0.08	0.01	628	17	2.1	2.66	0.09	0.01
M+90N	766	26	4.1	2.96	0.08	0.03	569	23	2.2	1.39	0.12	0.01
Onamudian												
Control	620	15	1.8				482	13	1.6			
30N	826	20	3	6.9	0.17	-	695	16	2.9	7.1	0.10	-
60N	867	26	3.2	4.1	0.18	-	766	22	3.5	4.7	0.15	-
90N	987	31	3.6	4.1	0.18	-	605	26	2.5	1.4	0.14	-
30P	1202	23	4.4	19.4	-	0.09	798	19	3.1	10.5	-	0.05
60P	1077	23	4	7.6	-	0.04	734	23	3.1	4.2	-	0.03
90P	1131	27	4.3	5.7	-	0.03	717	20	3.2	2.6	-	0.02
Manure	993	24	3.7	13.8	0.33	0.07	790	24	3.7	11.4	0.41	0.08
M+30N	1037	26	3.7	7.3	0.19	0.03	820	26	4.1	5.9	0.23	0.04
M+60N	1293	31	5.4	7.7	0.18	0.04	858	22	4.1	4.3	0.10	0.03
M+90N	1241	36	5.8	5.3	0.18	0.03	1001	26	4.4	4.4	0.11	0.02

[1] Agronomic efficiency = (yield treatment- yield control)/amount nutrient applied; ANR = (N uptake treatment- N uptake control)/Amount of nitrogen applied; APR = (P uptake treatment- P uptake control)/Amount of P applied. Amount of N and P in manure is computed based on % N and P in manure, see Table 2).

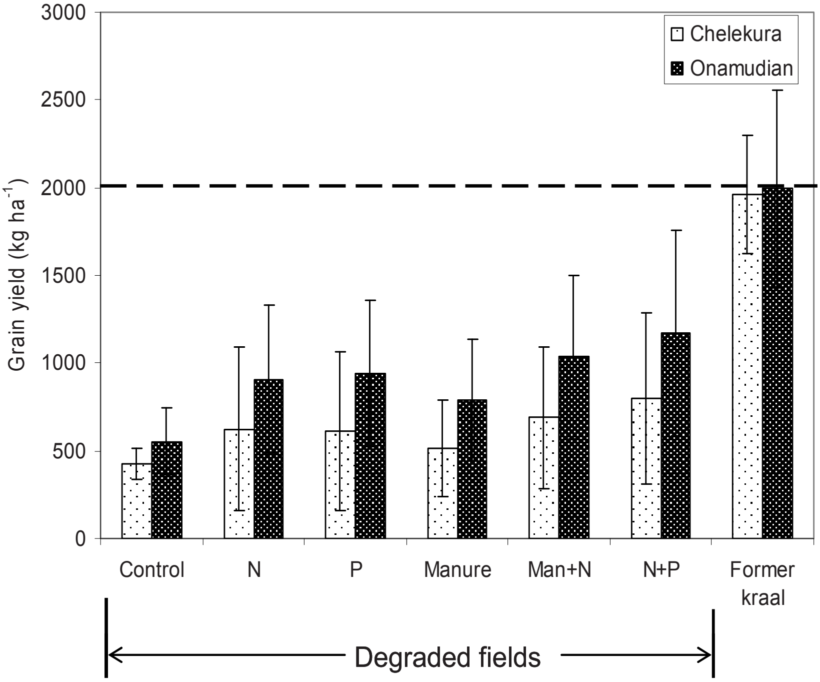

Figure 4 Average responses of finger millet grain yields per applied treatment on degraded fields in comparison with the former kraal sites in the study villages, 2006. Bars are standard deviations.

Overall, grain yield responded more strongly to N+P application than to sole applications of either N or P implying that both nutrients are limiting on both sites.

5.2.2 Other limiting nutrients

In the pot experiment conducted to explore whether nutrients other than N and P were limiting crop response in the field experiments (Figure 5), N alone significantly increased biomass yields of finger millet in degraded soils from Onamudian but not in the soils from Chelekura. When N and P were applied together, shoot growth increased much more strongly in soils from Chelekura and the increase in growth was doubled on Onamudian soils compared with the sole nutrients. Addition of K, together with N and P significantly increased growth above the N+P treatment only in the soil from Onamudian. Adding sulphur increased plant growth only in the soil from Chelekura. Based on total biomass production, it appears that multiple nutrients limit productivity of millet on the degraded fields but that plant growth response depended on the interactions of N × P × S in Chelekura and N × P × K in Onamudian village.

Adding other cations (Ca and Mg) or other micronutrients did not result in significant increases in biomass; to the contrary they tended to give slightly depressed biomass yields.

5.3 Discussion

Although biomass production and yield of finger millet responded strongly when both N and P were supplied, in no case did yields match those found when finger millet was grown on sites where kraals had been situated in the past. These former kraal sites are areas where manure has been accumulated over long periods of time through night corralling of cattle, though none of the sites where the experiments were situated had been used by cattle in the previous five years. Persistence of good fertility in soils for at least four decades where kraals were formerly located has been reported from East Africa (Augustine, 2003).

The seasonal differences in millet yield response were strongly influenced by rainfall. No yield was obtained in the first season (2005B) due to drought. Yield and growth response in the subsequent season 2006A was dependent on nutrients applied as fertilizer and manure in the poor season (2005B), and thus observed variability in responses in 2006A may have been due to variability in nutrient losses. Although fertilizers and manure were applied again in the 2006B season, excessive rainfall (Figure 1) is likely to have caused substantial losses of N. Despite the excessive rainfall, strong responses in growth and yield of finger millet to combined applications of N and P were observed in both 2006 seasons, though yields obtained were often only half those observed in the former kraal sites.

Soils differed between the two villages: the soils in Onamudian had greater silt + clay content (36%; sandy loam) than for those in Chelekura (31%; sandy clay loam). Silt + clay determine organic carbon storage through influencing physical protection of soil organic matter (Feller and Beare, 1997). In turn, these properties determine the capacity of soils to retain and supply cations. The soils in the former kraal sites had twice to three times as much SOC compared with the degraded fields in each of the landscape positions of each village. Variations in soil quality of former kraals between villages were also equally influenced by the differences in % silt + clay of the soils, but could also vary due to different amounts of manure previously accumulated in those sites.

Multiple nutrient deficiencies of N, P, Ca and Zn were reported to constrain rehabilitation of productivity on degraded sandy soils in Zimbabwe (Zingore et al., 2008). The limiting nutrient experiment that we conducted in pots showed that S and K were additionally limiting millet growth in soils from Pallisa (Figure 5). We had expected that treatments where manure was added would have supplied other nutrients such as K, S and micronutrients, but it seems that manure was unable to provide sufficient quantities of these nutrients in the short-term. In field experiments in Zimbabwe, responses in growth and yield of maize to old kraal manure were seen only in the third year after application (Nyamangara et al., 2005; Zingore et al., 2007). We further observed yield declines when P was applied at rates above 60 kg P ha^{-1} that may be associated with Zn-P antagonism arising from precipitation of zinc phosphate (Marschner, 1995). Soil organic matter also determines the physical properties of soils. The soils in the area are prone to surface sealing and often crusts are observed following rain events. Enhanced soil organic matter contents can improve the water balance in the degraded fields by reducing the susceptibility to crusting and enhancing infiltration. The good productivity of finger millet on the former kraal sites could be attributed to the beneficial effects of manure on many aspects of soil fertility: improving structure, moisture availability, nutrient availability including micronutrient supply and biological activity which can enhance nutrient cycling.

It is noteworthy that the conditions created in soils at former kraals arise from long-term accumulation of manure. To improve the conditions in the degraded fields will therefore require substantial time and large applications of manure. The quantities of manure available in this region are limited and difficult to increase - the smallholder farmers lack grazing land to feed cattle producing manure (Ebanyat et al., 2009) which means that more cattle cannot be supported in the area. Fertiliser use and recovery efficiencies were low probably because of the low SOC in the degraded fields and other losses. Rehabilitation of the degraded fields will require building up of organic matter to thresholds that can enhance fertiliser use efficiencies (Tittonell et al., 2007) but it is unclear how the required amounts of organic matter can be sourced or created.

Attention to balanced crop nutrition, ensuring that fertilisers supply all of the necessary nutrients for crop growth may give sufficient crop residues which, if returned to the soil may contribute to increase soil organic matter contents. Our results indicate that the declaration of the African Fertilizer Summit made in Abuja 2006 to aim for farmers to use 50 kg of fertiliser per ha needs careful consideration because it will not yield much unless degraded fields are first rehabilitated. Responses of finger millet differed between sites with fields in the Chelekura site being less responsive compared with Onamudian because of the initial soil quality. The degraded fields in Onamudian had larger amounts of SOC compared with Chelekura (Table 1). Different amounts of inputs are required to raise productivity of fields in these two different villages reiterating the need for site specific nutrient management and that such blanket fertilizer recommendations are inappropriate. Our experiments over three seasons yielded reasonable responses to fertilisers and manure and from the knowledge that the process of rehabilitation takes time, dynamic modelling may help in designing strategies for intensification (e.g. Tittonell et al., 2008). Further experimentation is required to determine the quantities of organic manure and nutrients needed and the period it may take to restore fertility. Further field experiments are needed to assess the effects of application of all the limiting nutrients, including S, K and micronutrients on millet yield in the degraded fields.

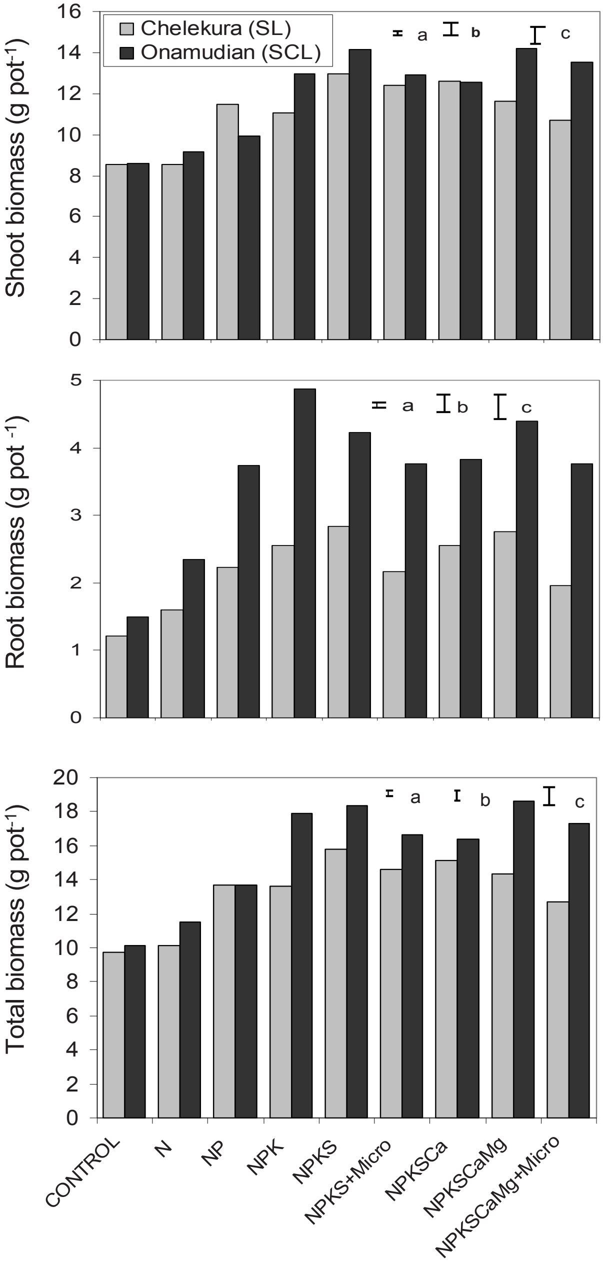

Figure 5 Millet biomass response on soils from study villages amended with macro and micronutrients in a green house pot experiment over 8 weeks of growth. Bars are standard errors of difference: a = soil type (village); b = treatment; c = soil type x treatment.

5.4 Conclusions

Although growth and grain yield of finger millet in degraded soils were increased strongly by application of fertiliser and manure, none of the treatments could completely close the difference in yields obtained on sites of former kraals. The short-term nature of the experimentation, covering only three seasons, was insufficient to restore fertility of these degraded soils, even where cattle manure was applied in farmer's fields. The amounts of manure accumulated in former kraal sites were very large compared with the amounts added in the experiments, and probably insufficient to address the multiple nutrient limitations of S and K. Combined application of N+P fertilizer gave the strongest yield response compared with other options, but the strength of the crop response was variable with season, soil type and to a less extent, landscape position. Management aimed at increasing nutrient recovery efficiencies will need to accompany technological interventions to enhance sustainability. Thus combining organic and inorganic resources (integrated nutrient management) because of their complementary benefits could lead to improved productivity of the degraded fields. Repeated applications of manure would be required to increase soil organic matter contents sufficiently to assist in improving capture (infiltration) and storage of water. The scarcity of manure in the area, due to the small number of cattle and the lack of grazing land, means that other means to restore soil organic matter contents of the soils and supply of other limiting nutrients must be sought.

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Chapter 6

Site specific nutrient management for finger millet (*Eleusine coracana* (L.) Gaertn) using a modelling approach [†]

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Abstract

Heterogeneity in soil fertility across smallholder farms in sub-Saharan Africa renders blanket recommendations of limited value. The Quantitative Evaluation of Fertility of Tropical Soils (QUEFTS) model was calibrated for finger millet to explore the potential of this approach to develop site-specific nutrient management recommendations. Fertiliser response data from experiments conducted in eastern Uganda over 3 seasons were used to determine the model constants (kg grain kg^{-1}) respectively for maximum accumulation (a) and maximum dilution (d) of 21 and 53 kg grain kg^{-1} N, 76 and 261 kg grain kg^{-1} P and 11 and 46 kg grain kg^{-1} K. The relationship between observed and model-predicted yield was good (r^2 = 0.76; RMSD = 262 kg ha^{-1}). Balanced fertilisation requirements for a target millet yield of 2000 kg ha^{-1} were estimated at 83 kg N ha^{-1}, 52 kg P ha^{-1} and 56 kg K ha^{-1} for the sandy loam soils of Chelekura village and 64 kg N ha^{-1}, 31 kg P ha^{-1} and 40 kg K ha^{-1} for the sandy clay loam soils in Onamudian village. In degraded fields, other nutrient limitations besides N, P and K and soil physical aspects restricted nutrient uptake and hence resulted in prediction of yields above those which are obtained when finger millet is reliant on soil nutrient supply and N-P-K fertiliser.

Key words: *Integrated nutrient management; Heterogeneity in soil fertility; QUEFTS; fertiliser requirements; yield gap; Uganda; sub-Saharan Africa*

6.0 Introduction

Although listed amongst the lost crops of Africa, finger millet (*Eleusine coracana* (L.) Gaertn)) has superior nutritional value compared with the commonly-consumed cereals i.e. wheat, rice and maize (NRC, 1996). The growing demand for the crop in East Africa now exceeds supply and is attracting research focus to increase its productivity (Mgonja et al., 2007). In Uganda, finger millet is the second most important cereal crop after maize and is grown in northern, western and eastern regions of the country for food and to sell (Oryokot, 2001).

Despite its importance in the livelihoods of smallholders, finger millet yields are small, often less than 500 kg ha^{-1} and constrained by poor soil fertility and shortage of labour in eastern Uganda (Tenywa et al., 1999). Little is known about fertiliser nutrient requirements of the crop. Wide gaps ranging from 450 to 2500 kg ha^{-1} between on-station and on-farm yields of finger millet have been reported (Tenywa et al., 1999). Within farms, heterogeneity in soil fertility also contributes to yield variability and yield differences ranging from 1000 to 1500 kg ha^{-1} have been observed between good soil fertility niches (former cattle kraal sites) and fields of poor fertility in eastern Uganda (Ebanyat et al., 2009). Such heterogeneity in soil fertility needs to be considered to make efficient use of inputs through deriving site-specific nutrient management recommendations for improvement of millet productivity.

In the Teso farming system in eastern Uganda, N and P are the major nutrients limiting millet production (Tenywa et al., 1999; Nyende, 2001). Fertiliser recommendations that consider the interaction between these nutrients are necessary to support farmer management. The quantitative evaluation of fertility of tropical soils (QUEFTS) is a modelling approach that considers soil nutrient availability and major nutrient interactions to predict crop yield (Janssen et al., 1990). The generic model was developed initially to predict maize response to soil fertility in Kenya (Smaling and Janssen, 1993). QUEFTS uses an empirical approach to estimate crop yield based on measurements of the nutrients available from soil, nutrients from fertiliser added and the cultivar-specific potential yield under given environmental conditions. Further, the approach considers interactions of the major nutrients N, P and K in determining yield and differs in this aspect with the single nutrient-yield response approaches commonly used. Beyond estimating yields, fertiliser requirements and economic benefits of fertiliser use can also be estimated. The usefulness of the QUEFTS approach has been demonstrated by the large number of applications and adaptations that have been made for different crops (e.g. rice, wheat, pearl millet) in tropical and subtropical environments (Witt et al., 1999; Haefele et al., 2003; Samaké, 2003; Liu et al., 2006; Das et al., 2008; Tittonell et al., 2008a). QUEFTS had not been calibrated for finger millet and we undertook this with the aim of deriving site-specific recommendations for millet production. Our specific objectives were: (i) to determine the physiological model parameters for finger millet; (ii) to assess the relationships between soil analytical data and the soil supplies of available N, P and K; (iii) to estimate fertiliser requirements for finger millet production with balanced application of nutrients at target yield specified by niches with high soil fertility within the farming system; and (iv) to predict finger millet yield response to application of N and P fertilisers on nutrient-depleted fields.

6.1 Materials and Methods

6.1.1 Data used

Data used for calibration came from field experiments conducted in Chelekura village, Chelekura Parish (1°17′N; 33°30′E) and Onamudian village, Akadot parish (1°11′N; 33°43′E) in Pallisa district (1°09′N; 33°48′E), eastern Uganda to determine yield response of finger millet grown on nutrient-depleted fields to application of fertilisers and manure. The yield responses in the degraded fields were compared with millet yields on benchmark sites with highly fertile soils (former cattle kraals). Fields used for the experiments were selected based on farmer's local knowledge of fertility of their own fields. Surface soils were collected from 20 fields at depth of 0–20 cm, air dried, sieved through 2 mm and analysed for pH, SOC, Total N, CEC and particle size distribution at the ICRAF laboratory Nairobi using methods described by Shepherd and Walsh (2002). Extractable P was determined by wet chemistry analysis using the modified Olsen method (Anderson and Ingram, 1993) at Kawanda National Agricultural Research Laboratories Institute in Uganda. N and P fertiliser response experiments with 3 × 3 m plots were conducted on degraded fields located on both the upper and middle landscape positions in each village. Treatments were N and P alone at rates of 0, 30, 60, 90 kg ha^{-1}, N combined with P each at same rates (i.e. N30+P30; N60+P60, N90+ P90 kg ha^{-1}), and manure at 3 t ha^{-1} combined with N at the each of the above specified rates. Neither fertiliser nor manure was applied to plots on the former kraals. Finger millet variety SEREM 2 was the test crop and recommended agronomic practices were followed in its production. At maturity of finger millet in each season, dry weights of grain and straw yields were measured. The total N, P and K contents in the grain and straw were determined in digests with H_2SO_4/H_2O_2 with salicylic acid and selenium catalyst (Anderson and Ingram, 1993). The experiments were conducted over three seasons but only data of the two seasons of 2006 from 16 farms could be used in this study because the crop produced no grain yield in the 2005 season due to late-season drought.

