Msimu wa Kupanda

Targeting resources within diverse, heterogeneous and dynamic farming systems of East Africa

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Targeting resources within diverse, heterogeneous and dynamic farming systems of East Africa

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[†] Swahili for: 'Planting season', or 'The time to plant'

A mis padres

Abstract

Soil fertility decline is the major single factor explaining the decrease in per capita food production in sub-Saharan Africa. Integrated soil fertility management (ISFM) is an approach to improving or restoring soil productivity, based on combinations of organic and mineral fertilisers, improved germplasm and N_2-fixation, but its adoption by farmers has been limited. Smallholder farms in sub-Saharan Africa are highly diverse, heterogeneous and dynamic, and operate in complex socio-ecological environments. Much of the heterogeneity within the farming systems is caused by spatial soil variability. This affects the performance of ISFM technologies, which must be then targeted strategically within heterogeneous farming systems to ensure their propensity to enhance the efficiency of resource (e.g. land, labour, nutrients) use at farm scale. An analytical framework in which systems analysis is aided by survey, experiments and simulation modelling was used to analyse farming futures in the highlands of East Africa. Case study farms from six moderate to high potential agricultural areas in central and western Kenya and eastern Uganda were characterised to identify the diversity of livelihood strategies and understand the main drivers of farm heterogeneity. Constraints to the performance of ISFM technologies and opportunities for efficient targeting of resources within heterogeneous smallholder farms were analysed considering short and long-term horizons, scaling up from field to farm scale, and contextualising livelihood opportunities at regional scale.

Across sites, population densities varied from 250 to 1000 inhabitants km^{-2}, which translated in 11 to 4 months $year^{-1}$ of food self-sufficiency. Based on resource endowment, dependence on off-farm income and production objectives, households were grouped into five Farm Types: 1. Subsidised by off-farm employment; 2. Market-oriented, cash-crops farms; 3. Expanding, medium resource endowment farms; 4. Subsisting, partly on non-farm activities; and 5. Dependent, wage labourers. Despite their differences in access to resources for soil management, these Farm Types differed more in the degree of soil heterogeneity than in the average fertility status at farm scale. Across sites, soil heterogeneity was smaller on farms owning more cattle. The productivity of maize, the main crop in most of the region, was highly variable within individual farms, strongly influenced by variation in both current crop management (e.g. planting dates, fertilizer rates) and soil fertility (influenced by past soil and crop management). In a classification and regression tree analysis (CART), resource use intensity, planting density, and time of planting were the principal variables determining yield, but at low resource intensity, total soil N and soil Olsen P became important yield-determining factors. Soil heterogeneity also affected crop responses to fertilisers from a maximum of 4.4-fold to –0.5-fold relative to the control in soils varying in organic C and P availability. Across sites in western Kenya, P was the most limiting nutrient for crop production, and P availabilities > 10 mg kg^{-1} were only measured in soils with > 10 g kg^{-1} organic C. Such co-variation is induced by day-to-day management decisions farmers make when facing trade-offs in the allocation of their limited resources. A study using inverse modelling allowed analysing tradeoffs of this nature, coupling the dynamic crop/soil simulation model DYNBAL with a Metropolis-type of search algorithm (MOSCEM) and linking crop husbandry practices to labour availability. In a heterogeneous farm, the allocation of fertiliser and labour favoured the fields around the homestead, where the efficiency of nutrient capture was the largest. Productivity could be increased up to a certain threshold beyond which N losses by leaching and soil erosion losses increased abruptly, when fertilisers were applied to the most degraded outfields of the farm. These fields must be rehabilitated through ISFM technologies ensuring organic matter additions, before crops growing on them can respond to nutrient applications. However, the quality of manure common in smallholder farms (e.g., 23 – 35% C, 0.5 – 1.2% N, 0.1 – 0.3% P) and their availability are restrictive. This prevents a quick (hysteretic) soil restoration. Competing uses for crop residues on the farm limit the capacity of fertilisers to restore soil fertility. In simulations using the crop/soil model for long-term dynamics FIELD, which was developed, calibrated and tested against 4 independent datasets, soils receiving combined manure and fertiliser applications over 12 years stored between 1.1 to 1.5 t C ha^{-1} $year^{-1}$ when 70% of the crop residue was retained in the field, and between 0.4 to 0.7 t C ha^{-1} $year^{-1}$ when only 10% of residues were retained. In mixed crop-livestock systems, crop residues are used to feed livestock, which in turn provide manure to fertiliser crops. When farmers in western Kenya designed *ideal farms* through participatory prototyping, they emphasised on the importance of such interactions, but tended to overestimate the necessary nutrient flows. A study using the farm-scale model FARMSIM, which integrates FIELD with livestock and manure-cycling models dynamically, showed that although tightly-managed crop-livestock interactions allowed a more efficient use of nutrients brought in the system as fertilisers, the trajectory of change from the current to the ideal farming system is hardly feasible for a majority of farmers.

Sustainable intensification should be an aim in the design of ISFM options, partly by intensification of nutrient inputs (removing constraints) and partly by implementing qualitative changes in the configuration of the farming systems (removing inefficiencies). However, the context in which farming systems operate cannot be overlooked. Based on their agroecological potential and market opportunities, and conditioned by population pressure, different sites or regions have a certain propensity to stimulate either: hanging-in (subsistence), stepping-up (market orientation) or stepping-out (off/non-farm income) livelihood strategies.

Keywords: Farm typology, Livelihood strategies, Near-infrared spectroscopy, Sub-Saharan Africa, Trade-off analysis, Soil fertility gradients, Farm-scale modelling, Farming Systems Design, NUANCES.

Preface

Day-to-day decisions that African farmers make when allocating their scarce physical, financial and labour resources have consequences for the long term sustainability of their farming. When I started conducting research in western Kenya for my MSc thesis in 2002, I aimed to understand the reasons behind the wide variability in crop yields commonly observed within single farms, with the firm hypothesis that soil nutrient availabilities would stand out as the major yield-limiting factors. Soon after I started observing and listening to farmers in the field, however, it became clear that it was not enough to sample and analyse soils to explain the poor performance of crops on their farms. Management practices in general, and crop husbandry in particular, were as important as nutrient deficiencies, or more – as formal analysis of the data confirmed later. If nutrient availability was not the major problem, this implied that fertilisers or other nutrient inputs were not the only 'solution' to improve crop (and food) productivity. Delayed planting of crops in the rainy season, poor weeding of the fields due to lack of labour, or the decision to invest in fertilisers in detriment of other expenditures equally necessary for the household were key decisions determining crop productivity and efficiency in the use of productive resources at farm scale.

Most decisions on 'resource' allocation are made around the time of planting and hence the title I chose for this thesis: *Msimu wa Kupanda*. Instead of providing a poor translation from Swahili, I prefer to share what my friend and colleague Michael Misiko and I exchanged by email when I consulted him about this title. I wrote to him: "*Dear Mike, I've chosen the following title for my thesis: "*Msimu wa kupanda!*"* […] *I want to mean: the "time to plant" or "planting season" or "planting out" - which is when most decisions on resource allocation are made, and gives also a positive message: let's get started! Please let me know your opinion…* ". Here is what he answered:

> "Dear Pablo,
> It depends on what you want to emphasise: *Msimu wa Kupanda* – Planting Season; *Wakati wa kupanda* – Time to Plant. Most Swahili speakers wouldn't really tell the difference without critical analysis. I would prefer season (*Msimu*); it is both poetic and agricultural. Most farmers would say, *Msimu huu* (this season), or *Msimu ujao* (next season), etc, during normal interactions. And in reference to major decisions, such as inputs, or even referring to harvests. *Msimu* also denotes period, rain or whether/climate, social phases, etc. *Msimu wa Kupanda* may therefore denote "right moment", while *Wakati wa Kupanda* may denote some command…"

I hope the work reported in this thesis will one day contribute to improve the conditions under which resource-poor farmers make decisions, by helping to broaden the choices for better targeting of their scarce resources.

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Chapter 1

Introduction

1. Background

Soil fertility is a major constraint to food production and economic performance of smallholder farms in sub-Saharan Africa, and the restoration of soil productivity a major challenge to the international research, development and donor communities (Sanchez, 2002). A significant step towards identifying practical solutions to the problem of poor soil productivity was the Fertiliser Summit held in 2006 in Abuja, Nigeria, where heads of African states agreed on the need to promote the use of mineral fertilisers in rural Africa. Past experience shows that while the 'Green Revolution' took place since the 1960's in agricultural systems of Asia and Latin America through wide adoption of improved germplasm, mineral fertilisers and pesticides, Africa kept lagging behind. Reasons for Africa missing the green revolution have being ascribed to the particularities of African smallholder farming systems and their context (e.g., Dudal, 2001).

Smallholder farms in SSA are highly dynamic, diverse and heterogeneous, and operate in complex socio-ecological environments. Much of the heterogeneity within the farming systems is caused by spatial soil variability, which results in its turn from the interaction between inherent soil/landscape variability and human agency through the history of management of different fields (e.g., Prudencio, 1993; Tittonell et al., 2005b). Soil management technologies aimed at increasing crop production often generate weak responses in the poorest fields of smallholder farms, as evidenced for example by the large variability in fertilizer use efficiencies within single farms observed in East, West and Southern Africa (Vanlauwe et al., 2006; Wopereis et al., 2007; Zingore et al., 2007b) or the poor performance of atmospheric N_2-fixation by legumes on degraded fields (Ojiem et al., 2007). Options to restore soil productivity must be targeted strategically within heterogeneous farming systems to ensure their effectiveness and propensity to enhance the efficiency of resource (e.g. land, labour, nutrients) use at farm scale. In spite of these considerations, the prevailing model of agricultural extension in sub-Saharan Africa has relied on 'blanket recommendations' per crop type and/or agroecological zone (e.g. Schnier et al., 1997) or, in the best of cases, on recommendations that considered soil maps – yet at scales too large to capture soil heterogeneity (Smaling et al., 2002).

The drivers of diversity and heterogeneity of farming systems can be grouped, in decreasing order of spatio-temporal scale, as: site-specific conditions (agroecology, markets, population, ethnicity, etc.), soil-landscape associations, farm resource endowment, land use (crop types, livestock system), and long- and short-term management (respectively, current soil fertility status and operational resource and labour allocation decisions). Although most smallholder families in rural Africa are resource-poor households, different livelihood strategies can be identified within single locations. Households differ in their level of resource endowment, production objectives, risk attitudes and long term aspirations. Rather than static entities, farming systems are dynamic, subject to changing socioeconomic and environmental contexts and risks (through, for example, climatic or market variability). Potential options to improve soil productivity should not only be evaluated in terms of immediate benefits (which can be crucial in determining the adoption of a certain technology by farmers) but also by assessing their contribution to livelihood strategies and sustainability of the farming system in the long term (Giller et al., 2006).

The overall aim of this work is to provide a framework for the analysis and categorization of diversity and heterogeneity of smallholder farming systems, and evaluation of the potential impact at farm scale of integrated soil fertility management options (or similar interventions) at different temporal scales. Diverse methodologies for farming systems analysis, from on-farm participatory research methods to experimentation and simulation modelling are used to identify: (i) the drivers of soil heterogeneity at different scales; (ii) the impact of such heterogeneity on crop productivity, resource use efficiency and crop response to technological interventions; (iii) options and tradeoffs farmers face when making resource allocation decisions that reinforce the effects of soil heterogeneity; and (iv) opportunities for restoration of current soil and system productivity through sustainable intensification.

2. The problem of poor soil fertility in sub-Saharan Africa

Food production in sub-Saharan Africa is not keeping pace with population growth. Sub-Saharan Africa has the lowest land and labour productivity rates in the world, with annual growth in cereal yields averaging only 10 kg grain ha^{-1} yr^{-1} — about 1 percent. Counting growth in harvested area as well, food production in sub-Saharan Africa increases at an annual rate of c. 2%, while population growth rates average 3 % (Breman and Debrah, 2003). In much of sub-Saharan Africa, soil fertility management has traditionally relied on shifting cultivation, extended periods of fallow and/or use of animal manure to fertilise crops. Human population growth in rural areas exerts increasing pressure on natural resources. As a consequence, the area of communal land that is used for grazing or collecting different resources decreases, as does the area for cultivation available per family. Small farm sizes prevent the practice of fallow, while soils that are degraded after continuous cultivation need increasingly longer periods under fallow to recover. In many mixed crop-livestock systems, rural families have integrated both activities through use of animal manure to fertilise crops and use of crop residue as fodder. However, the availability of animal manure is often insufficient to sustain soil fertility in a substantially large area of cropland.