6.1.2 The QUEFTS model

To calibrate the QUEFTS model to estimate fertiliser requirements and yield of finger millet a four step process is followed (Janssen et al., 1990):

1. Quantification of the potential indigenous soil supply (uptake under optimum conditions) of available N (SN), P (SP) and K (SK) using soil chemical data or from crop nutrient uptake measured by preference in NPK factorials, or in nutrient-omission trials; the supply of available nutrients from fertilizers and other inputs is found as the product of the quantity and the maximum recovery fraction of the fertiliser nutrient;
2. Estimation of the actual crop uptake of N, P and K (UN, UP and UK, respectively) as a function of the available supply of that nutrient from the soil plus the available supply from nutrient inputs, taking into account the available supplies of the other nutrients;
3. Estimation of N-, P- and K-determined yield ranges as a function of calculated nutrient uptake and a cultivar-specific potential yield (Ymax), considering minimum and maximum physiological efficiencies (yield per unit of nutrient uptake) of N, P and K. These relations between yield and nutrient uptake vary between a maximum value at low nutrient availability (maximum dilution) and a minimum value at maximum yield (maximum accumulation). Sequentially minimum and maximum N, P and K determined yields (YNA: yield at maximum N accumulation, YND: yield at maximum N dilution, etc.) are obtained; and,
4. Yield ranges are combined in pairs (N and P, N and K, P and K); Final yield is obtained by averaging calculated yields of paired nutrients.

6.1.3 QUEFTS Model calibration

Physiological efficiency

Model calibration requires setting of the maximum accumulation (*a*) and maximum dilution (*d*) parameters. These parameters are physiological efficiencies (PhE) or internal efficiencies and are derived as:

$$\mathrm{PhE}\mathit{Nutrient}\ (\mathrm{kg\ kg^{-1}}) = \mathrm{GY/\ TU} \qquad \text{(Equation 1)}$$

Where: GY = economic yield (kg) and TU is the total nutrient uptake (kg) in grain and straw. The parameters were determined for N, P and K for finger millet under the environmental conditions of the study area. The sensitivity of the model to '*a*' and '*d*' parameters was analysed by taking data sets at 5 and 95th, 7.5th and 92.5th, and 10th and 90th percentiles of the estimated values (Witt et al., 1999).

Supplies of available nutrients from soil and fertilizer

Relationships between nutrient uptake and soil supply of available nutrients did not fit well using the default algorithms in the QUEFTS model. Multiple regression analysis between soil available nutrients (indigenous supply) and measured soil variables was conducted to derive

Table 1 Selected soil characteristics of degraded fields and former kraal sites used for experimentation by landscape position per study village in Pallisa district.

Village/ landscape position	pH (H_20)	SOC	Tot N	Olsen P	Exc.K.	CEC	Tot P	Sand	Clay	Silt
		------------%-----------		(mg kg^{-1})	-----($cmol_c$ kg^{-1})------		------------------------------%----------------------------			
Degraded fields										
Chelekura										
Upper	6.2	0.59	0.06	4.7	0.30	3.2	0.01	69	20	11
Middle	6.1	0.55	0.06	6.2	0.26	3.9	0.01	70	18	12
SED (LP)	0.29	0.08	0.01	1.7	0.07	0.9	0.002	3	3	1
Onamudian										
Upper	5.3	0.90	0.11	4.56	0.30	8.6	0.03	60	27	13
Middle	6.3	0.81	0.09	7.13	0.41	6.6	0.02	69	20	11
SED (LP)	0.3	0.21	0.02	1.01	0.15	1.6	0.01	5	4	2
SED (village)	***0.21****	***0.11****	***0.01****	***1.00***	***0.08***	***0.98*****	***0.003****	***3***	***3***	***1***
Former kraals										
Chelekura										
Upper	7.2	1.7	0.15	14	0.8	7.5	0.03	67	22	10
Middle	7.3	1.6	0.16	18	1.1	8.4	0.04	65	23	11
SED (LP)	0.32	0.39	0.03	3.9	0.2	1.3	0.01	3.8	3.1	1
Onamudian										
Upper	6.6	2.1	0.20	24	0.7	12.0	0.06	59	26	15
Middle	6.7	2.4	0.23	21	0.8	11.2	0.05	66	25	9
SED (LP)	0.4	0.34	0.04	6.2	0.16	1.40	0.02	2.6*	1.95	1.5
SED (Village)	***0.24****	***0.25****	***0.03****	***3.5***	***0.13***	***0.89*****	***0.01****	***2.5***	***1.71***	***1.4***

Significance: * $P<0.05$; ** $P<0.01$; *** $P<0.001$

appropriate equations for estimating soil nutrient supply using Genstat statistical package version 11.1. Soil supply of available nutrients (SAv) or indigenous supply were taken as averages of the maximum values obtained from treatments without N (for N) and without P (for P) and N+P treatments for K across the experimental farms in each village. Recovery fractions of applied fertiliser were estimated nutrient uptake differences between N+P and P treatments for N, N+P and N treatments for P divided by the applied rate of the nutrient. Nutrient recoveries from manure were computed as difference between manure + N and N treatments. Nutrients and recovery fractions for fertiliser requirement computations were obtained by taking arbitrarily 95th percentile of all recovery data for each nutrient in each village.

Estimation of fertilizer requirement

Fertiliser requirement for various target yields equal to or less than the given yield potential can be determined from the relationships between nutrient uptake at target yield, physiological efficiency of nutrient use, the nutrient supply from the soil, and recovery efficiencies of applied fertilizers. The yields on the former kraals were used as target yields (≈2000 kg ha^{-1}) to estimate fertiliser requirements to produce the same grain yield obtained on degraded fields (i.e. to eliminate the yield gap between the former kraals and degraded fields). Fertiliser requirements (FR in kg ha^{-1}) for N, P and K based on uptake and fertiliser recovery efficiencies at a target yield have been computed as (Pathak et al., 2003; Liu et al., 2006):

$$FR = (NU_{target} - N_{ind})/MRE \qquad \text{(Equation 2)}$$

We use the symbol SAv (available soil supply) instead of N_{ind} (indigenous nutrient), and calculate NU_{target} as *Y/PhE* where; *Y* is the target yield (kg ha^{-1}); *PhE* physiological nutrient efficiency (kg kg^{-1}). *Y/PhE* is also the same as target uptake (NU_{target} in kg ha^{-1}). MRE is maximum recovery efficiency (kg kg^{-1}).

In reality, however, crops do not take up all of the total supply of nutrients. In case of balanced supplies of N, P and K, the actual uptake is 96% of the supply (Janssen, 2009). Also the yield may be somewhat less than the product of uptake and physiological efficiency. Following Janssen (2009), the relationship between yield (Y) and available nutrient supply (Av) was set at:

$$Y = 0.9 \times Av \times PhE \qquad \text{(Equation 3)}$$

Table 2 Descriptive statistics for yield, nutrient uptake and physiological efficiency data across seasons and sites used for calibration of the QUEFTS model (n = 442).

Variable	Mean	SD	Minimum	Lower quartile	Median	Upper quartile	Maximum
Straw yield (kg ha^{-1})	1711	1046	270	972	1422	2189	5681
Grain yield (kg ha^{-1})	847	535	64	474	683	1030	2918
Harvest index	0.34	0.10	0.04	0.28	0.34	0.40	0.63
Grain N (kg ha^{-1})	10.3	6.8	0.92	5.6	8.2	12.6	35.2
Grain P (kg ha^{-1})	2.0	1.2	0.13	1.1	1.6	2.5	7.4
Grain K (kg ha^{-1})	2.5	1.7	0.22	1.3	2.5	3.0	9.1
Straw N (kg ha^{-1})	13.9	8.7	1.8	7.8	11.2	17.4	51.1
Straw P (kg ha^{-1})	3.8	2.9	0.43	1.8	2.9	4.9	18.8
Straw K (kg ha^{-1})	36	26	4	18	27	45	167
Total N uptake (kg ha^{-1})	24	14	5	14	20	30	85
Total P uptake (kg ha^{-1})	5.8	3.9	1.0	3.1	4.5	7.3	23.9
Total K uptake (kg ha^{-1})	39	29	4	20	29	48	175
Phe*N* (kg kg^{-1})	36	10	4	29	37	42	71
Phe*P* (kg kg^{-1})	161	61	17	115	153	202	379
Phe*K* (kg kg^{-1})	25	12	2	17	23	31	79

n = number of observations; SD = standard deviation; Phe*N* = Physiological efficiency of nitrogen; Phe*P* = Physiological efficiency of phosphorus; Phe*K* = Physiological efficiency of potassium

The available supply (Av) consists of available soil supply (SAv) and available fertilizer supply (FAv), where FAv is FR × MRE. Substituting Av in Equation 3 and expressing it in FR (kg ha^{-1}) results in:

$$FR = (1.11 \times Y/PhE - SAv)/MRE \qquad \text{(Equation 4)}$$

Equations 2 and 4 can be seen as shortcuts of QUEFTS. They are especially useful when supplies of N, P and K are well balanced.

6.2 Results

6.2.1. Soil characteristics of the experimental fields

Characteristics of experimental fields are summarised in Table 1. The degraded fields had medium soil acidity, and were poor in SOC, total N and extractable P, but adequate in exchangeable K. These qualities differed significantly between villages but not between landscape positions within villages. Chemical characteristics of former kraals were significantly better in Onamudian village compared with Chelekura village except in extractable P and exchangeable K. The soils in the study sites were sandy loams in Chelekura and sandy clay loams in Onamudian villages.

6.2.2. QUEFTS Model calibration

Physiological efficiency

Descriptive statistics of crop data used for calibration of the QUEFTS model (Table 2) showed wide variations in measured yields and physiological variables. This was due to the extreme variability in soil fertility which encompassed very poor soils and very fertile soils on former kraal sites. Grain yields ranged from 64 to 2918 kg ha^{-1}. The largest observed yield from a former kraal site is close to the potential yield for the variety used in this environment. The wide range of soil conditions meant that the data was useful for calibration of the QUEFTS model as it encompassed the full range of soil heterogeneity where finger millet is cultivated on smallholder farms in eastern Uganda.

The physiological parameters were derived from grain yield and total nutrient uptake relationships for N, P and K at the 5th and 95th percentiles of physiological efficiencies of each nutrient for '*a*' and '*d*' respectively (Figure 1). The parameters determined for maximum accumulation (*a*) and maximum dilution (*d*) were 21 and 53 kg grain kg^{-1} N, 76 and 261 kg grain kg^{-1} P and 11 and 46 kg grain kg^{-1} K. Yields were calculated with these calibrated values for PhE as a function of the measured uptake, using the procedures of steps 3 and 4 of the QUEFTS Model. The plots of observed yields were made along the Y-axis and the

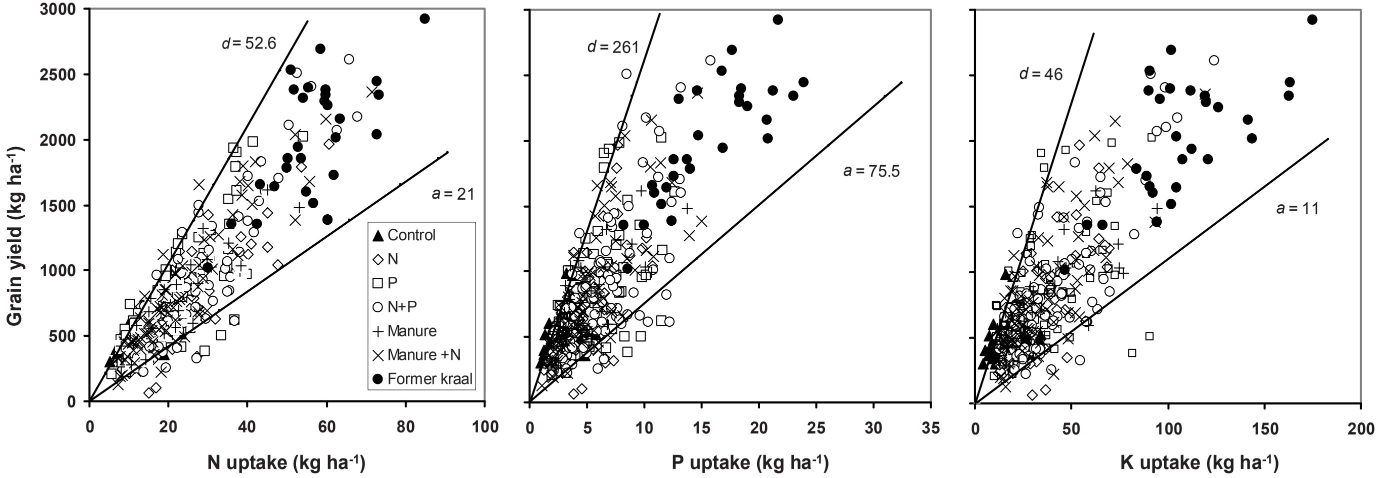

Figure 1 Relationship between finger millet grain yield and uptake of N, P and K. The upper and lower boundaries indicate yields with maximum dilution and maximum accumulation. The slopes '*a*' and '*d*' are physiological efficiencies in Table 4.

calculated yields along the X-axis, as recommended by Piňeirio et al. (2008). The calculated yields slightly overestimated yields as reflected in the regression coefficient of 0.98, but the fit between calculated yields and measured yields was rather good with R^2 =0.76 and root mean squared deviation (RMSD) of 262 kg ha^{-1} (Figure 2A). For sensitivity analysis, two other sets of '*a*' and '*d*' parameters were used. They were derived at 7.5th and 92.5th, and 10th and 90th percentiles, respectively (Table 4). With set II parameter values, the model further overestimated grain yield of finger millet as shown by the regression coefficient of 0.93, and with Set III the overestimation was still larger (regression coefficient of 0.91). Statistically, the Set I values gave the best results.

Supplies of available nutrients from soil and fertilizer

The relationships between soil data and soil supply of available nutrients were studied for season 2006A only, as Season 2006B was too wet to produce normal relationships. Table 3 shows the best fitting simple equations between chemical soil data and soil supply of available nutrients (SAv) measured as the maximum nutrient uptake from the soil. A negative relationship between exchangeable K and SOC has been reported earlier (Janssen et al., 1990; Smaling and Janssen, 1993). It is explained by the decreasing relative K saturation of the cation absorption complex with increasing SOC contents (Mengel and Kirkby, 1980).

Table 3 Regressions equations for soil available nutrients (SAv in kg ha^{-1}) and soil parameters.

Nutrient	Equation	R^2	P
N	SAvN = 38 × Tot N (g kg^{-1})	0.50	<0.01
P	SAvP = 161 × Olsen P(mg kg^{-1})/total P (mg kg^{-1})	0.58	0.001
K	SAvP = 104 × Exch. K(mmol kg^{-1})/SOC (g kg^{-1})	0.64	0.001

Table 4 Sets of model parameters '*a*' (maximum accumulation) and '*d*' (maximum dilution) relating grain yield and N, P and K uptake by finger millet. Sets II and III of parameters were used for sensitivity analysis.

Nutrient	Model parameters [a]					
	Set I		Set II		Set III	
	a	*d*	*a*	*d*	*a*	*d*
N	21	53	23	52	23	49
P	76	261	81	253	91	243
K	11	46	13	44	15	40

[a] The parameters *a* and *d* of each nutrient were respectively determined from data of physiological efficiencies at the 5th and 95th (Set I), 7.5th and 92.5th (set II), and 10th and 90th percentiles.

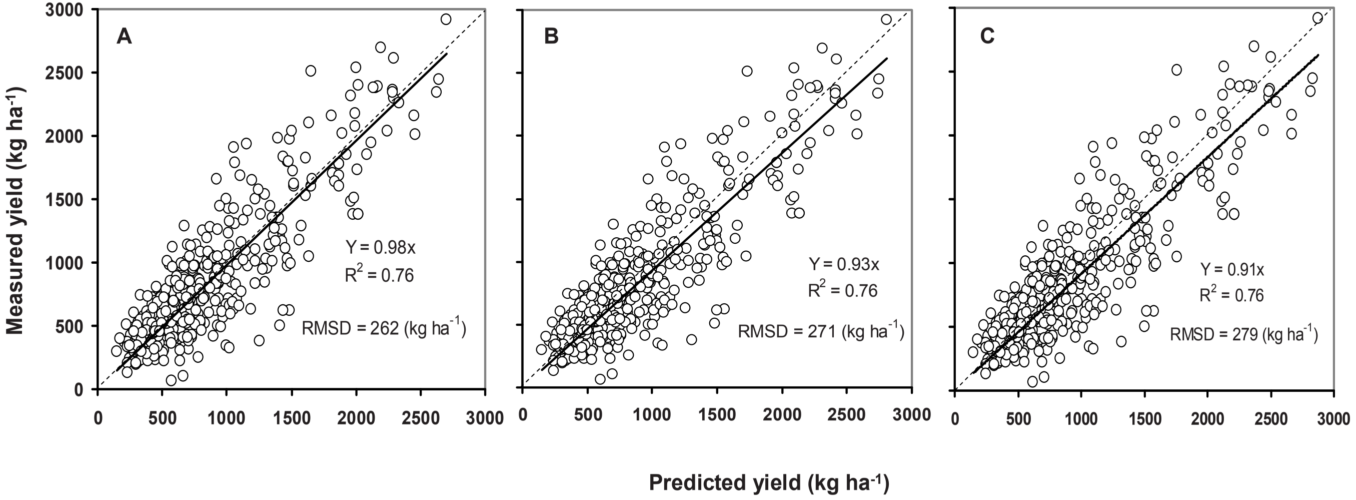

Figure 2 Sensitivity of model to changes in crop physiological parameters ‘*a*’ and ‘*d*’ (A) set I, (B) set II and (C) set III at potential yield of 3000 kg ha^{-1}. Upper and lower boundary lines are physiological efficiencies at maximum dilution (*d*) and maximum accumulation (*a*) respectively. Sets II and III were used for sensitivity analysis. Yields were calculated with Steps 3 and 4 of QUEFTS, using measured uptake as input data.

The relationship for SAvP is surprising because in the original QUEFTS studies (Janssen et al. 1990; Smaling and Janssen, 1993) a positive relation between SAvP and total P was found. We observed that SAvP was smaller in Onamudian village despite the high total P and extractable P on this site (data is not presented). For the calculation of the available supply of fertilizer nutrients (FAv), the maximum recovery efficiency (MRE) is needed. MREs of fertilizers N, P and K were found at the 95% percentile of all the data obtained from the experimental fields in each village (Figure 3). Fertiliser N and P recoveries were poor and ranged from -0.4 to 0.51 for N and -0.2 to 0.32 for P.