In most of sub-Saharan Africa, cattle densities are below five heads per km^2 (Figure 1). Denser cattle populations are distributed as an inverted L-shape, from the Sahel of West Africa to the East African highlands, and from there south to the high and low *velds* of eastern South Africa. Large areas with low densities correspond to pastoralist systems, where crop-livestock interactions do not take place. The highest concentrations (> 50 cattle km^{-2}, or 0.5 per ha) are found in the highlands: different areas of Ethiopia, areas around Lake Victoria (the focus of this study), and in some areas of South Africa, Zimbabwe and Zambia. Not surprisingly, these are also areas of denser human population. In these systems, livestock may contribute substantial inputs of carbon and nutrients that are harvested in communal grasslands to the soils in cultivation through cattle manure. Early studies in Zimbabwe indicated that farming on the sandy soils that cover large areas of the country was not sustainable without such transfers, and that about 30 ha of communal grassland per farm of 3 ha would be necessary to sustain soil productivity (Rodel and Hopley, 1973). By contrast, some rural areas in the highlands of East Africa support up to 1000 inhabitants per km^{-2} – communal lands for grazing have vanished in such areas. This has led to predominance of poor soil fertility in areas of Africa with dense human population, which are normally also areas of high agroecological potential.

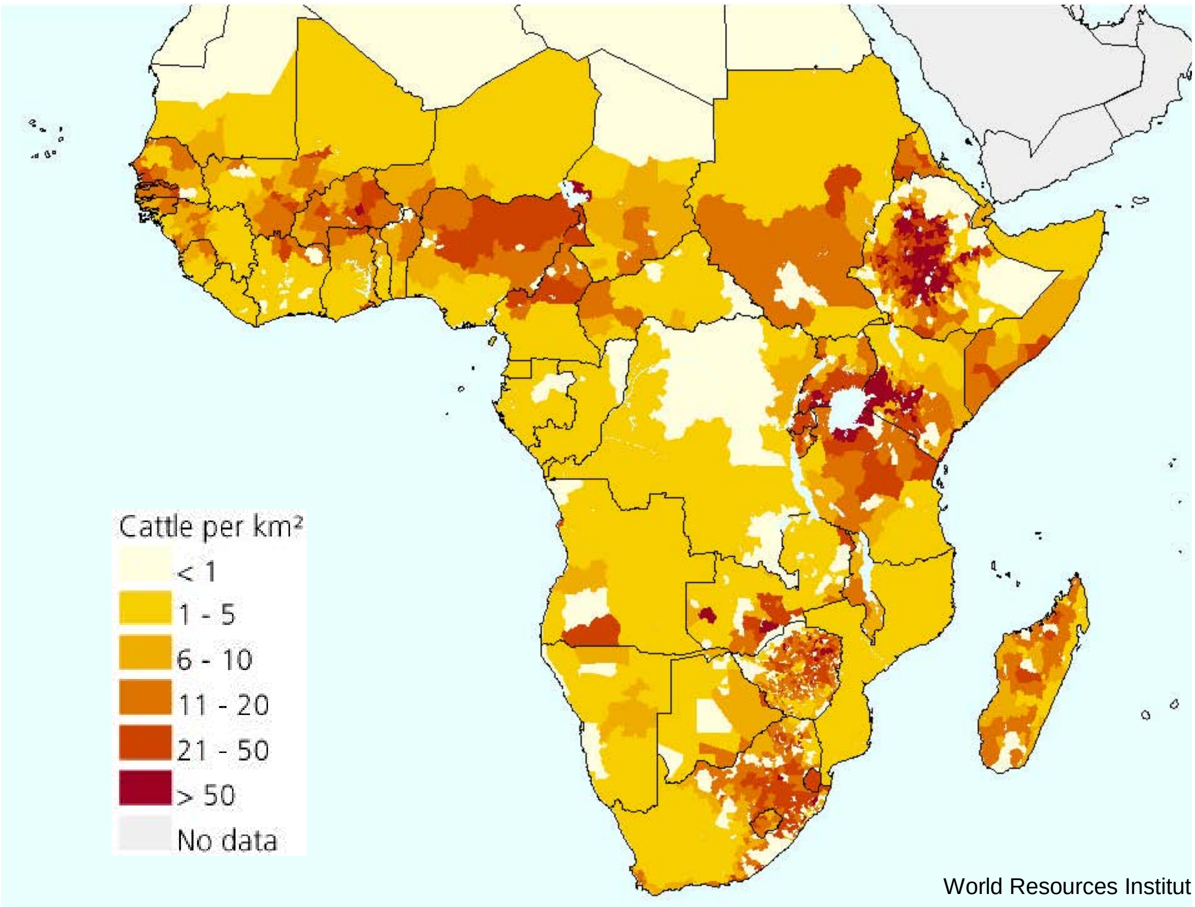

Figure 1: Cattle densities in sub-Saharan Africa (World Resources Institute; www.earthtrends.org). Denser cattle populations (between 20 and more than 50 cattle per km²) are distributed across an east-west band of northern grassland, and along a northeast-southeast band of eastern grassland. Countries with the highest densities include Ethiopia, Kenya, Uganda, Tanzania, Zambia, Zimbabwe, South Africa, and Madagascar.

Alternatives for soil fertility management include use of mineral fertilisers, N_2 fixation by legumes grown in rotations or as green manure, certain agroforestry (legume) trees, and use of different organic resources applied to the soil (e.g., biomass transfer) or produced *in situ* (e.g., no-tillage systems). There are also a number of localised, indigenous management systems – such as e.g. the Mambwe mound cultivation system in northern Zambia (Strømgaard, 1989) – which are adapted to local particularities and thus more difficult to generalise. While N_2 fixation is rather poor when, for example, soils have little phosphorus or are too acidic, the adoption of agroforestry or biomass transfer options is often limited by land and labour constraints (Kiptot et al., 2007). In this context, mineral fertilisers are one option to improve food security, a means to bring nutrients into the farming systems and to restore/maintain soil productivity in the longer term. However, mineral fertilisers are not always a solution *per se* to poor land and labour productivity in sub-Saharan Africa. In most of the region 10 kg nutrient ha^{-1} $year^{-1}$ on average are used (FAO statistics, available on: www.earthtrends.org). Accessibility to mineral fertilisers is often limited in rural areas, their cost increases if split into small packs (1 – 2 kg), and farmers are poorly informed as to their composition and/or unaware of their effect. For example, the price farmers pay per kg of N fertiliser in rural areas of Kenya is KSh 35, which is equivalent to c. US$ 500 per tonne – about five times its international price[†]. The small amounts that farmers can access must be used strategically to ensure efficiency and minimise negative consequences to the environment.

3. Integrated soil fertility management

Despite the limitations outlined above, soil productivity must be restored in sub-Saharan Africa in order to ensure food security. If Africa seeks to rely on agriculture for economic development, an annual increase of 4 to 7% in food production is required (Breman and Debrah, 2003). Integrated soil fertility management (ISFM) is proposed as an overarching approach to restoring and maintaining soil productivity, better suited to the particularities of smallholder farming systems in sub-Saharan Africa. A comprehensive but yet simple definition of ISFM refers to the combined use of organic and mineral resources and resilient germplasm to ensure efficient use and cycling of nutrients to achieve food security, while maintaining soil productivity in the long term (Vanlauwe et al., 2002). A core principle in ISFM is the use of organic resources in combination with mineral fertilisers, which often leads to synergies or additive effects. Although the mechanistic basis of such interactions was not always clearly understood, different technological options have been developed to capitalise such synergies. Palm et al. (2001) developed a database containing numerous organic resources of use in the tropics and derived a simple decision tree for managing such resources, based on their N, lignin and polyphenols contents. Extensive research

[†] KSh stands for Kenya Shilling; 1 KSh = 67.2 US$, October 2007 (Central Bank of Kenya); average price of urea 110 US$ $tonne^{-1}$ (IMF, International Financial Statistics)

efforts have been devoted to guide decisions on organic resource management that ensure a proper match between nutrient release from organic resources with crop demand for nutrients, with particular emphasis on N (see examples in Giller et al., 2002).

However, while a considerable body of information has been developed on different approaches for soil fertility management in smallholder African farms (see also Buresh et al., 1997, Vanlauwe et al., 2002), there is notably scarce uptake and implementation of such knowledge by farmers. Despite dissemination failures, restrictions to technology adoption can be sought among socio-economic, cultural and political factors. A fundamental problem is also the lack of integration and implementation of knowledge by the scientific community (Giller et al., 2006). Much information on different technologies for soil fertility management (e.g. multipurpose agroforestry trees, green manure, organic and mineral fertiliser combinations, etc.) has been derived from research done mainly at plot scale. Few studies have compared the potential of these options at the scale of a farm system, considering multiple constraints and opportunities in the short and long term.

The implementation of ISFM faces a number of challenges due to the particularities of smallholder farming systems in sub-Saharan Africa. Farming systems are diverse, heterogeneous and dynamic. While different regions, agroecological zones or types of farmers may experience different opportunities and constraints for the implementation of ISFM, heterogeneity within single farms affects the performance of various soil-improving technologies. Often the evaluation of ISFM technologies must be done considering long-term, strategic time horizons, while farmers are more concerned with meeting immediate needs. All these aspects must be considered when designing ISFM interventions. Characteristics of farming systems that may affect the design of IFSM interventions and the research questions derived in relation to them are discussed briefly in the following sections.

4. Characteristics of smallholder farming systems

The following are three key characteristics of smallholder farming systems in sub-Saharan Africa that must be considered in the design of ISFM technologies:

Smallholder systems are diverse

A rural family that can be considered as 'poor' in a certain area may be seen as 'rich' in another. The agroecological potential, socio-cultural aspects and market opportunities define diverse natural resource management systems across sub-Saharan Africa. Within a certain location, households differ in their resource endowment, livelihood strategy, aims and long-term aspirations. Even in areas where a large majority of households can be considered to be resource-poor, differences in livelihood strategies between households may be key in defining adoption of promoted ISFM technologies.

Smallholder systems are spatially heterogeneous
Differences in soil fertility within a single farm may be as wide as between agroecological zones. Next to inherent variability of soil types in the landscape, management decisions on the allocation of (scarce) resources generate gradients of soil fertility within individual farms. Often animal manure and/or composted crop residues are added to the fields near the homestead, creating zones of C and nutrient concentration within the farms. In undulating landscapes, the fields that are farther from the homestead are often also those located on steeper slopes. Due to soil heterogeneity, the performance of ISFM technologies may fluctuate from success to failure across the various fields of a single farm.

Smallholder systems and their context are dynamic
As in natural ecosystems, farming systems experience changes in their configuration and functioning with time; their capacity of adaptation through human agency differentiates them from natural systems. To understand the dynamics of a system it is necessary to consider the dynamics of the supra- and subsystems, that is, its context and internal components, by examining processes operating at immediately higher and lower scales. Sustainability of farming systems depends largely on their capacity to adapt to changes at both scales. The contribution of ISFM to the sustainability of smallholder systems, and their feasibility, should be evaluated in the long-term considering dynamic aspects of farming systems and their context.

5. Resource use efficiency, tradeoffs and indicators

The terms *efficiency* and *resources* have very specific meanings in different disciplines. Here, efficiency is defined generically as the ratio between outputs and inputs from and to a system or a process over a certain period of time. Resources are defined broadly, encompassing natural resources such as light, water and nutrients, to labour and financial resources. Resource use efficiency is conceptualised as the product of resource capture (or interception and absorption) efficiency times resource conversion (or utilisation) efficiency (Trenbath, 1986). Due to economic and environmental reasons, resources and inputs should be efficiently used within farming systems. Resource-constrained households make allocation decisions while facing trade-offs between diverse objectives; i.e., between immediate concerns and long term goals, between household food security and resource conservation, between farm productivity and resource use efficiency. Households make such decisions in uncertain and dynamic environments, often lacking market information and/or knowledge of basic biophysical processes governing their production system. Rural families undergo different phases along a ‘farm developmental cycle’ (Forbes, 1949 – cited by Crowley, 1997), which include establishment, maturity and dissolution, along which household resources and objectives vary accordingly (Figure 2 A). The position of the household along the farm developmental cycle constitutes a first step in the categorisation of household diversity to identify different livelihood strategies.