Nutrient uptake efficiency: relations between supply of available nutrients and actual uptake

In QUEFTS the actual uptake of a nutrient is equal to the supply only if the particular nutrient is the limiting and all other growth factors are abundantly available. Interactions with the other nutrients (e.g. in case of N with P and K) are taken into account, but not the interactions with other growth factors, and the effects of farmers' management skills. An example is given in Figure 4, showing the relationship between the actual uptake of N and the calculated soil supply of available N. The measured uptake is less than the calculated uptake, but the difference is not great except at the higher N supply. The measured uptake shows a tremendous variation. It may be equal to the supply but also far less. Similar pictures were found for P and K. The ratio of measured actual uptake to calculated actual uptake in the control treatments was about 0.7 for N, 0.65 for P and 0.5 for K, but it showed tremendous variation. A similar problem as for the soil supply holds for the recovery fractions of fertilizer N and P. Figure 3 shows that the median values for the recovery efficiencies of fertilizer N and P were about a quarter and one third of the values at the 95th percentile. These large variations are apparently caused by factors not considered in the QUEFTS model, and are probably difficult to measure. The weak and irregular pattern of the relationship between uptake and supply, and thus the nutrient uptake efficiency, weakens the relationships between QUEFTS-calculated and measured yields.

6.2.3 Yields calculated with the modified QUEFTS model

Using the relationships found between soil data and nutrient supply (Table 3), and the values for the physiological nutrient use efficiency (Table 5), yields for finger millet were calculated according to the procedures of the model QUEFTS. Calculated yields (with non reduced soil supply) were about twice as high as the observed yields (Figure 5). In view of the findings shown in Figures 2, 3 and 4, it is likely that the low nutrient uptake efficiency and the great variability in farmers' fields are responsible for the poor results in Figure 5. A second calculation was made taking into account the low uptake efficiency (reduced supply). The soil supplies of N, P and K were set at 0.7, 0.65 and 0.5, respectively, of the originally calculated supplies, and the recovery fractions were multiplied by 0.25 for N and P and by 0.3 for K. The

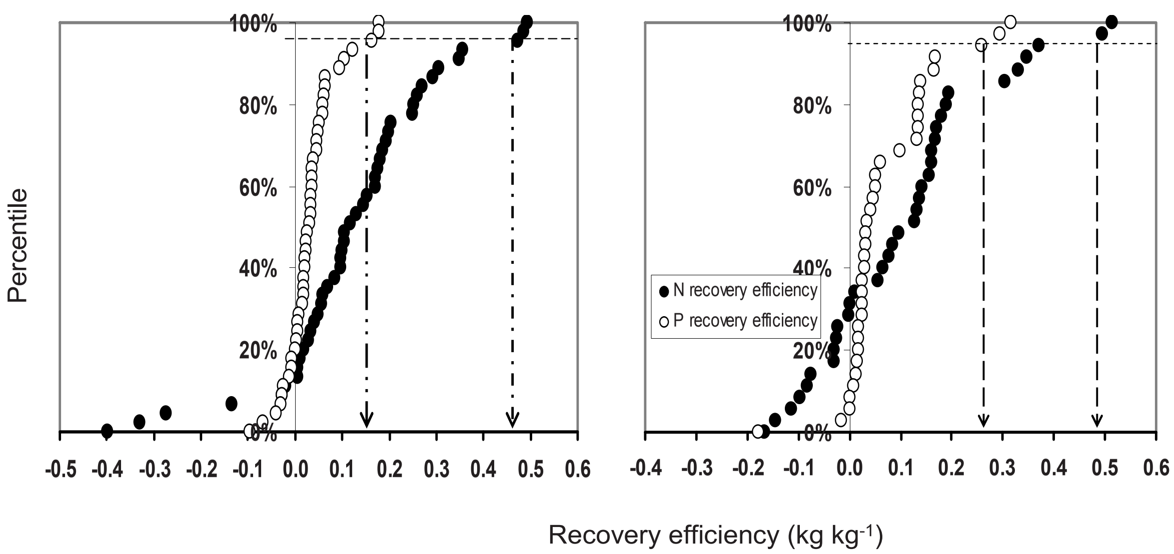

Figure 3 Percentiles of recovery efficiencies of fertilizer N (filled circles) and P (open circles) from experimental fields in (A) Chelekura village and (B) Onamudian village during season 2006A. The recovery efficiencies at the 95th percentiles are represented by points at which the arrows of dotted lines touch the X- axis. They are considered to represent maximum recovery efficiency (MRE) and are used for calculation of fertiliser requirements in Table 5 and yield with non reduced supply in Figure 5.

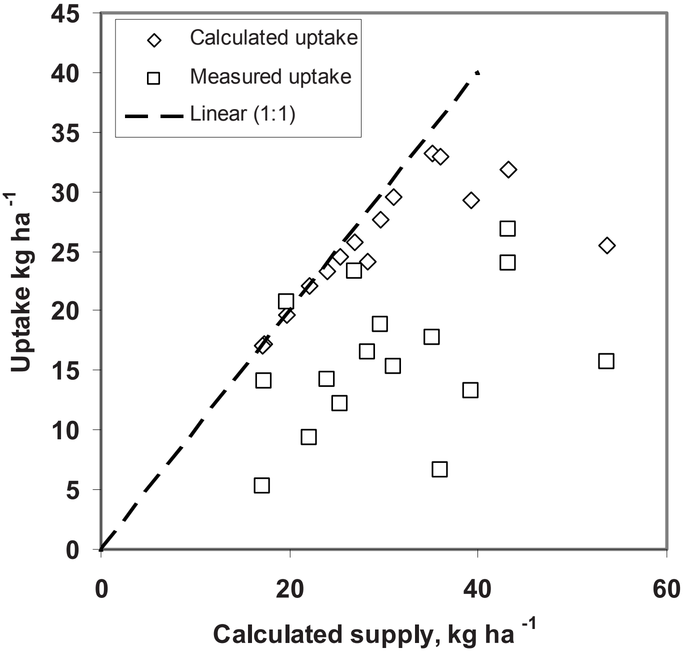

Figure 4 Relation between uptake (calculated or measured) and calculated supply of N on control plots.

average regression coefficients found for the two villages was close to unity in this case (Figure 5). The measured yields were higher in Onamudian than in Chelekura village, and on average also higher than the QUEFTS calculated yields (Figure 6). Probably the nutrient uptake efficiency in Onamudian was better than in Chelekura.

Calculated yields of finger millet at reduced soil supply were comparable to measured yields and were highest for N and P at the rate of 90 kg ha^{-1} N+P in both villages (Figure 7). This suggests that the adjusted supply is appropriate. With the calculated yields, the yield gaps of finger millet were about 2500 kg ha^{-1} at no nutrient input and about 2000 kg ha^{-1} for N+P at the highest rate in both villages.

6.2.4 Fertiliser requirements

Shortcut calculations of the amounts of fertiliser required for balanced nutrition were computed for a target yield of 2000 kg ha^{-1} from the target nutrient uptake estimated using the physiological efficiency (PhE) optimum and fertiliser recovery efficiencies (Table 5). In these calculations, recovery efficiency of K was set at 0.5 because the recovery ratio for N:K is

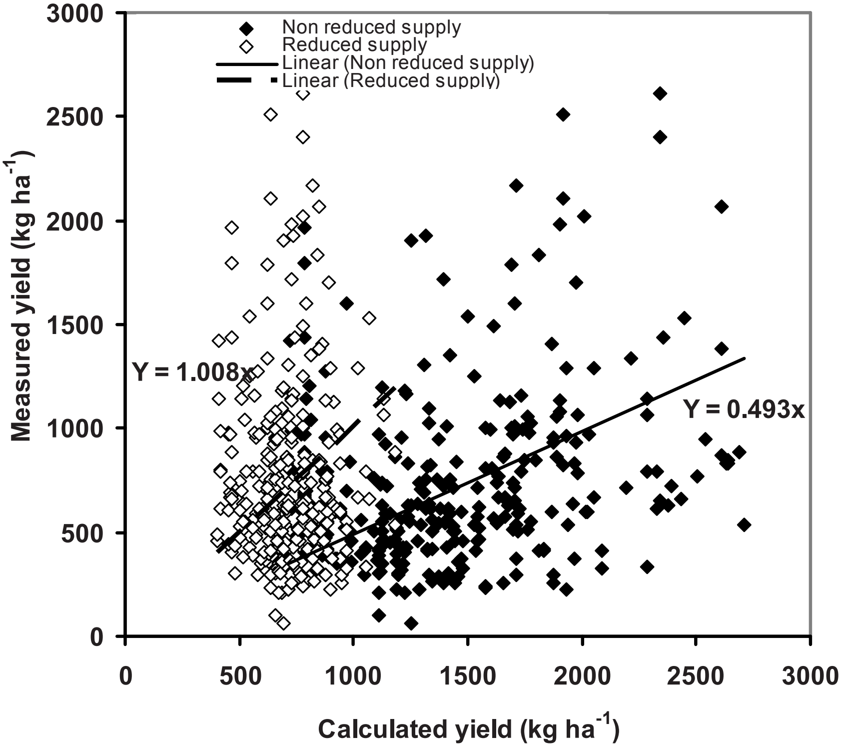

Figure 5 Relationship between measured and calculated yields of finger millet with non-reduced and reduced nutrient supply for all experimental data of the two study sites in Pallisa District, (2 seasons of 2006).

approximately 1:1 and from our experiments, maximum N recoveries ranged between 0.47 (Chelekura) and 0.49 (Onamudian) which are close to default recoveries in the QUEFTS model. The N and P recovery fractions at the 95th percentiles of recovery fractions for each nutrient in each village are presented in Figure 4.

Fertiliser requirements computed with the modified equation were higher than those with equation 2. With both equations however, the calculated fertiliser requirements were 1.3 to 1.7 times higher for soils of Chelekura village compared with those of Onamudian village. Noteworthy here is that K is also determined to be required, yet it has always been considered not important as a limiting nutrient in this system (Wortmann and Eledu, 1999).

Table 5 Physiological efficiencies, plant uptake, soil available nutrients (SAv) and fertiliser requirements for N, P and K for finger millet average target yield of 2000 kg ha^{-1} per village.

Village/ nutrient	Physiological efficiencies [a]			Recovery efficiency [c]	Sav [d]	Equation 2			Equation 4		
	a	*d*	*m*			Target uptake[b]	Input required	Fertiliser requirement	Total required	Input required	Fertiliser requirement
	kg kg^{-1}				kg ha^{-1}						
Chelekura											
N	21	53	37	0.47	21	54	33	70	60	39	83
P	76	261	169	0.15	5.4	12	6.6	38	13	8	52
K	11	46	29	0.50	50	70	20	40	78	28	56
Onamudian											
N	21	53	37	0.49	29	54	24	51	60	31	61
P	76	261	169	0.26	5.2	12	6.6	26	13	8	31
K	11	46	29	0.50	58	70	12	24	78	20	40

[a] Physiological efficiencies at maximum accumulation (*a*), maximum dilution (*d*) and medium (*m*)- an average of *a* + *d*

[b] Target uptake = Target yield/ optimum physiological efficiency, *m*

[c] Recovery efficiency for K is the model default value

[d] Soil available or indigenous soil supply of the nutrient determined from P and N+P treatments (N), N and N+P treatments (P) and N+P treatments (K)

[e] Fertiliser requirement at target yield using Equation 2: FR= (Target uptake –SAv)/RE and Equation 4: FR = (Target uptake × 1.11 –SAv)/RE

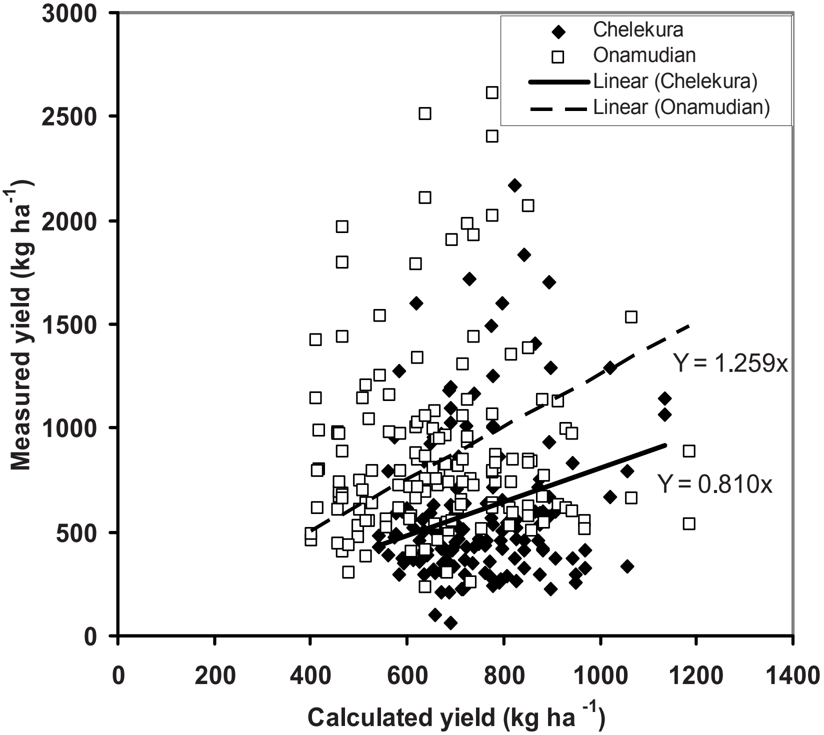

Figure 6 Relationship between measured and calculated yields of finger millet using reduced nutrient supplies per study village in Pallisa District (2 seasons of 2006).

6.3 Discussion

The QUEFTS approach was useful for understanding soil-crop relationships and deriving site-specific fertiliser recommendations for finger millet. The parameters determined for maximum accumulation and dilution, i.e. physiological efficiency, partly fell within the ranges for cereals reported by Janssen (2009) except in the case of K for which finger millet had smaller values. The ratio of the uptakes of N:P was less than that found earlier for other cereal crops. On the basis of the calibrated model, optimum ratios were determined for balanced nutrient fertilisation of finger millet as 1 : 0.28 : 1.3 for N : P : K, while according to Janssen (2009) these values for cereals are 1 : 0.145 : 0.8. The high portion of P in finger millet could be due to the small grain size of millet (Janssen, 1993) and the somewhat larger value for K is due to the smaller harvest index found in finger millet compared with cereals in general.

The values of medium physiological efficiency, fertilizer nutrient recovery efficiency and soil available nutrient supply were used to calculate the amount of fertiliser required to achieve the target yield of millet (2000 kg ha^{-1}) (Table 5). The fertiliser estimates were 83, 52 and 56 kg ha^{-1} (Chelekura) and 61, 31, and 40 kg ha^{-1} (Onamudian) for N, P and K respectively. The soils in Onamudian village were more fertile (e.g. had larger SOC contents) than those in Chelekura and thus a smaller fertiliser requirement for finger millet. This difference in the calculated fertiliser requirements is explained by larger recovery efficiencies of applied fertiliser and higher soil supply of nutrients in Onamudian than Chelekura village.

Application of QUEFTS is suitable for well-drained deep soils with pH (H_2O) of 4.5-7.0, SOC < 70 (g kg^{-1}), organic N < 7 (g kg^{-1}), total P < 2000 g kg^{-1}, Olsen P < 30 (g kg^{-1}), and Exch. K < 30 mmol kg^{-1} (Smaling and Janssen, 1993). These conditions were largely met (Table 1) except that in our experiments K was not applied as it was expected to be adequately supplied from soils in the study area (Wortmann and Eledu, 1999). Other conditions such as no limitation by other nutrients and moisture availability were not met in the degraded soils. Millet yields were reduced at higher rates of P (Figure 7D) and induced zinc deficiency (due to precipitation as insoluble zinc phosphate) may have impaired P uptake (Marschner, 1995). The soils were high in silt (Table 1), which predisposes the soils to surface-sealing and hence reduced infiltration and moisture availability. These factors affect nutrient availability and hence result in a measured uptake that is less than the calculated uptake (Figure 4). In consequence, model calculated yield responses (using non reduced supply) to soil available nutrients were overestimated (Figure 5). Over predictions with QUEFTS have also been reported for maize yield (Tittonell et al., 2008a), and were greater for farmer-managed fields than for researcher-managed fields. These observations indicate that soil variability and differences among farmers fields (related to both historical and current management) make it practically difficult to arrive at accurate predictions of yield from nutrients supplied by soils and fertilisers especially in degraded fields such as those in our study.

Although the calculated fertiliser requirements fall within the ranges of rates of applied nutrients in the field experiments, none of the rates was capable of closing the yield gaps of finger millet in the short term (Figure 7 C and D). The gap for no use of inputs was approximately 2500 kg ha^{-1} with only a slight reduction to about 2000 kg ha^{-1} at the highest fertiliser rate of N+P. Thus the calculated rates are uneconomic at the yield gains from fertiliser application given the prices (US$ kg^{-1}) of 1.14 (N), 1.27 (P) and 0.98 (K) and for millet grain of 0.23 at the time of our study. This indicates that rehabilitation of degraded fields will require investment without immediate profitable gains until productivity is regenerated. The period it takes to regenerate fertility is dependent on management practices employed but generally several years are required (Tittonell et al., 2008b; Zingore et al.,

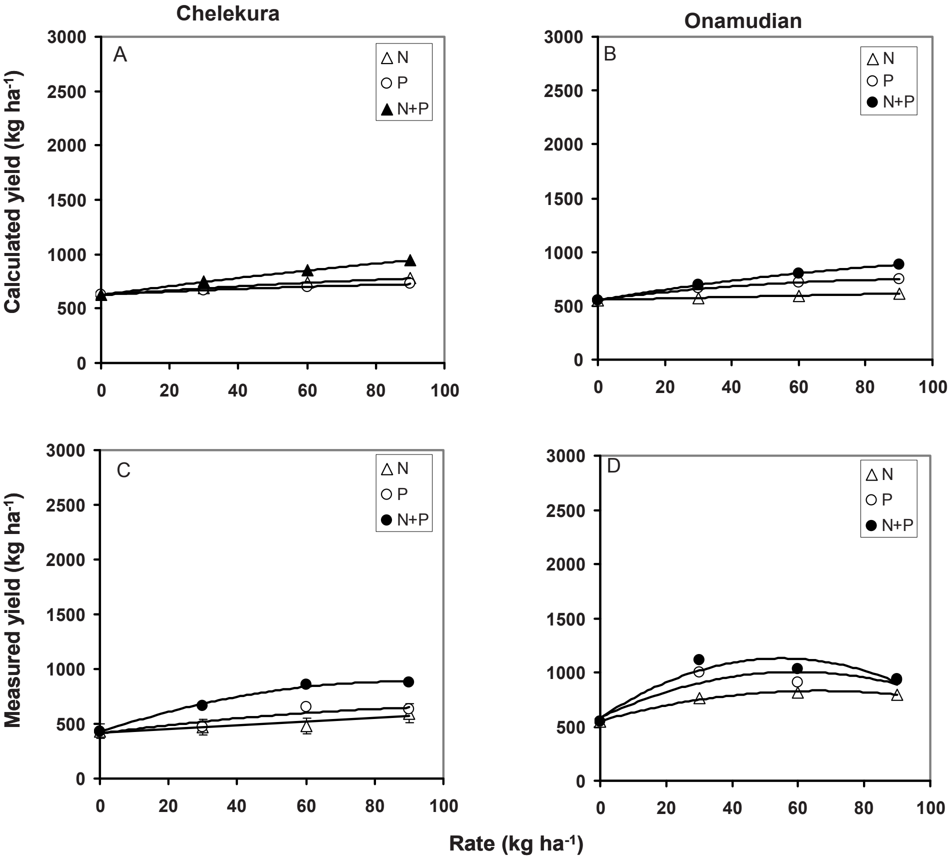

Figure 7 Average grain yield response to application rates of N, P, and N+P fertilisers on degraded fields in the study villages in 2006 (2 seasons). A and B are QUEFTS calculated yield with reduced supply and C and D measured yields in Chelekura and Onamudian villages.

2007). If the soil constraints that affect nutrient uptake are alleviated it is likely that the fertiliser requirements will reduce and the yield gap could be reduced further or closed.

Strategies for closing yield gaps would require addressing soil productivity constraints and using improved germplasm and good crop management. Degraded fields often have multiple nutrient deficiencies (Zingore et al., 2008) and a combining of organic manures and mineral fertilisers is a better approach to address such constraints. It has been shown that application of manure together with mineral P fertilisers increase P availability in poor fertility fields (Tittonell et al., 2007). Therefore improvement of SOC status of degraded soil to some thresholds is first needed so as to obtain better use efficiencies of mineral fertilisers. However what such thresholds are will vary with soil type (texture) and crop and therefore need to be established. In sandy soils in Zimbabwe, 0.5% SOC has been considered as a minimum threshold for efficient use of fertiliser (Mtambanengwe and Mapfumo, 2005). Organic matter provides N and also improves soil physical properties such as moisture capture and retention, cation exchange capacity, which are important for nutrient retention in sandy soils. Good fertiliser management to increase nitrogen recovery is required (Duivenbooden et al., 1996).

Yield calculations from soil supply of nutrients using the QUEFTS model can be improved by adding appropriate equations for other nutrients besides N, P and K such as Zn (cf. Das et al., 2008). This could be done to improve the uptake supply relationships for the degraded fields (Steps 2 and 3 of QUEFTS) by undertaking experimentation that addresses identified limiting nutrients and improving soil moisture availability. In this way the accuracy of fertiliser recommendations will be improved.

6.4. Conclusions

The QUEFTS model proved to be a useful tool for site specific nutrient management in finger millet provided soil conditions are considered. From this study, the physiological model parameters ‘*a’* and ‘*d’* for QUEFTS for finger millet are 21 and 53 (N), 76 and 261 (P) and 11 and 46 (K) respectively. The recommendations for N, P and K are respectively 83, 52 and 56 kg ha^{-1} for the sandy loam soils in Chelekura village and 64, 31, and 40 kg ha–1 for the sandy clay loams in Onamudian village. These rates, however, could change if other soil productivity limitations in the degraded fields are alleviated. Further validation of the model is needed with experimental data including K. In our QUEFTS calculations, K has been found to interact with N and P to limit millet production. Therefore, factorial designs with various rates of N, P and K are recommended, taking account of other nutrient limitations and improving soil water availability through soil organic matter management for improved nutrient availability and increased crop yields.

Acknowledgements

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Chapter 7

General discussion and conclusions

7.0 The food insecurity enigma in sub-Saharan Africa

Food insecurity is rampant in sub-Saharan Africa (SSA) and is driven by a spiral of intricately interlinked factors; poverty, land degradation and low crop productivity. The unbridled food insecurity and poverty is jeopardising the attainment of the Millennium Development Goal (MDG) 1 of halving the population of the hungry and poor by 2015 (FAO, 2008). Food insecurity and poverty are severest in rural areas where the majority of the poor population live and derive their livelihoods largely from agriculture (FAO, 2006). The food insecurity - land degradation - low crop productivity nexus has also been reported for farming systems in Uganda (Pender et al., 2004) including the Teso farming system, on which this research focused. Food insecurity affected 54% of the households in the study district (Ravnborg et al., 2004), 30-45% of the population are poor (Emwanu et al., 2003), crop productivity is low: for example on-farm yields of finger millet, an important staple and income crop is 400 kg ha^{-1} (Tenywa et al., 1999) and smallholder farming systems are unsustainable (Nkonya et al., 2005).

Developing the agriculture sector is regarded as a promising strategy for alleviating food insecurity and poverty for millions of smallholders (FAO, 2006). However, key concerns such as increasing agricultural productivity, access to resources and services, linking with markets, and development and strengthening supportive institutions need to be addressed (Andriesse et al., 2007). Tackling these concerns requires effective partnerships from farmer to the international community in order to realize the contribution of agriculture to reduce hunger and poverty. The international community and national governments play a critical role in putting in place enabling institutional frameworks. Recently, under the New Partnership for African Development (NEPAD) and the Comprehensive Africa Agricultural Development Programme (CAAD), the Abuja declaration 2006 called for increasing agricultural productivity and use of both organic and inorganic nutrient resources, a key principle in targeted soil fertility management (Vanlauwe et al., 2009) towards achieving a green revolution in Africa. In the case of Uganda, the plan for modernization of agriculture (PMA) (GOU, 2000) is in tandem with these guidelines. It is a multi-sectoral strategy calling for partnerships with various stakeholders to improve agricultural productivity for poverty eradication. While guidelines are in place, generation of practical knowledge for increasing agricultural productivity is a domain for research and extension in collaboration with farmers. This empirical research was therefore sought to contribute to understanding of how heterogeneity in soil fertility affects the effectiveness of integrated soil fertility management practices. This is useful for guiding the targeting of nutrient resources to increase crop productivity in the Teso farming system in Eastern Uganda. The research focused on evaluating efficacy of nutrient management options as affected by heterogeneity to increase productivity of finger millet. This crop is a major staple and income crop in the farming system and it is responsive to nutrient inputs. It is also comparatively of better nutritional value than the major cereals; rice, wheat and maize (NRC, 1996), yet finger millet has received only low research priority (Mgonja et al., 2007).

The major factors that have contributed to the low productivity of the Teso farming system have been identified (Chapter 2); between and within-farm heterogeneity in soil fertility was characterised and the potential scale for targeting integrated nutrient management interventions suggested (Chapter 3); the impacts of heterogeneity on legume-finger millet rotations were evaluated for the purpose of identifying field types and landscape positions to target legumes (Chapter 4); the efficacy of manure and mineral fertilisers to improve productivity of degraded fields was tested (Chapter 5); and the fertiliser requirements for production of finger millet developed by modelling approach (Chapters 6). In this last chapter (Chapter 7), a synthesis of the results from previous chapters is made and pathways for increasing productivity of the smallholder farming systems through targeting of integrated nutrient management options to heterogeneity in soil fertility are discussed. Specifically the opportunities and the challenges surrounding approaches for attaining food security by increasing food production with various nutrient management optionsare discussed, and finally concluding remarks made on priorities for the future.

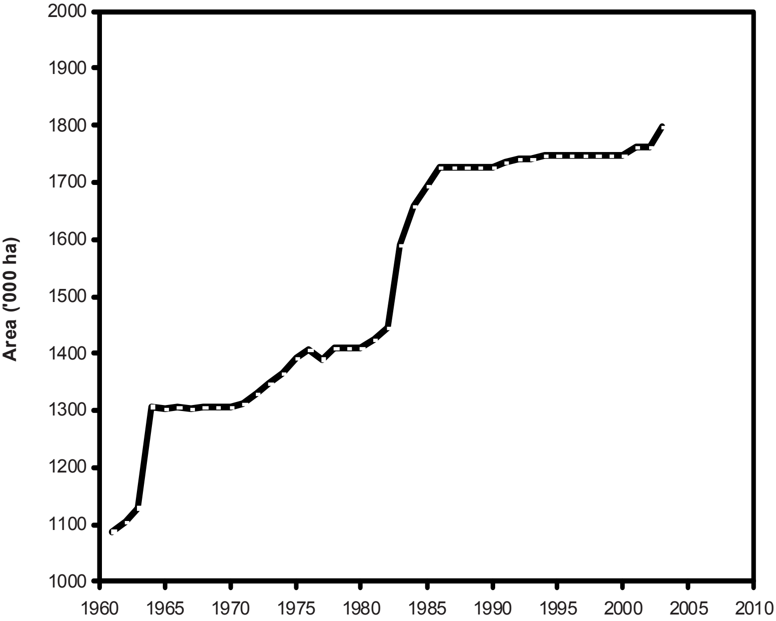

Figure 1 Trends in land area (ha) brought under cultivation in Uganda from 1961-2005 (Source: World Development Indicators database**).**

7.1 Which trajectory to achieve food security?

Food security can be achieved by either buying the food required or producing one's own food. To be able to buy food there should a steady source of cash. This is often the strategy for the working populations with assured salary incomes. For a majority of the rural population, food security is achieved by producing their own food through farming. As such, agricultural production has thrived on extensification i.e. expanding land area under cultivation. This has brought fragile and marginal lands into cultivation. The proportion of land brought under cultivation in Uganda increased from 16% to 27% from 1961-2003 (Figure 1) but the proportions were much higher in our study parishes - 24% to 65 % in Chelekura village and 53% to 100% in Akadot village between 1960 and 2001 (Chapter 2). Concomitantly, crop yields are poor and the farming system is unsustainable. The changes in land use observed over the 4 decades of analysis were due to smallholders' responses to external socio-economic and political forces rather than population growth alone (Chapter 2). Assuming the current management scenario of no input application, an additional 2547, 1498 and 219,457 ha of land respectively would be required to produce grain (in terms of millet) to feed the population in Chelekura, Akadot and Pallisa district by the year 2015 (Table 1). Clearly increasing food production through extensification is no longer a feasible strategy in the study area.

Alternatively, food security can be assured by reducing the population dependent on agriculture. Finding employment opportunities elsewhere in cities (a major cause of rural-urban migration) or better opportunities for labour productivity could not only increase and improve investments in agriculture through remittances and other forms of capital but also the ability to buy required food. In our study area, the wealthy households, which represented 5-10% of the households benefited from remittances from working relatives. Increasing such remittances can be possible if some of the family members can find off farm employment such as businesses and formal employments. A systematic strategy of farmers could also be followed to secure future remittances from sending children to formal education who then have enhanced opportunities to find off farm employment. Either of these strategies in search of better opportunities for labour productivity in the mean time is not sufficient for the rural population and the alternative trajectory of intensification is potential to increase agricultural productivity and to tackle food insecurity.

Intensification (increased investments of labour and capital in land) is necessary in order to improve and sustain the productive capacity of the land under rapid population growth. The benefits can be two-fold in that the increasing population can lead to increased

Table 1 Food deficits and additional amount of land required to produce finger millet to feed population at parish and district level in 2002 and 2015.

Parish	Arable area (ha)	Population in year (persons)		Millet production by field [a]			Total Grain production ($\times 10^6$ kg)	Grain required [b] ($\times 10^6$ kg)		Grain deficit ($\times 10^6$ kg)		Additional land required (ha)	
		2002	2015	Good	Medium	Poor		2002	2015	2002	2015	2002	2015
Parish													
Chelekura	1527	4731	7125	0.36	0.47	0.26	1.09	1.93	2.91	0.84	1.84	1179	2547
Akadot	1192	4449	6700	0.86	0.26	0.10	1.21	1.82	2.70	0.61	1.52	594	1498
District													
Pallisa	156400	520578	784010	71.4	41.7	20.4	133.5	212.8	320.5	79.5	187.2	93157	219457

[a] Calculation of millet production per field type is product of average millet yield per field type without nutrient inputs and proportions of field types as categorised by farmers during field characterisation (Chapter 3) in each village. They were 28%, 43%, 29% (Chelekura) and 63%, 24 and 13% (Onamudian) respectively for good, medium and poor field types. Total production is the sum of production across the field types per parish. At the district scale the yields are estimated based on field average proportions of field and yield per field type. The land area for the district excludes the areas occupied by water and wet lands.

[b] Computed using the FAO requirements

c Population for parishes and district by 2015 is estimated using the projected growth rate of 3.3% (UBOS 2005) supply of labour and the rise in labour investments in land is possible. There are findings however that question this linear relation in the projections as some farmers may require much more labour than they can provide from their own production units (Tiffen et al., 1994). Investments in land can be perceived here as increased planting of trees around fields and productivity management through the use of mineral fertilisers, pesticides, herbicides, organic manures and intensification of legume based rotations and diversification in cropping systems. Farmers in SSA are resource limited and strategic targeting of resources to increase use efficiency in intensification is vital.

7.2 Heterogeneity and efficacy of nutrient management options

Farming systems in SSA are diverse, dynamic and highly heterogeneous. The crop production strategy of nutrient mining has further reinforced heterogeneity in the farming systems. Thus has made fertiliser recommendations that were made at the agroecological zone level of limited relevance at the farm scale because field to field variability is as large as between agroecological zones and warrants recommendations to be made at such smaller scales. In the study area, farmers recognised large variability between field types in terms of productivity and classified them as good, medium and poor fields (Chapter 3). This is knowledge they have acquired through their long term experience cultivating fields within their farms. It is then imperative that heterogeneity in soil fertility is well characterised for the purpose of guiding the targeting of scarce nutrient resources. This will not only enhance efficiency in resource use, which is the objective with intensification but also helps to identify where special strategies such as rehabilitation are necessary.

Heterogeneity in soil fertility greatly affects the resource use efficiencies (Vanlauwe et al., 2006; Zingore et al., 2007; Tittonell et al., 2007a) and hence the potentials of the options to increase crop productivity in smallholder farms. The impacts of heterogeneity on the nutrient management options experimented with (legumes, manures and mineral fertilisers) are discussed in the subsequent sections and underlie the basis for their proposed targeting within soilscapes in the Teso farming system.

Legume-based soil fertility management is within the long tradition of crop rotation practiced in the Teso farming system (Uchendu and Anthony, 1975). The rotations followed by farmers are now obscure and also do not appear to be well synchronised to provide maximum contribution to the overall productivity of the smallholder farms. There is only a narrow range of legume species and suitable cultivars are lacking. So far the commonly available legumes to farmers are groundnut, cowpea and green gram. Productivity of these legumes is also hampered by climatic factors. During the course of our on-farm experimentation, the rainfall was poorer in 2005B season and affected the grain filling by legumes and finger millet (Chapter 3). Although the total amount of rainfall was 400 mm and

Table 2 Legume yield, grain yield, N_2-fixed, net N input and urea equivalents for legumes established with 0 (P0) and 30 kg P ha^{-1}(P30) and scaled to parish and district level.

Scale/legume	Biomass yield (t ha^{-1})[a]		GY (t ha^{-1}) [b]		Grain N (t ha^{-1})[c]		Average N_2-fixed (kg ha^{-1})[d]		Total N_2-fixed (t) [e]		Grain N (t)		Net N input (t)[f]		Urea Equivalent of N_2- fixed (t)	
	P0	P30	P0	P30	P0	P30	P0	P30	P0	P30	P0	P30	P0	P30	P0	P30
Chelekura parish																
Groundnut	1.38	1.40	0.62	0.63	0.04	0.04	24	25	5	6	9	9	-4	-3	12	12
Cowpea	4.20	4.95	1.43	1.68	0.07	0.08	101	123	23	28	15	18	8	10	49	60
Green gram	3.03	3.58	1.33	1.57	0.06	0.08	67	92	15	21	14	17	1	4	33	45
Soyabean	0.98	1.33	0.29	0.40	0.02	0.03	13	17	3	4	5	7	-2	-3	6	8
Pigeon pea	1.93	1.90	0.44	0.44	0.02	0.02	44	44	10	10	4	4	6	6	21	21
Mucuna	5.45	3.86	-	-	-	-	120	123	27	28	-	-	27	28	59	60
Akadot parish																
Groundnut	1.90	2.20	0.86	0.99	0.05	0.06	30	39	6	7	10	12	-4	-4	12	16
Cowpea	4.20	5.45	1.43	1.85	0.07	0.09	93	145	17	27	12	16	5	11	37	58
Green gram	3.33	3.93	1.46	1.73	0.07	0.08	70	82	13	15	13	15	0	0	28	33
Soyabean	2.35	2.53	0.71	0.76	0.05	0.06	46	44	8	8	10	11	-1	-3	18	18
Pigeon pea	3.08	3.03	0.71	0.70	0.03	0.03	70	60	13	11	5	5	8	6	28	24
Mucuna	5.70	7.10	-	-	-	-	127	149	24	28	-	-	24	28	51	60
Pallisa district																
Groundnut	1.64	1.80	0.74	0.81	0.05	0.05	27	32	848	1005	1452	1596	-604	-591	1845	2185
Cowpea	4.20	5.20	1.43	1.77	0.07	0.08	97	134	3026	4184	2099	2599	927	1584	6579	9095
Green gram	3.18	3.75	1.40	1.65	0.07	0.08	69	87	2147	2721	2098	2477	49	244	4667	5916
Soyabean	1.66	1.93	0.50	0.58	0.04	0.04	29	30	907	950	1186	1373	-279	-423	1972	2066
Pigeon pea	2.50	2.46	0.58	0.57	0.02	0.02	57	52	1775	1619	665	655	1110	963	3859	3519
Mucuna	5.58	5.48	-	-	-	-	124	136	3868	4254	-	-	3868	4254	8408	9248

[a] biomass refers to total above ground biomass computed from Table 2a Chapter 4 on the assumption that legumes occupy 20% of arable land meaning in Chelekura parish 1127 ha, Akadot parish 926 ha and Pallisa district 156,400 ha

[b] GY = grain yield and is calculated from average biomass using harvest indices: groundnut, 0.45; cowpea, 0.34; green gram, 0.44; soybean, 0.31; pigeon pea, 0.23

[c] Grain N is computed using % mass fraction values of Nijhof (1987): groundnut, 6.3; cowpea, 4.7; green gram, 4.8; soybean, 7.6; and of Ncube (2007): pigeon pea, 3.7

[d] Average N_2-fixed is derived from Table 2C Chapter 4

[e] Total N fixed is for above ground biomass

[f] Is the difference between total N-fixed and total grain N

could result in a crop harvest the rainfall distribution within this season was poor and affected the crop performance and total benefits from the legume-millet cropping systems (Chapter 3; Table 5). In particular seasons with low rainfall and increased temporal and spatial variability seem to have increased in frequency to once in every three to four seasons. Farmers' may need to adapt to this climate change with including legumes in their cropping systems that need to be enhanced through provision of appropriate germplasm and identification of biophysical niches within the farming system.