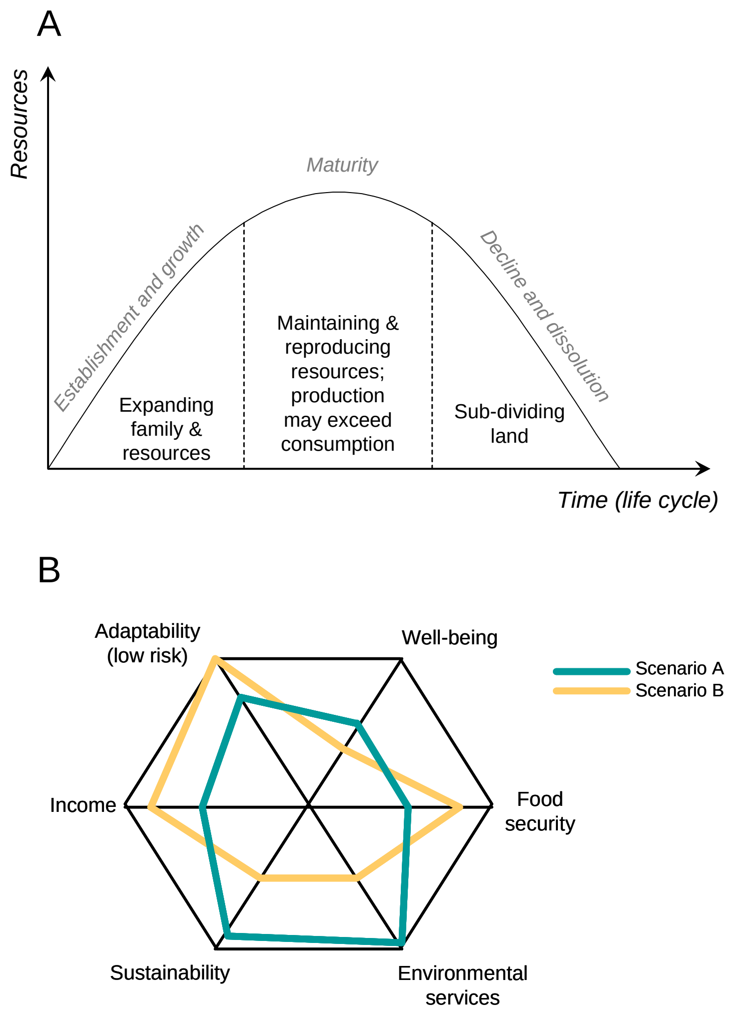

Figure 2: (A) A schematic representation of the developmental cycle of farm households (Forbes, 1949) and its implications for resource endowment. (B) A spider-web diagram derived during a workshop of the AfricaNUANCES consortium including soil scientists, agronomists and extension workers from eight African countries. It considers six major objectives that different stakeholders might be interested in when designing alternative farming systems, and two hypothetical scenarios that fulfil such objectives to different degrees.

Farmers' objectives and aspirations can be translated into quantifiable indicators by understanding the system attributes that are directly related with the achievement of such objectives (López-Ridaura, 2005). For example, economic profitability or crop yields are two different indicators pertaining to the same attribute of a farming system, productivity. Or, crop yields may be an indicator of fulfilment of more than one objective, for example, food security and income (Figure 2 B). The information contributed by different indicators also depends on the definition of system attributes and/or objectives adopted. The axis of the spider-web diagram of Figure 2 B and the two hypothetical scenarios outlined (A and B), were derived during a workshop of the AfricaNUANCES consortium including soil scientists, agronomists and extension workers from eight African countries. It considers six major objectives that different stakeholders might be interested in when designing alternative farming systems, and sustainability is included as one of the objectives. Approaches for sustainability evaluation, however, may define 'sustainability' as the fulfilment of the various axes of a spider-web diagram in which each axis represents a single attribute of a sustainable system; e.g., productivity, equity, stability, adaptability and self-reliance in the MESMIS framework – Masera et al. (1999).

The value of a certain indicator depends on its capacity to reflect relevant changes in the system being assessed, on being easy to measure, understand and communicate, and on the possibility of establishing clear threshold values within its range of variation. Soil organic matter is often proposed as an integrative indicator of sustainability in agricultural systems (e.g., Bouma, 2002). Thresholds in soil organic carbon (which represents, on average, 58% of the soil organic matter) can be derived from the capacity of soils to stabilise carbon, which is related to their clay plus silt (0 – 20 μm) fraction. Feller and Beare (1997) established a 'window' for the range of variation in the organic C content of soils of different texture; i.e., for a soil of a given texture (i.e., clay + silt content), there is an upper and a lower boundary for the fluctuation in its soil C content under different situations, and history, of use and management. The window these authors derived from a sample size n = 66 is, however, a conceptual rather than a predictive model for tropical soils, as the upper and lower boundaries proposed do not always contain all field measurements (Figure 3).

Table 1: Key issues relating to resource use efficiency (adapted from Giller et al., 2006) and categories of diversity (after Stocking, 2002) that need to be considered at different scales of analysis.

Spatial scale	Time scale			Category of diversity
	Short term (1 season)	*Medium term* (1-5 years)	*Long term* (5-50 years)	
Field	Production efficiencies Resource (water, nutrient) balances	Efficiency of rotations Resource (nutrient) stocks	Soil erosion Soil carbon content Yield stability	Biophysical diversity
Farm	Resource tradeoffs Farm scale efficiency Labour allocation	Risk avoidance Allocation of production activities (e.g. rotations)	Livelihood stability Farm development cycle	Management diversity
Village	Fodder production Fuelwood availability	Rangeland improvement	Soil erosion Livestock carrying capacity	Agrobiodiversity, organizational and social diversity

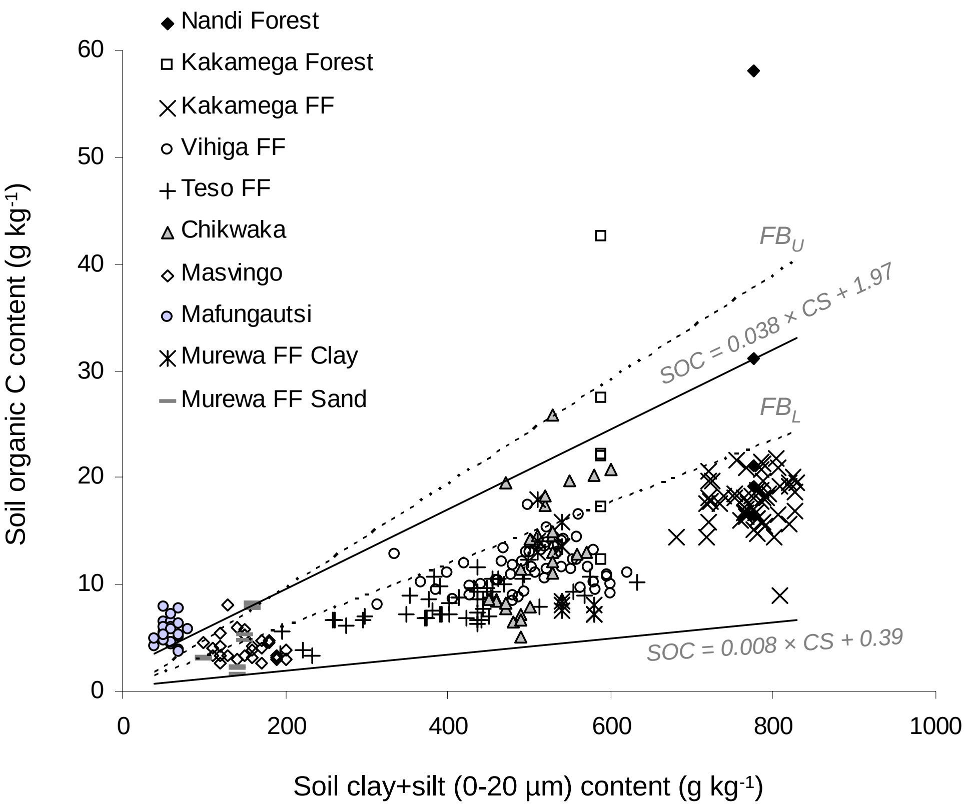

Figure 3: Soil organic carbon content in soils of Kenya and Zimbabwe plotted against their clay plus silt content in the topsoil (*n* = 273). Kenya: two chronosequences of forest clearance (0 to 100 years) around Nandi and Kakamega forest (Solomon et al., 2007) and measurements on farmers' fields (FF) in three areas of western Kenya (Tittonell et al., 2005b,c). Zimbabwe: soils that were cleared of natural vegetation (Miombo woodland) for cultivation between 0 to 60 years ago at Chikwaka, Masvingo and Mafungautsi (Zingore et al., 2005), and farmers' fields under similar agroecological conditions sampled at Murewa on clayey and sandy soils (Zingore et al., 2007b). Full lines indicate +/- 1 standard deviation with respect to a simple regression line through the data; the respective equations are given in the graph. (Based on the upper line, maximum C contents can be estimated roughly as 2 plus 40% of clay+silt expressed as %). The dotted lines were calculated with the equations provided by Feller and Beare (1997) for cultivated (lower boundary, FB_L) and non-cultivated (upper boundary, FB_U) soils. Soil C contents are not mass-corrected.

Farmers' decisions on resource allocation result from the integration of their knowledge on the system, and recognise also different temporal frames: operational, tactic and strategic. In (soil fertility) research, scaling-up of processes and balances to the farm level implies consistent aggregation on both the spatial and the temporal dimensions. Thus, as less detail is considered when scaling up from the field/plot to the farm level, the type of questions to be addressed also changes, from those of an operational to a strategic nature. Farm scale issues relating to efficiency may also be different from the more biophysically-oriented resource use efficiency indicators at plot scale (Table 1). At farm scale, the overall resource use efficiency (e.g. the efficiency of nutrient 'capture' and use within the system) depends on processes and resource balances operating at immediately lower levels of integration (i.e. soil, plant, animal, field) and on farmers' decisions on the allocation of (some of) the available resources. Since this integration naturally takes place at farm scale, improving farm productivity through technology development/dissemination or enhancement of current management practices requires integrated rather than compartmentalised research approaches.

6. Objectives

The general objective of this thesis was to reveal inefficiencies (nutrient, labour, financial) in resource allocation and routes towards optimal use of scarce resources, with emphasis on implementation of integrated soil fertility management to improve food production in smallholder agricultural systems of the East African highlands. The specific objectives were:

1. To identify and categorise the drivers of farm heterogeneity operating at different scales, from region to households, assessing the influence of agroecology, population density, market development and household diversity on soil fertility management systems;
2. To assess the effect of agroecology, soil heterogeneity and farmers' management decisions, and their interaction, on variability in current crop productivity at farm scale;
3. To assess the effect of agroecology, soil heterogeneity and farmers' management decisions, and their interaction, on nutrient use efficiencies and crop responses to applied fertilisers;
4. To investigate how operational, day-to-day farmers' management decisions contribute to the creation of farm heterogeneity, and the nature of the tradeoffs that farmers face when deciding on the allocation of their scarce resources;
5. To explore alternatives for targeting nutrient resources for integrated soil fertility management within heterogeneous farms, with emphasis on the rehabilitation of degraded fields in the long-term;
6. To explore the physical feasibility for the sustainable intensification of farming systems through improved management of crop-livestock interactions, while considering farmers' views on desirable management systems.

7. Methodological approach

Systems analysis, aided by simulation modelling, constitutes a means to evaluate options for sustainable intensification of farming systems while considering: (1) their diversity, spatial heterogeneity and variability in time; (2) the scaling-up in space and time of the effect of interventions operating at field plot scale, to infer consequences at farm and village scales in medium to long-term time horizons (i.e. strategies); and (3) the possibility to perform scenario analysis with prospective or explorative purposes, evaluating *ex-ante* the potential impact of factors that are external to the farm system (e.g., effects of changing population densities on farm size). The various system analytical methods employed in this thesis constitute examples of application of an integrative analytical framework, NUANCES (**N**utrient **U**se in **AN**imal and **C**ropping systems – **E**fficiencies and **S**cales - www.africanuances.nl), which combines participatory research, farm typologies, data-mining, experiments and modelling tools to identify intervention opportunities and pathways towards the sustainable intensification of smallholder systems in sub-Saharan Africa. Different steps in the methodology are articulated using the 'DEED' approach:

1. **D**escribe, current production systems and their problems;
2. **E**xplain, current farmers' decisions on resource allocation and their consequences;
3. **E**xplore, options for agro-technological improvement in face of possible future scenarios;
4. **D**esign, new management systems that contribute to the sustainable intensification of smallholder agriculture.

A first step in farming systems analysis and scenario evaluation is to define representative prototypes of fields, cropping sequences, farms or localities that capture the key management, socio-economic and agro-ecological aspects of the systems under study. Their heterogeneity and diversity at different scales should be categorised, relying on solid understanding of the key drivers of such variability and using methodologies that allow comparisons across systems. Such cross-scale categorisation may also serve to define recommendation domains or socio-ecological niches (e.g. Ojiem et al., 2006) to which resources/technologies can be targeted. The four DEED steps were implemented in practice following the quantitative analysis of farming systems (QAFS) cycle (Figure 4), except that no formal methodology was followed to ensure contribution to discussion-support or policy-making.