Heterogeneity in soil fertility shows further impacts on the potential benefits from legumes and fertiliser P application and challenges generalised recommendation of legumes for low input systems. Legumes are recommended for low input systems because of their low cash requirements and the potential to fix and turning over nitrogen to subsequent crops (Giller, 2001). In this study, the amounts of nitrogen fixed were variable and the contribution of groundnut for example (the most preferred legume by famers) was far less than that obtained from, mucuna or cowpea (Table 2). Planting groundnut alone to 20% of the land in the parishes would result in N_2-fixed equivalent to 12-60 tons of urea at the parish scale and 1845 to 9248 tons of urea fertiliser at the district scale. Planting with 30 kg P ha^{-1} is beneficial and would result in substantial additional N_2 being fixed especially by cowpea in both parishes and equally at the district scale. Legume N productivity was larger in Onamudian than Chelekura because of the rather comparatively better soil fertility. Thus better N_2 accumulation in good compared with poor fields reiterates that fertility of soils underlies legume growth - fitting the 'no free lunch' principle (Vanlauwe and Giller, 2006). In general, the legumes could not profitably increase millet production on poor fields (Chapter 4) because of multiple problems - physical and other nutrients such as K and S that were later identified (Chapter 5). Such fields require improving fertility before benefits from the legumes can be obtained. Beyond the agronomic responses, social acceptance is critical. Mucuna produced the largest biomass and resulted in better responses of finger millet. Farmers however preferred groundnut despite the lowest performance. It is because they anticipated additional benefits rather than just soil fertility improvement which is secondary. Such considerations enable best fitting of the options as elaborated by the socio-ecological niche concept (Ojiem et al., 2006).

It can of course be understood that the season in which the legumes were grown was during a poor rainy season. In a good rainy season, farmers can gain from grain and may explain the farmers' preference of groundnut and this may change the benefits that can be received from legumes in terms of net N inputs to the system (Table 2). In general legumes that would produce high biomass could have positive net N inputs. Mucuna would be the best and could produce N equivalents of about 30 tons and 43000 tons of urea at the Parish and district scales respectively.

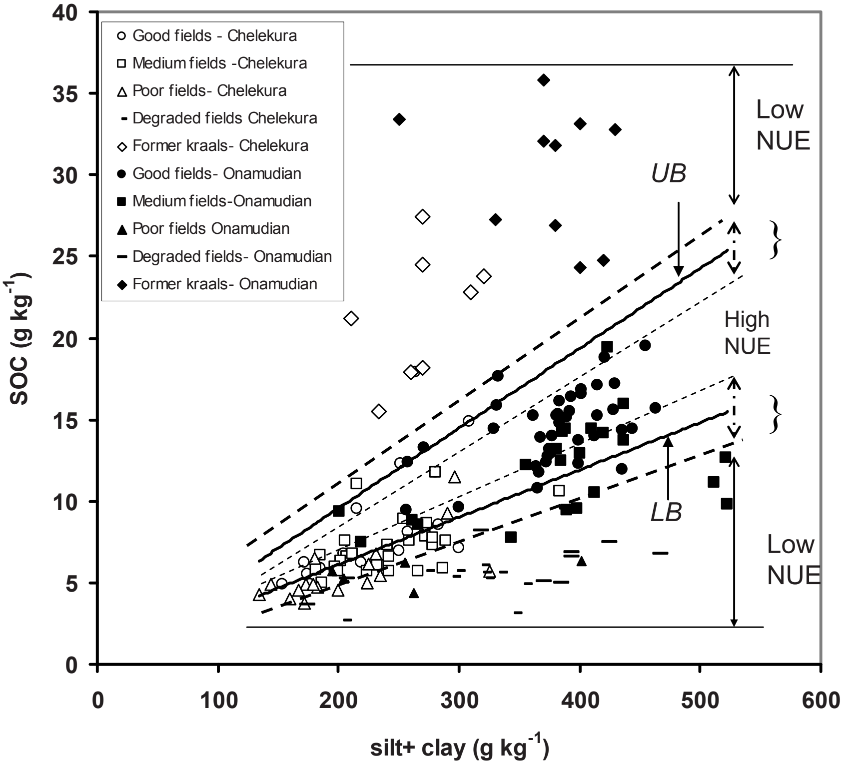

Figure 2 Relationship between SOC and silt + clay by field type as classified by farmers in the study villages. The regression lines as found for cultivated (*LB*) and non-cultivated, fallow (*UB*) land according to Feller and Beare (1997). NUE = Nutrient use efficiency. The textural characteristics of the study sites fall within the silt + clay ranges of soils used in Feller and Beare (40-800 g kg^{-1}). Sampling is quite different. Soils in our case are mainly from cultivated fields.

In the subsequent study, manure and mineral fertilisers were targeted to poor fields (Chapter 5). Neither manure nor mineral fertilisers alone could raise millet production to levels comparable to former kraals (niches of high fertility) but there was evidence of added benefits from combined application of manure + N fertilisers and N+P fertilisers implying both N and P were limiting. Other nutrients, K and S were also identified to be limiting. It has for long been regarded that only N and P are limiting crop production in the Teso farming system due to reliance on fertiliser recommendations in the 1970s (Foster, 1976). Over time with continuous cultivation, other nutrient limitations have emerged in the case of finger millet.

There is no doubt that increasing productivity will need use of mineral fertilisers. However the question of their use efficiency is central: to know where to target them to get high use efficiencies and optimally increase crop yield. In this study, use efficiencies were low (less that 30%) and differed strongly between the sites (soilscapes). Better fertiliser use efficiencies are associated with soil characteristics such as CEC, texture and SOC. SOC alone, however, can be used as an overall indicator for nutrient use efficiencies. Feller and Beare (1997) provide a generalised relationship between SOC and texture for fallow and cultivated fields and suggest an envelop within which SOC can be increased. For our experimental sites, there are former kraal sites which have SOC way above the line representing the fallow fields and there are fields of SOC mass fractions far below the line representing the cultivated fields (Figure 2). NUE will be small when SOC mass fractions are very large or very small for a given soil texture. It is expected that application of mineral fertilisers to former kraals will be non responsive and will only be meaningful to be applied when SOC in poor and degraded fields has been built up to some thresholds. In theory, there must be a SOC mass fraction for a given soil and crop at which NUE will be largest - when all other conditions for crop growth are optimal but mineralisation of organic N does not replace the need for N fertiliser. Distinctively the window for increasing SOC differs between soils of varying texture (silt + clay contents) with soils of low silt + clay like the Chelekura site having a narrower window for building up SOC than Onamudian village. In the management context, this also has implications for nutrient input requirement reiterating the need for site specific nutrient management. The precise thresholds of SOC have not been determined and could fall within the zones with brackets in Figure 2, but these thresholds need to be determined to assist implementation of the spirit of the Abuja declaration to increase mineral fertiliser usage to increase food production. Areas such as those with high SOC (former kraal sites) should be cultivated without fertiliser until SOC drops to critical thresholds warranting mineral fertiliser application. Whereas Keulen (2001) argues that it is impractical to determine SOC for any soil, the fact that enhancements of mineral fertilisers use at certain SOC mass fraction suffice it to be used as an indicator for other effects in soils. Tittonell et al. (2007b) found the collocation effects of manure application and P fertiliser application to explain the relationship between SOC and extractable P and hence SOC can be an (imperfect) indicator for NUE for crop response to P in western Kenya. There should thus be attempts to determine such thresholds in smallholder farming systems in SSA.

The general recommendation of using 50 kg of fertiliser is only generic and appropriate recommendations considering the heterogeneity in soil fertility are clearly needed. In Chapter 6, fertiliser recommendations for finger millet were found to be higher in Chelekura with poor soils compared with Onamudian village which was higher in SOC. The amounts of fertiliser were together higher than the Abuja recommendation on both sites, as obviously the Abuja declaration was a political statement to set a goal to encourage fertiliser use and not an agronomic guideline. The applicability of QUEFTS to site specific management in the degraded fields is challenged by other factors that are not taken into account as surface crusting and nutrient imbalances in the degraded fields which must first be addressed for fairly more precise recommendations to be developed. With such great variability even between fields with similar soil type (per village) due to historical management differences, recommendations may have to be developed per farm or per field, a task which may be so enormous.

7.3 Concluding remarks

Targeting nutrient management options can result in larger benefits from nutrient management interventions and specific attention can be afforded for specific constraints to avoid waste of resources. Benefits from legumes to increase millet production are economic on the good fertility fields. If the soil quality of the poor fields is gradually improved to be equivalent to that of good fields at the farm scale, larger benefits can be reaped and would have major positive impacts at the higher spatial scales of parish and district.

Cattle manure is possibly the only organic resource that can be obtained in the system in significant amounts. However the livestock population is small. This is explained by the insurgency in the eastern region of the country that resulted in depletion of cattle (Chapter 2). Even with the now prevailing security and peace, farmers aim at having oxen for draught power and a cow or two for milk. There is a constraint of lack of grazing pastures as change in land use resulted in conversion of most communal grazing land for rice cultivation. The farmers owing cattle even at the time of this survey faced a challenge of feeding their cattle and this constrains free range grazing of cattle especially during the cropping seasons. During dry periods and after crop harvest, cattle can be grazed anywhere in the community. The nutritional quality of the fodder is poor and inadequate during the dry seasons. This raises the question as to how can quantities of manure be increased and its quality improved. Manure in the study area is also of poor quality especially in N because of the poor management practices. Concern then is whether to completely change the system into stall feeding which can improve manure collection but fodder banks would have to be developed and pasture quality improved. The challenge is whether farmers will have enough labour to keep up with stall feeding and manure management as the greater proportion of family labour, the children are now going to school through universal primary and universal secondary education policies in Uganda. It is only likely to be feasible to switch to stall feeding systems if milk production could become profitable to compensate for the labour demand.

The use of inorganic fertilisers in SSA is very restricted compared with the rest of the world (9 vs. 100 kg ha^{-1}) and average use in Uganda is less than 2 kg ha^{-1} (Camara and Heinemann, 2006). The limited fertiliser imports to Uganda (Figure 3) have been the result of the political and economic climate. In the 1960s, fertiliser was used on cash crops such as coffee, cotton, and the tea and sugarcane plantation estates. Through the years of political instability and economic collapse, use was negligible. Structural adjustment and economic

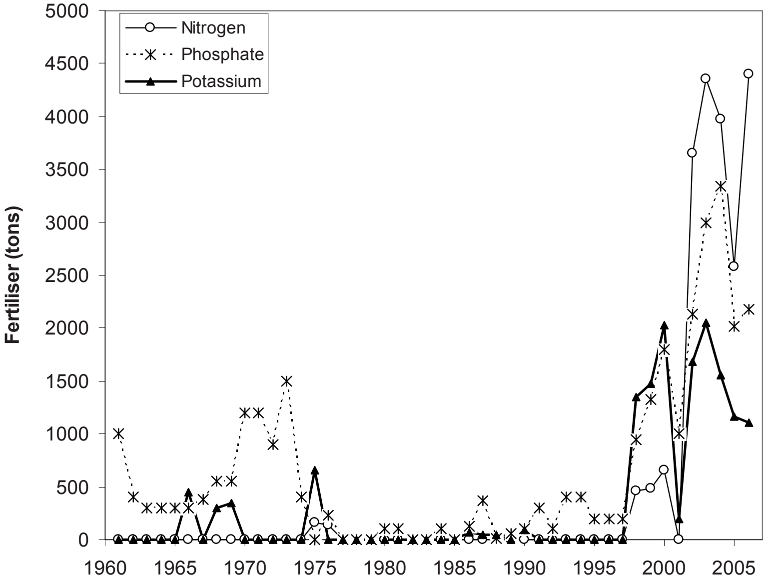

Figure 3 Fertiliser imports to Uganda from 1960 to 2005.

liberalisation policies further affected the consumptions of fertilisers through the 1980s because abolition of subsidies. The increases in the 1990s may be explained by emergence of private sector dealing in fertilisers, emergence of profitable enterprises such as the flower industry, rehabilitation and expansion of the sugar cane and tea estates, and tobacco contract farming. Despite these increases in fertiliser consumption, fertiliser use in food production remains negligible. This is associated with the myths of Ugandan soils being fertile, and increasing environmental crusades against fertilisers by environmentalists who advocate organic farming. Strong advocacy for judicious use of fertilisers is needed. The results of this thesis provide strong arguments that could help in demonstrating the need for fertiliser to increase food production, but also the need for targeting to ensure efficient use of fertiliser.

The soil organic matter status of poor fertility fields needs to be increased up to thresholds that enhance high use efficiencies. The thresholds should be determined for different soil types and also for different crops. Long term experimentation will be needed and/or explorations with dynamic modelling combining yield responses, SOC and texture with nutrient use efficiencies.

The context specific targeting of nutrient resources to heterogeneity can only become a road to increasing food production and addressing food insecurity when the socioeconomic environment is suitable. It is noteworthy to remember that the collapse of institutional arrangements together with political instability and population growth resulted in the declines in productivity and the lack of sustainability in the Teso farming system (Ebanyat et al., 2008). To improve this system, creation of development pathways that will increase production and attract reinvestment in soil fertility management are needed. When production is low the use of external inputs is needed but this is beyond the farmer's capacity to afford because of poverty. External interventions are needed in such cases and the assumption is that once farmer's capacity is built to use of nutrient resources to a certain critical optimum, they can then independently begin to search for most appropriate economic optima for their own farms enterprises (Wit, 1992). Mali's white revolution (Tefft, 2004) provides an example of strong public-private partnerships around profitable commodity cotton. Technical assistance (extension) was rendered to farmers on cotton agronomy and their production skills enhanced. Access to credit in terms of fertilisers and other inputs and also household capital in terms of cattle which addressed other livelihood aspects, provided manure and alleviated the farm labour constraints through animal traction. Manure produced and mineral fertiliser was targeted to cotton fields. The residual effects of the nutrient inputs resulted in increasing overall systems productivity (Benjaminsen, 2001). Both extensification and intensification took place simultaneously in the system. This success was hinged on political will, guiding policy and building of appropriate institutions and partnerships (Bingen, 1998). Thus win-win situations are needed to balance profitability of the enterprises and soil fertility improvements - otherwise technologies interventions alone can fail.

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Appendices

Appendix 3.1.

Morphological characteristics of soil profiles along toposequences and soil classification

Chelekura village *(Profile chemical data is in Table 2, Chapter 3)*

Pit No. 1

I. Information on the site:

(a) Location: Uganda, Pallisa District, Chelekura A Parish, lower slope facing north, dissected plateau.

(b) Soil Name:

(c) Higher Category Classification: Possibly Plinthic Ferrasols (FAO): Petroferric Kandiustox (USDA)

(d) Date of Examination: 22/02/2005

(e) Author: P. Ebanyat and J. Aniku

(f) Site: Chelekura A village, Mr. Okodoi's Farm (575289, 142784)

(g) Elevation: 1072 masl

(h) Land form:

  i. Physiographic position: on gentle concave upper slope

  ii. Surrounding landforms: intricately dissected uplands with numerous drainage ways and streams

  iii. Microtopography: nil

(i) Slope on which profile is sited: Gently sloping (2-3%)

(j) Land-use:

At the time of examination, the land was not under any crop as many crops had been harvested the previous season. The land is generally used for cultivation of cotton, maize and cow peas and sorghum. Ploughing is by bullocks; no chemical fertilizers are applied to the fields.

(k) Climate:

No accurate data available, but annual rainfall is about 1200 mm with a dry period January through March. Average annual temperature ranges from 22ºC - 26ºC with June to September being the coolest months.

II. General Information on the Soils

(a) Parent material: Sandy lacustrine deposits over weathered granite.

(b) Drainage: Somewhat excessively drained.

(c) Moisture conditions in profile: Dry up to laterite layer.

(d) Depth of groundwater table: Unknown but certainly more than 6 meters.

(e) Presence of surface stones, rock outcrops: Common (5% - 15%) large granite boulders.

(f) Evidence of erosion: None at site

(g) Presence of salt or alkali: None
(h) Human influence: Very light, confined to plough layer.

III. Brief Description of the Profile:

Moderately deep very well drained, grey sandy loam profile with coarse blocky structure. Very friable, very porous.

IV Profile Description

Ap 1: 0 - 13 cm	Dark reddish (10 YR 4/2) moist, greyish brown (10 YR 5/2) dry; loamy sand; weak fine crumb structure; many very fine and medium interstitial pores; abundant fine and medium roots; clear, wavy boundary.
Ap 2: 13 - 23 cm	Dark reddish brown (10 YR 4/2) moist, greyish brown (10 YR 5/2) dry, sandy loam; strong coarse sub angular blocky; slightly sticky, slightly plastic; very friable moist; slightly hard dry; many fine interstitial pores; few fine roots; clear smooth boundary.
B: 23 - 60 cm	Brown (7.5 YR 4/2) moist, brown (7.5YR 5/3) dry; sandy clay loam; strong coarse angular blocky structure; slightly sticky, slightly plastic; hard dry, firm moist; many fine and medium interstitial pores, few termite galleries; many fine and medium roots; abrupt smooth boundary.
C: > 60 cm	Continuous layer of cemented iron oxide concretions and nodules of irregular shape.

SOIL CLASSIFICATION

Diagnostic surface horizon (Eipedon): Ochric
Diagnostic sub-surface horizon: Oxic
Petroferric contact
Moisture regime: Ustic
Soil temperature: Isohyperthermic
Family Differentiae: Fine-loamy; probably mixed clay mineralogy
Reaction class: Acid
Depth class: Shallow

Classification according to FAO Revised Legend 1998

Ochric A Horizon; Ferralic B Horizon
Haplic Ferralsols, Petroferric phase

Pit No. 2

I. Information on the Soil:

(a) Location: Uganda, Pallisa District, Chelekura A Parish, on summit of a broad plateau.

(b) Soil name;

(c) Higher category classification: Plinithic Ferrasols (FAO), Petroferric Kandiusto (USDA)

(d) Date of examination: 22/02/2005

(e) Authors: P. Ebanyat and J. Aniku

(f) Site: Chelekura A Parish, Mr. Kupliano Oluka's farm (574508, 142400)

(g) Elevation: 1070 masl

(h) Landform

  i. Physiographic position: pediment of broad plateau

  ii. Surrounding landforms: Intricately dissected midland with numerous drainage ways and streams.

  iii. Microtopography: Nil

(i) Slope: Plain to gently sloping (1%-2%)

(j) Land use: Formally under cassava crop but the crop was harvested a few months before examination of profile. Natural vegetation is savanna with acacia species.

(k) Climate

No accurate data available, but annual rainfall is about 1200mm with a dry period January through March. Average annual temperature ranges from 22ºC - 26ºC with June to September being the coolest months.

II. General Information

(a) Parent material: Weathered granite:

(b) Drainage: Well drained

(c) Moisture condition in profile: Profile dry throughout

(d) Depth of ground water table: Unknown possibly > 10m

(e) Common (5%-15%) granite large boulders

(f) Evidence of erosion: Slight sheet erosion

(g) Presence of salts and alkali: None

(h) Human influence: Very slight, confined to plough layer

III. Brief Description of the Profile

Generally a shallow, well drained profile; red, sandy loam over laterite gravel at 38cm depth

IV. Profile Description

Ap: 0 – 10cm	Red (2.5 YR 4/6) moist, light red (5 YR 6/6) dry; coarse sandy loam; strong coarse angular blocky structure; slightly sticky, slightly plastic, slightly firm moist, hard dry; many fine and medium interstitial pores, few tubular pores; many fine and medium roots; clear wavy boundary.
B1: 10 -30cm	Reddish brown (2.5 YR 4/4) moist, light red (2.5 6/6) dry; clay loam; weak coarse sub angular blocky structure; sticky, plastic, friable moist, hard dry; many fine and few interstitial pores, many fine and few medium roots; clear smooth boundary.
B2: 30-38cm	Reddish brown (2.5 YR 4/4) moist, red (2.5 YR 5/6) dry; clay loam; weak coarse angular blocky structure; sticky, plastic, friable moist, hard dry; many fine and medium interstitial pores; many fine and medium roots, many few small iron oxide nodules; abrupt smooth boundary.
C: > 38cm	Continuous layer of cemented iron oxide concretions of irregular shape

SOIL CLASSIFICATION

Diagnostic surface horizon (Epipedon): Ochric
Diagnostic sub-surface horizon: Oxic, Petroferric contact
Moisture regime: Ustic
Soil temperature: Isohyperthermic
Family Differentiae: Fine loamy; probably mixed mineralogy
Reaction class: Acid
Depth class: Shallow

Classification according to FAO Revised Legend 1998

Ochric A Horizon and Ferralic B Horizon
Haplic Ferralsols, Petroferric phase

Pit No. 3

I. Information on the soil:
(a) Location: Uganda, Pallisa District, Chelekura A Parish, Mr. Oluka Kupliano’s farm on lower slope facing west.
(b) Soil Name:
(c) Higher Category Classification: Possibly Plinithic Ferrasols (FAO); Plinithic Acrustox (USDA)
(d) Date of examination: 22/02/2005
(e) Authors: P. Ebanyat and J. Aniku
(f) Site: Chelekura A Parish, Mr. Oluka Kupliano’s farm, (574258, 142550)

(g) Elevation: 1068 masl

(h) Landform:

  i. Physiographic position: On a gentle convex middle slope
  ii. Surrounding landform: Intricately dissected uplands with numerous drainage ways and streams
  iii. Microtopography: Nil

(i) Slope on which profile is located: Gentle sloping (2%-3%)

(j) Land use: At time of examination land had no standing crops. The land is generally used for cultivation of cotton, maize, sorghum millet and cow peas, some times in rotations or mixed cropping. Ploughing is done by bullocks: no chemical fertilizer applied.

(k) Climate: No accurate data available, but annual rainfall is about 1200 mm with a dry period January through March. Average annual temperature ranges from 22ºC - 26ºC with June to September being the coolest months.

II. General Information on the Soil:

(a) Parent material: Sandy colluvial or lacustrine deposit over weathered granite and laterite.

(b) Drainage: Well drained

(c) Moisture condition in profile: Dry to the gravel layer

(d) Depth of groundwater table: Unknown but probably more that 4 meters

(e) Presence of surface stones, rock outcrops: Few (2% - 5%) large granite boulders

(f) Evidence of erosion: None at site

(g) Presence of salts and alkali: None

(h) Human influence: Very light, confined to plough layer

III. Brief description of profile:

Moderately deep, well drained, reddish brown sandy loam profile with coarse blocky structure. Friable, porous with uniform appearance. Laterite gravel and rounded granite rock at 90cm depth.

IV. Profile description

Ap: 0 - 15 cm	Dusky red (2.5 YR 3/2) moist, pale reddish brown (2.5 YR 6/2) dry; coarse sandy loam; moderate to strong coarse angular blocky structures; slightly sticky, non plastic, friable moist, hard dry; many fine interstitial pores; abundant fine roots, clear wavy boundary.
A: 15 - 22 cm	Dark reddish brown (5YR 3/2) moist, reddish brown (5 YR 5/3) dry; clay loam; strong coarse angular blocky structure, slightly plastic, firm moist , hard dry; many fine and medium interstitial pores; abundant fine and coarse roots; clear smooth boundary.

B1: 22 - 54 cm	Dark reddish brown (5 YR 3/3) moist, reddish brown (5 YR 4/3) dry; clay loam; strong coarse angular blocky structure; sticky, plastic, firm moist, hard dry, many fine and medium interstitial pores; abundant fine and medium roots, few coarse roots; diffuse wavy boundary.
B2: 54 - 90 cm	Brown (7.5 YR 4/4) moist, brown (7.5YR 5/4) dry; clay loam, moderate to strong angular blocky structure; sticky, plastic, firm moist, hard dry; many fine and medium interstitial pores; many coarse roots; abrupt smooth boundary.
C: > 90 cm	Compact layer of iron oxide concretions and granite rock.

SOIL CLASSIFICATION

Diagnostic surface horizon (Eipedon): Ochric
Diagnostic sub-surface horizon: Oxic (Assumption CEC is low)
Petroferric contact at a depth of 90 cm
Moisture regime: Ustic
Soil temperature: Isohyperthermic
Family Differentiae: Fine loamy, probably mixed mineralogy?
Reaction class: Acid
Depth class: Shallow

Classification according to FAO Revised Legend 1998

Ochric A Horizon and Ferralic B Horizon
Haplic Ferralsols, Petroferric phase

Pit No 4.

I. Information on the soil:

(a) Location: Uganda, Pallisa District, Chelakura A Parish, Mr. Oluka Kupliano’s Farm at the bottom of a broad valley.
(b) Soil name:
(c) Higher Category Classification: Dystric Fluvisols (FAO) Aquic Ustifluvents (USDA)
(d) Date of examination: 23/02/2005
(e) Authors: P. Ebanyat and J. Aniku
(f) Site: Chelekura A Parish, Mr. Oluka Kupliano’s Farm (573508, 142550)
(g) Elevation: 1058 masl
(h) Landform:
  i. Physiographic position: Flat broad valley bottom
  ii. Surrounding landform: Intricately dissected uplands with numerous drainage ways and streams

iii. Microtopography: Common (5%-15%) large anthills and termite mounts.

(i) Slope: Flat

(j) Land use: Previously under cotton crop. Generally used for rice cultivation.

(k) Climate

No accurate data available, but annual rainfall is about 1200 mm with a dry period January through March. Average annual temperature ranges from 22ºC - 26ºC with June to September being the coolest months.

II. General Information on the Soil

(a) Parent Material: Alluvial deposit

(b) Drainage: Poorly drained

(c) Moisture condition and profile: Dry 0-20cm, moist below 20cm to the mottled laterite layer

(d) Depth of groundwater table: Unknown but possibly less than 2m. Nearby fields had a shallow water wells at 30cm depth; possibly from a patched water table.

(e) Presence of surface stones, rock outcrops: None

(f) Evidence of erosion: None

(g) Presence of salt of alkali: Presence of salts suspected as the sandy soil cakes on drying.

(h) Human influence: Very slight, confined to the plough layer. There are some drainage channels.

III. Brief description of the profile

Deep, poorly drained soil occurs in nearly levels flats between the uplands. They developed from sediments washed from the uplands. Have a coarse sandy surface and subsurface layers. Saturated for long periods every year. Many, medium prominent mottles at the gravel layer.

IV. Profile description

Ap: 0 - 14 cm	Dark grey (10 YR 4/1) moist, grey (10 YR 6/1) dry, sand, coarse sub angular blocky breaking into medium sub angular blocky structure; non sticky, non plastic, very friable moist, hard dry, many fine and medium interstitial pores; many fine roots; abrupt smooth boundary.
A: 14 - 41 cm	Dark grey (10 YR 4/1) moist, greyish brown (10 YR 6/1) dry; coarse loamy sand; massive structure; non-sticky, non-plastic, firm dry, hard dry; few fine interstitial pores; non visible roots; clear smooth boundary.
B1: 41 - 63 cm	Dark reddish brown (10 YR 4/2) moist, greyish brown (10 YR 6/1) dry; coarse sand; massive structure, extremely hard dry, very firm moist; no visible pores; no visible roots; diffuse wavy boundary.

B2: 63 - 110 cm.	Light yellowish brown (10 YR 6/4) moist, matrix, strong brown (7.5 YR 4/6) moist mottles; sandy clay; strong coarse prismatic structures; sticky, plastic; very firm moist, very hard dry; no visible pores; no visible roots; 10% hard iron modules; abrupt smooth boundary.
C: > 110 cm	Compact layer of iron oxide concretions

SOIL CLASSIFICATION

Diagnostic surface horizon (Eipedon): Ochric
Diagnostic sub-surface horizon: Cambic
Moisture regime: Ustic
Soil temperature: Isohyperthermic
Family Differentiae: Loamy over clayey
Reaction class: Acid
Depth class: Deep

Classification according to FAO Revised Legend 1998

Ochric A Horizon
Cambic B Horizon
Fluvic properties
Dystric Fluvisols

Onamudan village *(profile chemical properties are in Table 3, Chapter 3)*

Pit No. 1

I. Information on the Site

(a) Location: Uganda, Pallisa District, Onamudian Village, Mr. Obiro Lambert's Farm, lower slope facing east in a dissected plateau.

(b) Soil Name:

(c) Higher Category Classification. Plinithic Ferrasols(FAO), Petroferric Kandiustox (USDA)

(d) Date of examination: 23/02/2005

(e) Authors: P. Ebanyat and J. Aniku

(f) Site: Onamudian Village, Mr. Obiro Lambert's farm (585108, 133000)

(g) Elevation: 1119 masl

(h) Landform

i. Physiographic position: On gentle concave lower slope

ii. Surrounding landform: Intricately dissected uplands with numerous drainage ways and streams.

iii. Microtopography: Few large one meter high anthills.

(i) Slope on which the profile is sited: Gently sloping (2%-3%) facing to the east.

(j) Land use: At the time of examination, maize had been harvested. Land generally used for cultivation of cotton, maize, sorghum, millet, cassava and cow peas. Ploughing is by bullocks. No mineral fertilizer added to fields.

(k) Climate

No accurate data available, but annual rainfall is about 1200 mm with a dry period January through March. Average annual temperature ranges from 22ºC - 26ºC with June to September being the coolest months.

I. General Information with soil

(a) Parent material: Weathered granite

(b) Drainage: Well drained

(c) Moisture condition in profile: Dry throughout

(d) Depth of groundwater table: Unknown but certainly more than 6m

(e) Presence of surface stones, rock outcrops: None at site

(f) Evidence of erosion: None at site

(g) Presence of salt or alkali: None

(h) Human influence: Very light, confined to plough layer

III. Brief Description of the Profile

Shallow to moderately deep, well drained, reddish brown sandy clay profile; course angular blocky structure, friable, porous, over compact cemented layer of laterite gravels.

IV. Profile Description

Ap1: 0 - 8 cm	Dusky red (2.5 YR 3/2) moist, reddish brown (2.5YR 4/3) dry; sandy loam; weak coarse sub angular blocky, breaking into crumb structure; slightly sticky, slightly plastic, friable moist, slightly hard dry; many fine and medium interstitial pores; abundant fine and coarse roots; clear smooth boundary.
Ap 2: 8 - 17 cm	Dark reddish brown (2.5 YR 3/3) moist, reddish brown (2.5 YR 4/3) dry; sandy clay loam; moderate medium angular blocky, sticky, plastic, firm moist, slightly hard dry; many fine interstitial pores; abundant fine and coarse roots; clear smooth boundary.
B1: 17 - 34 cm	Dark reddish brown (2.5 YR 3/4) moist, reddish brown (2.5 YR 4/4) dry; sandy clay; strong coarse angular blocky structure; sticky, plastic, friable moist, hard dry; many fine and medium interstitial pores; abundant fine roots; clear smooth boundary.
B2: 34 - 58 cm	Dark reddish brown (2.5 YR 3/4) moist, reddish brown (2.5YR 4/4) dry; gravelly sandy clay loam; coarse angular blocky structure; sticky, plastic, firm moist, hard dry; many fine and medium interstitial pores; abundant fine and coarse roots; clear smooth boundary.
B3: 58 - 72 cm	Reddish brown (5 YR 4/4) moist, yellowish red (5 YR 5/6) dry; gravely clay loam; weak medium angular blocky structure; slightly sticky, slightly plastic, many fine interstitial pores; few coarse roots in channels; abrupt boundary.
C: > 72 cm	Compact cemented layer of laterite gravel.

SOIL CLASSIFICATION

Diagnostic surface horizon (Eipedon): Ochric
Diagnostic sub-surface horizon: Kandic horizon
Petroferric contact
Moisture regime: Ustic
Soil temperature: Isohyperthermic
Family Differentiae: Fine-loamy over clayey
Reaction class: Acid
Depth class: Shallow

Classification according to FAO Revised Legend 1998

Ochric A-Horizon
Ferralic B Horizon

Classification: Humic Ferralsols, Petroferric phase

Pit No. 2

II. Information on the Soil

(a) Location: Uganda, Pallisa District, Onamudian Village, Mr. Opolot's Farm, on the crest of a broad plateau.
(b) Soil Name:
(c) Higher category classification: Plinithic Ferrasols (FAO), Pettroferric Kundiustox (USDA)
(d) Date of examination: 22/02/2005
(e) Authors: P Ebanyat and J. Aniku
(f) Site: Onamudian Village, Mr. Opolot's Farm (584608, 132650)
(g) Elevation: 1111 masl
(h) Landform:
(i) Slope: flat
(j) Land use: At time of examination cotton had been harvested, generally cultivated to maize, cassava, millet, sorghum and cow peas. Ploughing by bullocks; no chemical fertilizer applied to the fields.
(k) Climate:

No accurate data available, but annual rainfall is about 1200 mm with a dry period January through March. Average annual temperature ranges from 22-26°C with June to September being the coolest months.

II. General Information on the Soil

a) Parent material: Weathered granite
b) Drainage: Well drained
c) Moisture condition in the profile: Dry throughout
d) Depth of groundwater table: Unknown, possibly more than 10 meters
e) Presence of surface stones, rock outcrops: None on the site
f) Evidence of erosion: None on the site
g) Presence of salts or alkali: None
h) Human influence: Very light, confined to plough layer

III. Brief Description of the Profile

Moderately deep, well drained, reddish brown, clay loam profile, coarse angular blocky structure, friable, porous, uniform appearance of horizons over compact iron oxide gravels.

IV. Profile description

Ap1: 0 - 6 cm	Dusky red (2.5 YR 3/2) moist, reddish brown (2.5 YR 4/4) dry; loam; weak fine granular structure; slightly sticky, plastic, friable moist, soft dry; many fine and medium interstitial pores; many fine roots; clear smooth boundary.
Ap2: 6 - 16 cm	Dusky red (2.5 YR 3/2) moist, reddish brown (2.5 YR 4/4) dry; clay loam; strong coarse angular blocky structure; sticky, plastic, friable moist, slightly hard dry; many fine and medium interstitial pores; abundant fine and medium roots; clear smooth boundary.
B1: 16 - 30 cm	Dark reddish brown (2.5 YR 4/4) moist, red (2.5 YR 4/6) dry; clay loam; strong medium angular blocky; sticky, plastic, firm moist, hard dry; many fine and coarse interstitial pores; many fine and few coarse roots; clear wavy boundary.
B2: 30 - 42 cm	Dark reddish brown (2.5 YR 3/4) moist, red (2.5 YR 4/6) dry; clay loam; strong coarse angular blocky structures; sticky plastic, firm moist, hard dry; many fine and medium pores, few termite galleries, few fine and coarse roots; clear wavy boundary.
C1: 42 - 70 cm	Red (2.5 YR 4/6) moist, dark red (2.5 YR 5/8) dry; clay loam; weak medium angular blocky structure; slightly sticky, slightly plastic, firm moist, hard dry; many fine interstitial pores; abundant fine roots; clear smooth boundary.
C2: > 70 cm	Compact layer of cemented iron oxide concretions.

SOIL CLASSIFICATION

Diagnostic surface horizon (Eipedon): Ochric
Diagnostic sub-surface horizon: Oxic
Moisture regime: Ustic
Soil temperature: Isohyperthermic
Family Differentiae: Fine Loamy, Probably mixed mineralogy
Reaction class: Acid
Depth class: Shallow

Classification according to FAO Revised Legend 1998

Ochric A Horizon
Ferralic B Horizon
Petroferric phase
Rhodic Ferralsols, Petroferric phase

Pit No. 3

I. Information on the Site:

(a) Location : Uganda, Pallisa District, Onamudian Village, Ms. Pricilla Akol's Farm, lower slope facing west in a dissected plateau

(b) Soil Name:

(c) Higher category classification: Plinithic Ferrasols (FAO), Petroferric Kandiustox (USDA)

(d) Date of examination: 23/02/2005

(e) Authors: P. Ebanyat and J. Aniku

(f) Site: Onamudian Village, Ms. Pricilla Akol's Farm (584608,132650)

(g) Elevation: 1094 masl

(h) Land form

i. Physiographic position: Gentle concave lower slope

ii. Surrounding landform: Intricately dissected uplands with numerous drainage ways streams.

iii. Microtopography: Nil

(i) Slope on which the profile is sited: Gently sloping (2%-3%) facing the west.

(j) Land use: At the time of examination the field was under weeds. It was previously under crops. Land generally is used for cultivation of cotton, maize, sorghum, millet, cassava and cowpeas. Ploughing by bullocks no chemical fertilizer applied to the fields.

(k) Climate: No accurate data available, but annual rainfall is about 1200 mm with a dry period January through March. Average annual temperature ranges from 22-26°C with June to September being the coolest months.

II. General information on the soil

(a) Parent material: Weathered Granite

(b) Drainage: Well drained

(c) Moisture condition in profile: Dry throughout

(d) Depth of groundwater table: Unknown, possibly more than 6m

(e) Presence of surface stones, rock outcrops: None at Site

(f) Evidence of erosion: None At Site

(g) Presence of salt or alkali: None

(h) Human influence: Very Light, Confined To Plough Layer

III. Brief Description of Profile

Very deep, well drained, red clay loam, coarse angular blocky structure, friable, porous, uniform appearance of horizons over weathered granite fragments.

IV. Profile description:

Ap1: 0 - 15 cm	Dark reddish grey (10 YR 3/1) moist, dark reddish grey (10 R 4/1) dry; sandy loam; moderate coarse angular blocky structure; slightly sticky, slightly plastic, friable moist, slightly hard dry; many fine and medium interstitial pores; abundant fine and medium interstitial pores; abundant fine and few coarse roots; clear smooth boundary.
A: 15 - 31 cm	Dusky red (2.5 YR 3/2) moist, weak red (2.5 YR 4/2) dry; sandy clay loam; moderate medium angular blocky structure; slightly sticky, plastic, friable moist, hard dry; many fine and few interstitial pores; abundant fine and medium roots; clear smooth boundary.
B1: 31 - 58 cm	Very dusky red (2.5 YR 2.5/2) moist, weak red (2.5 YR 4/2) dry; sandy clay; strong coarse angular blocky structure; sticky, plastic friable moist, hard dry; many fine and medium interstitial pores; many fine and coarse roots confined in cracks and animal holes; diffuse smooth boundary.
B2: 58 - 85 cm	Dark reddish brown (5 YR 3/3) moist, reddish brown (5 YR 4/3) dry; sandy clay; strong coarse angular blocky; sticky, plastic, friable moist, hard dry; many fine interstitial pores, few termite galleries; few fine roots diffuse smooth boundary;
B3: 85 - 140 cm	Reddish brown (5 YR 4/4) moist, reddish brown (5YR 5/4) dry; sandy clay; strong medium angular blocky, breaking into medium blocky structure; sticky, plastic, friable moist, slightly hard dry; few fine interstitial pores; few coarse and fine roots; clear smooth boundary.
C: > 140 cm	Weathered fractured granite rock fragments.