There are various approaches to involve local farmers' views and perspectives within systems analysis research. Lynam et al. (2007) divide them into three classes: (1) diagnostic and informing methods that extract knowledge, values or preferences from a target group; (2) co-learning methods in which the perspectives of the group change as a result of the process; and (3) co-management methods in which all actors involved are learning. While in the first two cases the information generated is supplied to a decision-making process, in co-management all actors are involved in decision-making. The appropriateness of the participatory approach to follow depends on questions, objectives and often also logistics. The first approach was followed in this thesis, through engagement with existing farmer field schools, surveys and repeated visits to and discussion with individual farmers.

The analysis of scenarios around diverse and heterogeneous farming systems operating within dynamic contexts is a complex task. When using/developing simulation models for scenario analysis, the complexity in the description of the system components should not be added to the complexity of the system itself and of the problems analysed – unless there is a good reason to do so. For analysis of options and tradeoffs at farm scale, the models for the various subsystems (crops, soil, livestock) should be kept as simple as possible – too much complexity may be overwhelming – but detailed enough to capture the major processes determining systems behaviour in relation to the research questions raised (de Wit, 1968). Adding detail in the description of the model does not necessarily add to our capacity to represent the system or to the explanatory capacity of the model, defined by Stoorvogel and Antle (2007) as 'model quality', when the availability of data to parameterise and test the model are restrictive (Figure 5 A). Data on farming systems in sub-Saharan Africa, of the type needed to calibrate and test detailed simulation models, are generally scarce.

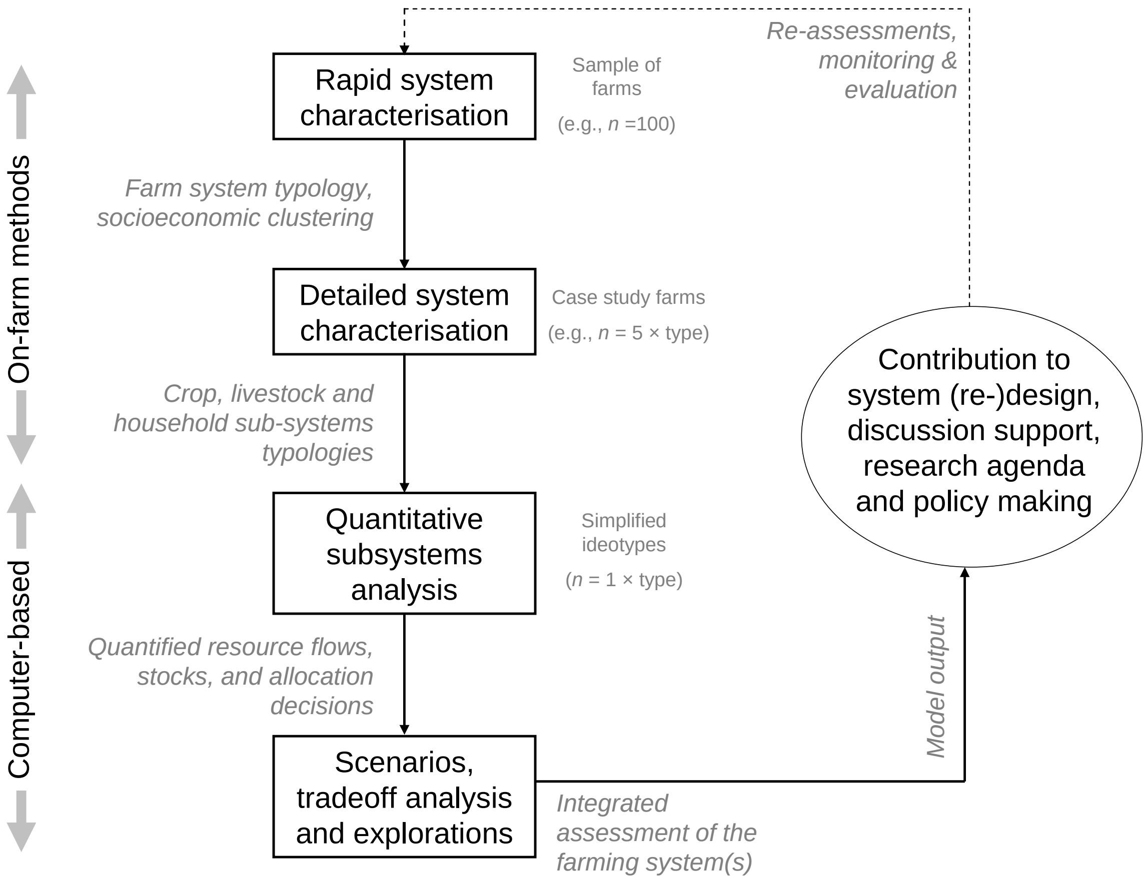

Figure 4: Steps in the quantitative analysis of farming systems, integrating 'on-farm system analysis' (largely participatory methods) with computer-based methods using models (e.g., nutrient balances, econometric, optimisation and/or dynamic simulation models). Detailed system characterisation is done on a sub-sample of farms selected to represent different household categories or farm types. Quantified resources and strategies pertaining to each individual system component (e.g., crop/soils, livestock/manure, household) are integrated at farm system scale for scenario analysis, contributing to system (re-)design.

Rather than a 'saturation' curve, Leffelaar (1990) pointed to the existence of an 'optimum' level of detail in terms of the number of processes modelled that allows the closest approximation to system reality (Figure 5 B). Reaching the system reality is not only impossible but also undesirable; models are a simplification of reality. Different optima may exist, depending on the characteristics of the system being modelled (i.e., Case 1 vs. Case 2 in Figure 5 B).