SOIL CLASSIFICATION

Diagnostic surface horizon (Eipedon): Mollic
Diagnostic sub-surface horizon: Oxic
Moisture regime: Ustic
Soil temperature: Isohyperthermic
Family Differentiae: Fine-loamy
Reaction class: Acid
Depth class: Deep

Classification according to FAO Revised Legend 1998

Mollic A-horizon
Ferralic B horizon
Humic Ferralsols

Pit No. 4

I. Information on the Soil:

(a) Location: Uganda, Pallisa District, Onamudian Village, Ms. Priscilla Akol's Farm, on nearly level flats between the uplands.

(b) Soil Name

(c) Higher Category Classification: Dystric Fluvisols(FAO), Tropaquepts (USDA)

(d) Date of examination: 23/02/2005

(e) Authors: P. Ebanyat and J. Aniku

(f) Site: Onamudian village, Priscilla Akol's Farm (583208,132000)

(g) Elevation: 1087 masl

(h) Landform:

  i. Physiographic position: On nearly level land
  ii. Surrounding landform: Dissected plateau with wide flat bottomed valleys
  iii. Microtopography: Common (5%-20%) large anthills

(i) Slope on which the profile is sited: Nearly flat (0%-1%)

(j) Land use: Under young rice crop

(k) Climate

No accurate data available, but annual rainfall is about 1100 mm with a dry period January through March. Average annual temperature ranges from 22ºC-26ºC with June to September being the coolest months.

II. General Information on the soil

(a) Parent material: Alluvial and colluvial deposits

(b) Drainage: Very poorly drained

(c) Moisture condition in profile: Wet throughout

(d) Depth of groundwater table: Water table at 66cm depth

(e) Presence of surface stones, rock outcrops: None

(f) Evidence of erosion: None

(g) Presence of salts or alkali: Salts possibly present as shown by caking of the sandy soil on drying

(h) Human influence: Light construction of drainage canals; cultivation of surface by ploughing

III. Brief description of the profile

This profile was studied in auger holes using 7.5cm Ø bucket auger at 10cm depth intervals. It is a very deep, very poorly drained soil that occurs in nearly level flats between the uplands. They have developed on sediments washed from the uplands. They have a thick coarse sandy surface and subsurface layers; a bluish grey clayey substratum occurs at 90cm depth.

IV. Profile description

Ap: 0 - 10 cm	Dark grey (10 YR 4/1) moist, grey (10 YR 6/1) dry, sand, coarse sub angular blocky breaking into medium sub angular blocky structure; non sticky, non plastic, very friable moist, hard dry, many fine and medium interstitial pores; many fine roots; abrupt smooth boundary.
A: 10 - 30 cm	Dark grey (10 YR 4/1) moist, greyish brown (10 YR 6/1) dry; coarse loamy sand; massive structure; non-sticky, non-plastic, firm dry, hard dry; few fine interstitial pores; non visible roots; clear smooth boundary.
B1: 30 - 80 cm	Dark reddish brown (10 YR 4/2) moist, greyish brown (10 YR 6/1) dry; coarse sand; massive structure, extremely hard dry. Very firm moist; no visible pores; no visible roots; diffuse wavy boundary.
B2: 80 - 110 cm	Light yellowish brown (10 YR 6/4) moist, matrix, strong brown (7.5 YR 4/6) moist mottles; sandy clay; strong coarse prismatic structures; sticky, plastic; very firm moist, very hard dry; no visible pores; no visible roots; 10% hard iron modules; abrupt smooth boundary.

SOIL CLASSIFICATION

Diagnostic surface horizon (Eipedon): Ochric
Diagnostic sub-surface horizon: Cambic
Moisture regime: Ustic
Soil temperature: Isohyperthermic
Family Differentiae: Fine loamy overclayey

Classification according to FAO Revised Legend 1998

Ochric A-Horizon
Cambic B- Horizon
Exhibiting some gleyic properties
Classification: Dystric Fluvisols

Appendix 3.2.

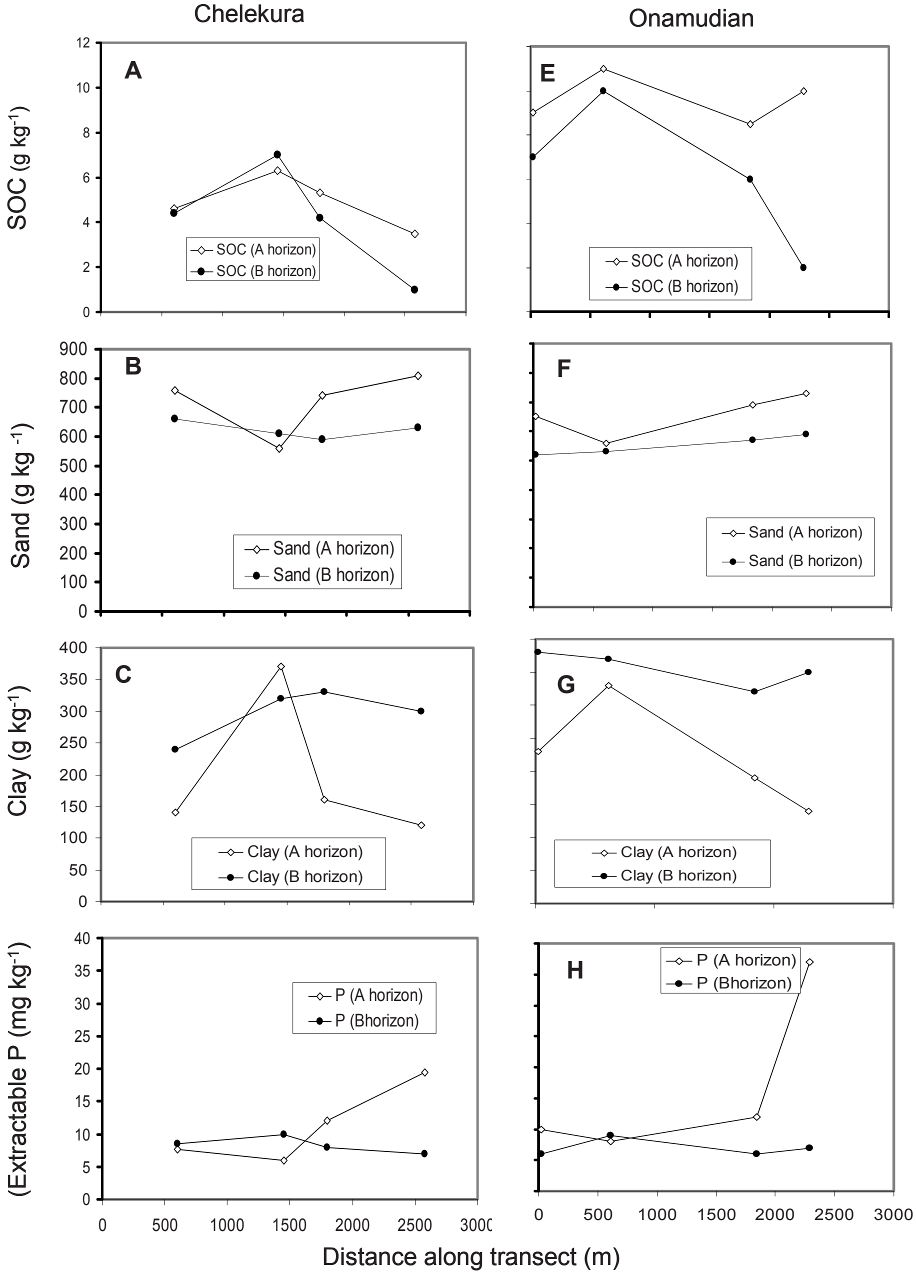

Figure 2.1 Variations of soil properties in profiles along transects in the study villages: (A) SOC, (B) Sand (C) Clay and (D) extractable P in Chelekura village; (E) SOC, (F) Sand (G) Clay and (H) extractable P in Onamudian village.

Appendix 3.3.

Table 3.1 Regressions equations and coefficients of determination of predicted soil properties with slope (%) in the study villages

Village/ soil property	Equation	Coefficient of determination (R^2)
Chelekura		
pH (units)	Y = 0.055x + 6.12	0.0060
SOC (g kg $^{-1}$)	Y = -0.093x + 7.37	0.0004
Tot N (g kg $^{-1}$)	Y = -0.012x + 0.78	0.0007
Extract P (mg kg^{-1})	Y = -0.932x + 18.53	0.0060
Exch. K (cmol$_c$ kg^{-1})	Y = -0.011x + 0.44	0.0030
Exch. Ca (cmol$_c$ kg^{-1})	Y = -0.004x + 1.76	0.0020
Exch. Mg (cmol$_c$ kg^{-1})	Y = -0.004x + 0.60	0.0030
Sand (g kg $^{-1}$)	Y = 0.260x + 760.16	0.0007
Silt + clay (g kg $^{-1}$)	Y = -0.067x + 140.37	0.0001
Onamudian		
pH (units)	Y = 0.063x + 6.04	0.017
SOC (g kg $^{-1}$)	Y = -0.890x + 17.59	0.040
Tot N (g kg $^{-1}$)	Y = -0.089x + 1.85	0.031
Extract P (mg kg^{-1})	Y = 0.652x + 12.20	0.015
Exch. K (cmol$_c$ kg^{-1})	Y = -0.0031x + 0.544	0.001
Exch. Ca (cmol$_c$ kg^{-1})	Y = -0.004x + 1.76	0.0020
Exch. Mg (cmol$_c$ kg^{-1})	Y = -0.051x + 7.68	0.0001
Sand (g kg $^{-1}$)	Y = 2.410x + 510.23	0.099
Silt + clay (g kg $^{-1}$)	Y = -2.500x + 480.57	0.1000

Summary

Smallholder farming systems in sub-Saharan Africa (SSA) are dynamic and their productivity status results from actions of human agency as conditioned by socio-economic and biophysical environments. Across these systems, poor soil fertility is recognised as a major factor responsible for low per capita food production. Increasing crop productivity on the poor fertility soils is needed to alleviate the food insecurity problems in SSA. In most smallholder farming systems however, population pressure has stretched land use without inputs to limits and are now in transitions to intensification. Efficient use of scarce soil fertility inputs is needed as the smallholders in SSA are resource constrained. Targeting nutrient management interventions to heterogeneity can greatly enhance their use efficiency if done at relevant scales and can help in identification of 'best fits' (most suitable options for niches within the systems). In identification of best fits from available options, efficacy of the interventions in a given biophysical environment, social acceptance, and economic viability are major initial concerns that must be ascertained. The goal of this thesis therefore, was to contribute to understanding how to improve crop production in the Teso farming system through targeting of nutrient management options to heterogeneity in soil fertility.

Changes in land use in two parishes in Pallisa district representative of the Teso farming system were quantified for the period 1960-2001 using remote sensing techniques and major driving factors identified through a comparative analysis with a similar system in southern Mali. Sustainability of the system and its determinants were assessed using nutrient balance analysis and regression analysis respectively. By 2001, 46% and 78% more land had been brought into cultivation in Chelekura and Onamudian parishes respectively. These increases were negatively correlated with the disappearance of forests (*r* = –0.07), grasslands (*r* = –0.84), bushlands, (*r* = –0.64), and papyrus swamp (*r* = –0.49) and positively correlated with rice cultivation (–0.87). Population increase was positively correlated with increase of cultivated land (*r* = 0.70). Farm nutrient balances for N, P and K were all positive on only larger farms (LF) that owned at least 9 heads of cattle compared to medium farms (MF) and small farms with (SF1) and without cattle (SF2). At the crop scale however, nutrient balances were negative on all the farm types. Sustainability of the farming system is driven by livestock, crop yield, labour availability and access to off farm income. Crop productivity in the system was low because of non use of nutrient inputs compared to a similar system in southern Mali. In conclusion, population growth and political-instability-mediated effects arising from the collapse of cotton marketing and land management institutions, communal labour arrangements and cattle rustling complement in explaining the changes in land use and the obtaining productivity status of the farming system.

The nature and magnitude of variability in soil fertility was characterised in Chelekura and Onamudian villages through soil profile observations along toposequences of soil types and analysis of surface soils from fields on 33 farms exhibiting different geo-morphological features. Down the toposequences, soil pH, SOC, total N, Exch. Mg, Exch. Ca, Exch. K, CEC, sand and clay did not exhibit topographic-gradients. Extractable P was however 3 and 5 times higher in the top soils of the profiles in the valley bottoms than those in the upper landscape positions of the toposequences in Chelekura and Onamudian respectively. Within the profiles of each local soil type, soil pH, SOC, sand, total N, extractable P, exchangeable bases and sand decreased with depth except in the valley bottoms where Ca increased with depth. SOC and silt + clay are used to illustrate the spatial variability in soil fertility within-farms. Significant differences ($P<0.05$) were observed in average SOC concentrations in surface soil properties between landscape positions in both villages. Larger and significant differences ($P<0.001$) in SOC were observed between field types. Fields classified as of good, medium and poor soil fertility by farmers had average SOC concentrations of, respectively 9.3 g kg^{-1}, 6.6 g kg^{-1}, 5.5 g kg^{-1} in Chelekura village and 15 g kg^{-1}, 11 g kg^{-1}, 7 g kg^{-1} in Onamudian village. In contrast with other studies in smallholder farming systems in sub-Saharan Africa, spatial analysis did not reveal a particular generalized pattern in variability in soil fertility (evaluated here using SOC as an indicator) across farms in each village. Within-farms, larger contents of SOC were associated with larger amounts of silt + clay and on locations where cattle kraals had been sited in the past. The field scale, which is easily recognised by farmers, is an important entry point for targeting soil fertility management technologies since management decisions are at the farm scale.

Experiments were conducted in the two villages to evaluate the impacts of landscape position and field type on the biomass yield, N accumulation and N_2-fixation by six legumes (cowpea, green gram, groundnut, mucuna, pigeonpea and soyabean) grown with and without P during the short rain season of 2005 and after harvest incorporated in the soil. Residual effects of the legumes on the productivity of finger millet were assessed for two subsequent seasons in 2006. Legume biomass and N accumulation differed significantly ($P<0.001$) between villages, landscape position, field type and P application rate. Mucuna accumulated the most biomass (4.8-10.9 Mg ha^{-1}) and groundnut the least (1.0-3.4 Mg ha^{-1}) on both good and poor fields in the upper and middle landscape positions. N accumulation and amounts of N_2-fixed by the legumes followed a similar trend as biomass, and was increased significantly by application of P. Grain yields of finger millet were significantly ($P<0.001$) higher in the first season after incorporation of legume biomass than in the second season after incorporation. Finger millet also produced significantly more grain in good fields (0.62-2.15 Mg ha^{-1}) compared with poor fields (0.29-1.49 Mg ha^{-1}) across the two villages. Farmers preferred growing groundnut and were not interested in growing pigeonpea and mucuna. They said that they would preferentially target grain legumes to good fields except for mucuna and pigeonpea which they said they would grow only in poor fields. Benefit-cost ratios indicated that legume-millet rotations without P application were only profitable on good fields in both villages. We suggest that green grams, cowpea and soyabean without P can be targeted to good fields on both upper and middle landscape positions in both villages but mucuna without P to poor fields on the middle landscape position in Chelekura village and cowpea without P to poor fields on the upper landscape position in Onamudian village. Although legumes are recommended for smallholder farming systems, they only suffice on good fertility fields and use of fertiliser P in their production is only economical if its price then was reduced by 30-40%.

Legumes could not profitably increase finger millet productivity on poor fields and as such effectiveness of inorganic fertilisers and kraal manure on the nutrient-depleted fields was tested through field experiments over 3 seasons. N, P fertilisers alone (0, 30, 60, 90 kg ha^{-1}), N+P at equal rates of single application, and manure (3 t ha^{-1}) supplemented with N (0, 30, 60 and 90 kg ha^{-1}) were applied to degraded fields located in upper and middle landscape positions in both villages. A second control treatment of millet grown on soils of former kraals (high fertility niches) was included as a benchmark. Average grain yield ranged from 404 kg ha^{-1} to 2026 kg ha^{-1} and differed significantly ($P<0.001$) between villages and seasons in 2006. Significant effects ($P<0.05$) of landscape position on grain yield were observed only in Onamudian village. The treatments significantly increased millet yields on degraded fields but could not eliminate the yield differences between degraded fields and former kraals. The largest grain yields on degraded fields were obtained with application of N+P with average yields of 800 kg ha^{-1} in Chelekura village and 1171 kg ha^{-1} in Onamudian village. These yield responses closed the within farm yield gap (with bench mark) by 24% and 43 % in Chelekura and Onamudian respectively. The inability of the options to close the yield differences was because of poor nutrient use efficiencies which were often less than 25% as a result of other nutrient limitations (S and K) and probably other physical limitations like moisture infiltration due to such as surface crusting.

With large heterogeneity in soil fertility within smallholder farming systems, blanket recommendations are of limited value. The Quantitative Evaluation of Fertility of Tropical Soils (QUEFTS) model was calibrated for finger millet to explore the potential of this approach to develop site-specific nutrient management recommendations. The model constants (kg grain kg^{-1}) were determined respectively for maximum accumulation (a) and maximum dilution (d) of 21 and 53 kg grain kg^{-1} N, 76 and 261 kg grain kg^{-1} P and 11 and 46 kg grain kg^{-1} K. The observed versus model-predicted yield was good ($r^2 = 0.76$; RMSD = 262 kg ha^{-1}). Balanced fertilisation requirements for a target millet yield of 2000kg ha^{-1} was estimated at 83 kg N ha^{-1} and 52 kg P ha^{-1} and 56 kg K ha^{-1} for the sandy loam soils of Chelekura village and 64 kg N ha^{-1} and 31 kg P ha^{-1} and 40 kg K ha^{-1} for the sandy clay loam soils in Onamudian village. Predictions of yield responses from soil application of nutrients however will need that soil conditions are taken into account. In the degraded fields, often other nutrient limitations and physical limitations such as water availability that affect nutrient uptake are not accounted for in QUEFTS. Thus model calculated yields will be higher as it depends on total available nutrients from soil and added fertiliser.

In conclusion, targeting nutrient management options can result in larger benefits from nutrient management interventions and specific attention can be afforded to specific constraints to avoid waste of resources. Overall, improving the quality of poor fertility fields is needed to benefit from nutrient management interventions. Application of manure to boost SOC in soils is needed first before high nutrient use efficiencies from applications of mineral fertilisers can be obtained. This underlines combined use of organic and mineral nutrient resources in rehabilitation of degraded fields. With small populations of cattle in the system, manure quantities are rather small. The prospect of increasing numbers is also constrained by poor quality and limited quantities of grazing pastures. A shift in cattle management to stall feeding could improve manure collection. This may be a potential approach but alongside fodder banks have to be developed and pasture quality improved. The feasibility to switch to stall feeding systems is impossible without profitable milk production to compensate for the higher labour demands of such a system. Mineral fertilisers on the other hand are scare and expensive for smallholders. Their use has to be strategically promoted. From the agronomic standpoint, the determination of SOC thresholds for higher mineral fertility use efficiencies is required. The thresholds differ with soil type (silt + clay) and crop and need to be established. The efficiencies at farm/ system scale also need to be determined and reconfiguration of cropping systems is needed. Crops that increase profitability of fertiliser use (as well as organic inputs) will attract reinvestment in soil fertility management. For systems like the Teso system with low production, use of external inputs particularly mineral fertilisers is inevitable. External interventions and enabling policy framework that enhances public-private partnerships around profitable commodities and addressing also broader livelihood needs could make targeting nutrient options to heterogeneity a road to sufficient food production.

Samenvatting

Bedrijven van kleine boeren in Afrika bezuiden de Sahara (AbS) zijn voortdurend onderhevig aan verandering doordat boeren reageren op veranderingen in hun sociaal economische en biofysische omgeving met als resultaat dat ook de productiviteit van deze bedrijven blijft veranderen. Door de bank genomen wordt bodemvruchtbaarheid gezien als de verklarende factor voor de lage per capita voedselproductie van deze bedrijven. Toename van de gewasproductie op arme bodems is noodzakelijk om de voedselonzekerheid in AbS te lijf te gaan. Meer land verbouwen zonder gebruik van externe inputs is geen optie meer omdat als gevolg van de bevolkingsgroei geen land meer beschikbaar is. Wat overblijft voor de kleine bedrijven is een transitie naar meer intensieve landbouw waarbij de productie per hectare wordt verhoogd door verbetering van de bodemvruchtbaarheid. De efficiëntie van het gebruik van de daarvoor nodige inputs is, gezien de beperkte middelen waarover de boeren beschikken, een essentiële voorwaarde. Bij het zoeken naar de meest efficiënte opties (in het Engels ‘best fits’) voor verbetering in het management van nutriënten speelt heterogeniteit tussen en binnen bedrijven een grote rol; niet elke optie is geschikt voor ieder bedrijf en voor alle delen van een bedrijf. Bij het zoeken naar niches waarvoor een optie geschikt is dient dus rekening te worden gehouden met de heterogeniteit in biofysiche factoren, sociale acceptatie and economische levensvatbaarheid. Het doel van dit proefschrift is de productie van gewassen in het Teso landbouw systeem (Oeganda) te verbeteren via nieuw te ontwikkelen kennis en begrip door opties in nutriëntenmanagement te koppelen aan heterogeniteit in bodemvruchtbaarheid.

De veranderingen in landgebruik in twee regio’s in het Pallisa district, representatief voor het Teso landbouwsysteem, zijn over de periode 1960-2001 vastgesteld met behulp van remote sensing technieken; de sturende factoren voor verandering zijn bepaald in een vergelijkingsstudie met een systeem in Zuid Mali. Duurzaamheid van het systeem wordt gekenmerkt door de nutriënten balans en factoren die dit bepalen werden vastgesteld via regressie analyse. Tot 2001 was in de twee regio’s Chelekura en Onamudian 45 en 78 % meer land in cultuur gebracht. Deze toename was negatief gecorreleerd met het verdwijnen van bossen ($r = -0.07$), graslanden ($r = -0.84$), woeste gronden ($r = -0.64$) en papyrus moerassen ($r = -0.49$) en positief gecorreleerd met de verbouw van rijst ($r = 0.87$). De bevolkingstoename over deze periode was positief gecorreleerd met de toename van in cultuur gebracht land ($r = 0.70$). De nutriënten balansen van N, P en K op bedrijfsniveau waren alleen positief op de grote bedrijven die minstens 9 stuks vee hadden (LF) in tegenstelling tot middelgrote (MF), kleine bedrijven met wat vee (SF1) en kleine bedrijven zonder vee (SF2). Op gewasniveau waren de balansen van alle nutriënten negatief in alle bedrijfstypen. De duurzaamheid van het systeem werd bepaald door veeteelt, gewasopbrengsten, arbeid beschikbaarheid en geld verdiend buiten de landbouw. De gewasproductie in Oeganda was laag in vergelijking met het systeem in Zuid Mali waar wel nutriënten inputs werden gebruikt. Concluderend, de bevolkingsgroei en de door politieke instabiliteit veroorzaakte ineenstorting van de katoenmarkt en van instituties voor landbeheer, het wegvallen van afspraken over gebruik van gemeenschappelijke arbeid en veeroof, verklaren de veranderingen in landgebruik en de huidige status van het landbouwsysteem.

De aard en mate van variabiliteit in bodemvruchtbaarheid in relatie tot geo-morfologische eigenschappen is in Chelekura en Onamudian enerzijds vastgesteld door beschrijving van bodemprofielen langs toposequenties van bodemtypen en anderzijds door bodem analyses van monsters van de oppervlakte laag van velden van 33 bedrijven. Afdalend langs de toposequenties werden geen graduele verschillen gevonden in de volgende bodemeigenschappen: pH, totaal N gehalte, uitwisselbare Mg, Ca en K, CEC, zand en klei fracties. Opneembare P was echter 3 (Chelekura) tot 5 keer (Onamudian) zo hoog in de bovenlaag van de bodems in de dalen in vergelijking tot die in hoger gelegen landschap posities van de toposequenties. In het bodemprofiel van elk bodemtype met uitzondering van die in de dalen, nam pH, organisch stof gehalte, zand fractie, totaal N gehalte, opneembare P en uitwisselbare basen af met de diepte in het profiel. In de dalen neemt het Ca gehalte met de diepte toe. Organisch stof gehalte en leem plus klei fracties zijn gebruikt om de ruimtelijke variabiliteit in bodemvruchtbaarheid in bedrijven te illustreren. Organisch stof gehalten van de bovenlaag van de bodems waren significant ($P<0.05$) verschillend tussen landschapschap posities in de regio's. Grotere en meer significante verschillen ($P<0.001$) in organisch stof gehalten werden gevonden tussen veldtypes. Velden door boeren geclassificeerd als goede, gematigde of arme velden in termen van bodem vruchtbaarheid hadden een organisch stofgehalte van 9.3 g kg^{-1}, 6.6 g kg^{-1}, 5.5 g kg^{-1} in Chelekura en 15 g kg^{-1}, 11 g kg^{-1}, 7 g kg^{-1} in Onamudian. In tegenstelling tot andere studies van kleine bedrijfssystemen in AbS heeft de ruimtelijke analyse niet een bepaald, algemeen geldend patroon in variabiliteit in bodem vruchtbaarheid (hier geëvalueerd met het organisch stofgehalte als indicator) opgeleverd. Binnen bedrijven werden de hogere gehalten aan organisch stofgehalte geassocieerd met hogere fracties van leem plus klei en met locaties waar zich vroeger veekralen bevonden. Het schaal niveau van veld is herkenbaar voor boeren en daarom een belangrijke ingang voor het bepalen van geschiktheid van bodemvruchtbaarheid maatregelen, ook omdat beslissingen daarover op het schaalniveau van het bedrijf door de boeren worden genomen.

Er zijn experimenten uitgevoerd in de twee dorpen om het effect van landschap positie en veld type op biomassa opbrengst, N accumulatie en N_2-fixatie van zes vlinderbloemigen (cowpea, green gram, aardnoten, mucuna, pigeonpea en sojabonen) te bepalen. Deze werden daartoe in het korte regenseizoen van 2005 met en zonder toediening van P geteeld; het geoogste plantenmateriaal werd vervolgens ingewerkt in de grond. De effecten op het volggewas gierst werden in de volgende twee seizoenen gemeten. De biomassa van vlinderbloemigen en de N accumulatie verschilden significant (P<0.001) tussen de twee dorpen, landschap posities, veldtypen en bij al of niet bemesten met P. De biomassa van mucuna was het grootst (4.8-10.9 Mg ha^{-1}) en van aardnoten het kleinst (1.0-3.4 Mg ha^{-1}) op zowel goede als arme velden gelegen op zowel hoge als midden posities in het landschap. De accumulatie en fixatie van N door vlinderbloemigen volgde een zelfde trend als de biomassa en was significant hoger wanneer P was toegediend. Korrel opbrengsten van gierst waren significant (P<0.001) hoger in het eerste seizoen na inwerken van de biomassa die geproduceerd was door de vlinderbloemigen dan een seizoen later. In beide dorpen werd ook significant meer gierst geproduceerd op de goede velden (0.62-2.15 Mg ha^{-1}) vergeleken met de arme velden (0.29-1.49 Mg ha^{-1}). Boeren gaven de voorkeur aan de teelt van aardnoten en waren niet geïnteresseerd in pigeonpea en mucuna. Verder, gaven zij de voorkeur aan teelt van vlinderbloemigen op de goede velden met uitzondering van mucuna en pigeonpea waarvan zij vonden dat die alleen op arme gronden zouden moeten worden geteeld. De kostenbaten verhoudingen in beide dorpen gaven aan dat rotaties van vlinderbloemigen zonder toediening van P gevolgd door gierst alleen profijtelijk is op goede velden. We concluderen dan ook dat green grams, cowpea en sojabonen in beide dorpen het best op de goede velden in zowel de hoge en midden landschap posities kan worden geteeld. Mucuna zonder P bemesting kan het best worden geteeld op arme velden in de midden-landschap-positie in Chelekura en cowpea zonder P bemesting op de hoge-landschap-positie in Onamudian. Hoewel vlinderbloemigen worden aanbevolen voor kleine boeren bedrijven, zullen die alleen succes hebben op de goede velden en wanneer P bemesting, die dient te worden toegediend, economisch haalbaar is. Dit is bij een prijs verlaging van 30-40% het geval.

Gebruik van vlinderbloemigen als mest voor verhoging van de gierst productie op arme velden levert geen profijt op. Daarom werd in beide dorpen ook de effectiviteit van kunstmest en mest van kralen op arme velden, uitgeput in nutriënten, getest in veld experimenten over drie seizoenen. Alleen N of P kunstmest (0, 30, 60, 90 kg ha^{-1}), combinaties van N+P kunstmest in gelijke hoeveelheden als één gift en mestgiften gecombineerd met N kunstmest (0, 30, 60 and 90 kg ha^{-1}) werden toegediend op gedegradeerde velden in zowel hoge als midden landschap posities. Gierst productie op gronden waar vroeger kralen stonden (niches met hoge bodemvruchtbaarheid) werd als referentie punt toegevoegd in de experimenten. De gemiddelde graanopbrengst varieerde van 404 kg ha^{-1} tot 2026 kg ha^{-1} en was significant (P<0.001) verschillend tussen dorpen en seizoenen in 2006. Significante (P<0.05) verschillen in graanopbrengst tussen landschap posities werden alleen in Onamudian gevonden. De bemesting kon de opbrengst op arme gronden significant omhoog brengen maar het verschil in opbrengst tussen gedegradeerde gronden en velden op vroegere veekralen konden door geen van de gebruikte bemesting worden overbrugd. De hoogste graanopbrengst op gedegradeerde velden werd bereikt met toediening van N+P kunstmest met opbrengsten van 800 kg ha^{-1} in Chelekura en 1171 kg ha^{-1} in Onamudian. Daarmee werd het gat tussen opbrengsten op gedegradeerde gronden en velden op vroegere veekralen voor 24% in Chelekura en 43 % in Onamudian gedicht. De lage efficiëntie in gebruik van toegediende nutriënten is een gevolg van beperkingen in andere nutriënten zoals S en K en mogelijk ook door fysische beperkingen van de bodem zoals beperkte infiltratie van regenwater door korstvorming aan het bodemoppervlak.

Bemestingsadviezen die geen rekening houden met de grote variabiliteit in bodemvruchtbaarheid binnen kleine boerenbedrijven zijn van beperkte waarde. Het model QUEFTS (Quantitative Evaluation of Fertility of Tropical Soils) werd gekalibreerd voor gierst ten einde de potentie van dit model te verkennen om locatie specifieke bemestingsadviezen te kunnen generen. De modelconstanten (kg graan per kg nutriënt) werden voor maximale accumulatie (a) en minimale verdunning (d) vastgesteld op 21 en 53 kg graan per kg N, 76 en 261 kg graan per kg P en 11 en 46 kg graan per kg K. De correlatie tussen waargenomen en door model berekende opbrengsten was goed (r^2 = 0.76; RMSD = 262 kg ha^{-1}). De uitgebalanceerde bemesting voor een na te streven gierst opbrengst van 2000 kg ha^{-1} werd geschat op 83 kg N ha^{-1}, 52 kg P ha^{-1} en 56 kg K ha^{-1} voor zand-leem gronden in Chelekura en op 64 kg N ha^{-1}, 31 kg P ha^{-1} en 40 kg K ha^{-1} voor zand-klei-leem gronden in Onamudian.

Echter, wanneer reacties van toegediende nutriënten op opbrengst moeten worden voorspeld dan moet er rekening worden gehouden met de condities van de bodem. Andere nutriënten net als fysische factoren als beperkte waterbeschikbaarheid door beperkte infiltratie kunnen op gedegradeerde gronden een effect hebben op de nutriënten opname, iets waar het QUEFTS model geen rekening mee houdt; berekende model opbrengsten zullen dan hoger uitkomen omdat die alleen afhankelijk zijn van de totaal beschikbare nutriënten van zowel de bodem als van nutriënten die zijn toegevoegd.

Concluderend, opties die doelgericht nutriënten beheren kunnen tot hoger profijt leiden wanneer specifiek aandacht wordt geschonken aan specifieke beperkingen die anders zouden leiden tot verspilling van beschikbare middelen. Door de bank genomen dient de kwaliteit van velden met beperkte bodemvruchtbaarheid worden verbeterd om het profijt van interventies op het terrein van nutriëntenbeheer te verhogen. Toedienen van mest om het organische stofgehalte te verhogen is eerst nodig voordat de efficiëntie van nutriënten opname van toegediende kunstmest wordt bereikt. Dit onderstreept de noodzaak van het gecombineerde gebruik van mest en kunstmest wanneer gedegradeerde velden moeten worden opgewaardeerd. Bij kleine aantallen vee zijn de hoeveelheden mest echter klein en het vooruitzicht die aantallen te verhogen zijn slecht gezien de beperkte beschikbaarheid van voer van kwaliteit en van graslanden. Veranderen van het begrazingsysteem naar het houden van vee op stal kan de verzameling van mest verbeteren, maar daarnaast is de introductie van voederproductie en verbetering van de kwaliteit van de weiden misschien mogelijk. Een verandering naar het houden van vee op stal is onmogelijk als niet ook het profijt hoger wordt door melkproductie waardoor de hogere vraag naar arbeid in een dergelijk systeem kan worden gecompenseerd. Aan de andere kant is kunstmest schaars en duur voor de kleine boeren. Het gebruik daarvan moet strategisch worden gestimuleerd. Vanuit agronomisch standpunt, dienen limietwaarden van organisch stofgehalten, die hogere efficiëntie geven bij kunstmestgebruik, te worden bepaald. Deze limietwaarden verschillen per bodemtypen (leem en klei fracties) en gewas. De efficiëntie op bedrijfssysteem niveau moet worden bepaald en gewassystemen moeten daarvoor worden aangepast. Gewassen die het profijt van mest en kunstmest gebruik verhogen zullen investeringen in beheer van bodemvruchtbaarheid vergemakkelijken. In systemen met lage productie zoals het Teso systeem is het gebruik van kunstmest onvermijdelijk. Interventies van buitenaf en stimuleringspolitiek die partnerschappen rondom winstgevende producten tussen private en publieke sector verbeteren en ook in breder verband rekening houden met het bestaansminimum kunnen dan door doelgericht toepassen van opties, rekening houdend met de heterogeniteit, een route zijn tot voldoende voedselproductie.

Curriculum vitae

Peter Ebanyat was born on October 7, 1970 in Ngora, Kumi district, Uganda. He attended Bishop Kitching College Demonstration School for primary education and Ngora High School for both Ordinary level and Advanced certificates of education completing in 1990. He joined Makerere University for a BSc in Agriculture degree programme from 1990-1994. A year after, he enrolled for an MSc Soil Science at Makerere University and completed in 1998. In 1995, he was employed a Research Associate with the Francolite Fertilisers Research Project in the Department of Soil Science, Makerere University. Through this project he enrolled for an MSc Soil Science programme in the same department and conducted research on Phosphorus transformation in soils amended with phosphate rock. While on the MSc Programme, he was appointed Assistant Lecturer in the Department of Soil Science in 1996. After completion of the MSc in 1998, He was appointed lecturer in the same department; a position he holds to date. From 1998-2003, he was involved in various farmer collaborative participatory research through European Union funded projects; Low External Input Sustainable Agriculture (LEINUTS), Nutrient Networks and Stakeholder Participation (NUTNET), Integrated Nutrient Management to attain Sustainable Soil productivity increases in farming systems in Eastern Africa (INMASP), and FAO funded Technical Co-operation project on Conservation Agriculture through the Soil Fertility Initiative for Uganda. He was Faculty of Agriculture representative in the stakeholders' consortium on soil productivity improvement in Eastern Uganda. Through funding from the Rockefeller Foundation to the Integrated Soil Productivity Initiative through Research and Education (INSPIRE) project in Eastern Uganda, he started a PhD at Wageningen University with the Plant Production Systems group in October 2003 focussing on targeting of integrated nutrient management practices to variability in smallholder farms in eastern Uganda .

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Writing of Project Proposal (5 ECTS)

- Targeting integrated soil fertility management practices to variability in smallholder farms in eastern Uganda (2004)

Laboratory Training and Working Visits (2.7 ECTS)

- Soil and plant analysis using near infrared spectroscopy; World Agroforestry Centre, Nairobi, Kenya (2005)
- Training on application of DSSAT for fertiliser recommendations; Entebbe, Uganda (2007)

Post-Graduate Courses (6 ECTS)

- Multivariate analysis; PE&RC (2004)
- Advanced statistics; PE&RC (2008)
- Art of modelling; PE&RC (2008)

Deficiency, Refresh, Brush-up Courses (4 ECTS)

- Quantitative analysis of cropping and grassland systems; PPS (2003)

Competence Strengthening / Skills Courses (2.5 ECTS)

- Scientific writing; Language Centre (2004)
- Public awareness skills development course; International Institute Rural Reconstruction (2005)

Discussion Groups / Local Seminars and Other Scientific Meetings (3 ECTS)

- Soil and plant relationships (2003-2004)
- Graduate seminars, monthly meetings; Makerere University (2004-2007)

PE&RC Annual Meetings, Seminars and the PE&RC Weekend (1.4 ECTS)

- PE&RC Weekend (2003)
- Nutrient management in tropical agroecosystems; Wageningen University (2004)
- Farming futures in Sub-Saharan Africa; PE&RC (2008)

International Symposia, Workshops and Conferences (10.5 ECTS)

- Integrated nutrient management workshop for the INMASP project, oral presentation; Awassa, Ethiopia (2003)
- Integrated nutrient management workshop for the INMASP project, oral presentation; Mukono, Uganda (2004)
- FAO International Conference on Farmer Field Schools on Land and Water Management in Africa, oral and poster presentation; Jinja, Uganda (2006)
- International Meeting of the Africa Soil Fertility Network (*Afnet*). Innovations a Key to the Green Revolution in Africa: Exploring Scientific Facts; Arusha, Tanzania (2007)
- Africa NUANCES Workshop; Arusha, Tanzania (2007)

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