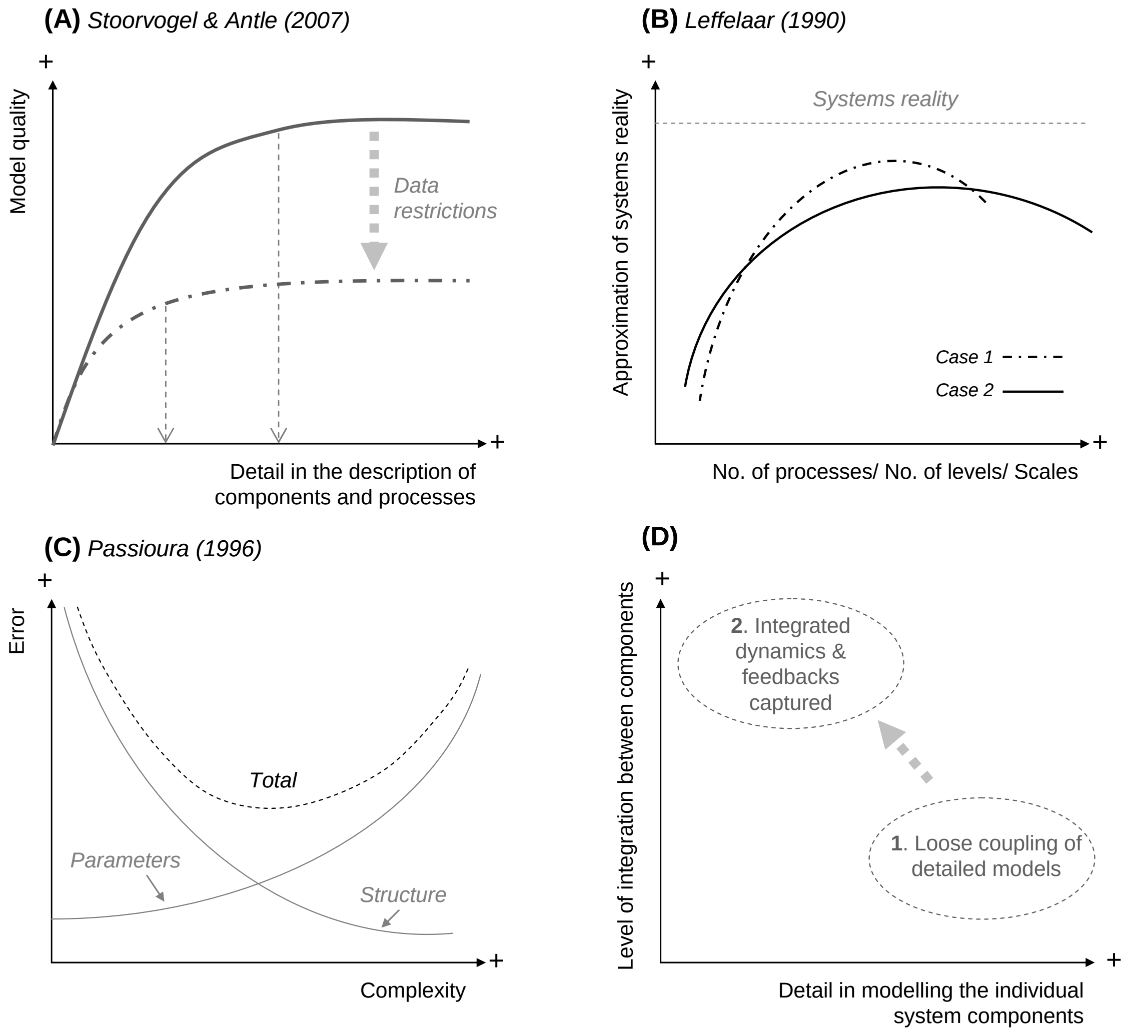

Figure 5: Considerations on the level of detail to include in simulation models. (A) Relationship between 'model quality' and level of detail in the processes being modelled, and the effect of data restrictions on the performance of the model; (B) There is an optimum level of detail to achieve the closest approximation to systems reality, or different optima, depending on the characteristics of the system being modelled; (C) When the structure of the system is well known, increasing model complexity reduces uncertainty in the representation of the processes but increases the uncertainty in parameterisation; (D) While complex models of individual sub-systems (e.g., crops, soils and livestock in a farm system) are often linked through loose coupling, reducing their complexity allows easier functional integration, reducing uncertainties and capturing feedbacks at farm scale.

When excessive detail is included, that is, in terms of number of processes and levels of integration, increasing uncertainty in the model parameters will reduce the performance of the model to represent reality. This is in agreement with the scheme developed by Passioura (1996) (Figure 5 C), who postulated that – when the structure of the system is well known – increasing model complexity (structure) may reduce the error (uncertainty) of the model in simulating a given process, but will lead to increasing error due to an increase in the number of parameters that need to be estimated. If we assume that model 'quality' or performance implies low error levels (low uncertainty), then there is an optimum level of complexity that minimises the total error, which is analogous to the maximum approximation of 'system reality' represented in Figure 5 B. It is still debatable, however, whether it is only the number of parameters that make the model error increase in Figure 5 C, or whether the error will also increase with increasing complexity in the structure of the model (M. van Wijk, pers. comm.).

In more practical terms, models of system components that are too complex cannot be linked easily for analysis of the behaviour of the whole system (at farm scale). Integrated assessments simulating different system components were often done by 'loose coupling' of detailed models, i.e., running the models individually and stepwise, using the output of one model as input for the next (e.g., Castelán-Ortega, 2003; Zingore et al., 2007c). With such approaches feedbacks are less easily captured, as compared with integrated models running in parallel and interconnected, for which simpler modules are often better suited (Figure 5 D). Using simpler models at higher scales of analysis is comparable with moving leftwards along the 'complexity' axis in the previous figures, in an attempt to find the optimum level of model performance.

Scenarios for farming systems should be analysed, ideally, using bio-economic models able to capture key biophysical feedbacks in time while accounting for farmers' decisions with regards to household economy, financial constraints or market dynamics (Thornton and Herrero, 2001). Brown (2000) reviewed a number of bio-economic models and ordered them in a continuum: on one extreme, the biophysical models to which an economic balance has been added (*ex-post*) and, on the other, the economic optimisation models that consider biophysical components as activities among the various choices for optimisation and which performance is represented by technical coefficients. The principles of 'appropriate detail' and 'bio-economic integration' have been pursued in the various approaches used in this thesis for scenario analysis.

There are differences in the way intensification pathways are viewed, which determines the type of intervention proposed to achieve sustainability of smallholder systems. These are illustrated in the simplified diagrams of Figure 6. At their initial stage (A), farming systems in Africa rely on soil nutrient stocks and fertility recovery during fallow periods, with little inputs and moderate rates of losses (variable across systems). After years of cultivation with larger output than input rates soil nutrient stocks decline and systems reach a low equilibrium (B), with losses reduced in proportion to stocks. Interventions to restore productivity often take place at this lower equilibrium stage. Input-based or 'green revolution' type of interventions are based on the simplistic assumption that large amounts of inputs will produce large outputs (C). However, the likely effect of solely increasing the rates of input is higher nutrient losses and not directly more output (D); not in the short term at least. Sustainable intensification (E) should ensure high nutrient capture and conversion efficiencies and proper recycling of nutrients within the system in order to restore the stocks to levels that allow responsiveness to inputs, and to less inputs needed in the long term. Simulation models were used in this thesis to contribute to the design of prototypes that comply with such requisites and to investigate the plausible steps to achieve them – symbolised as a question mark, "?" in Figure 6.

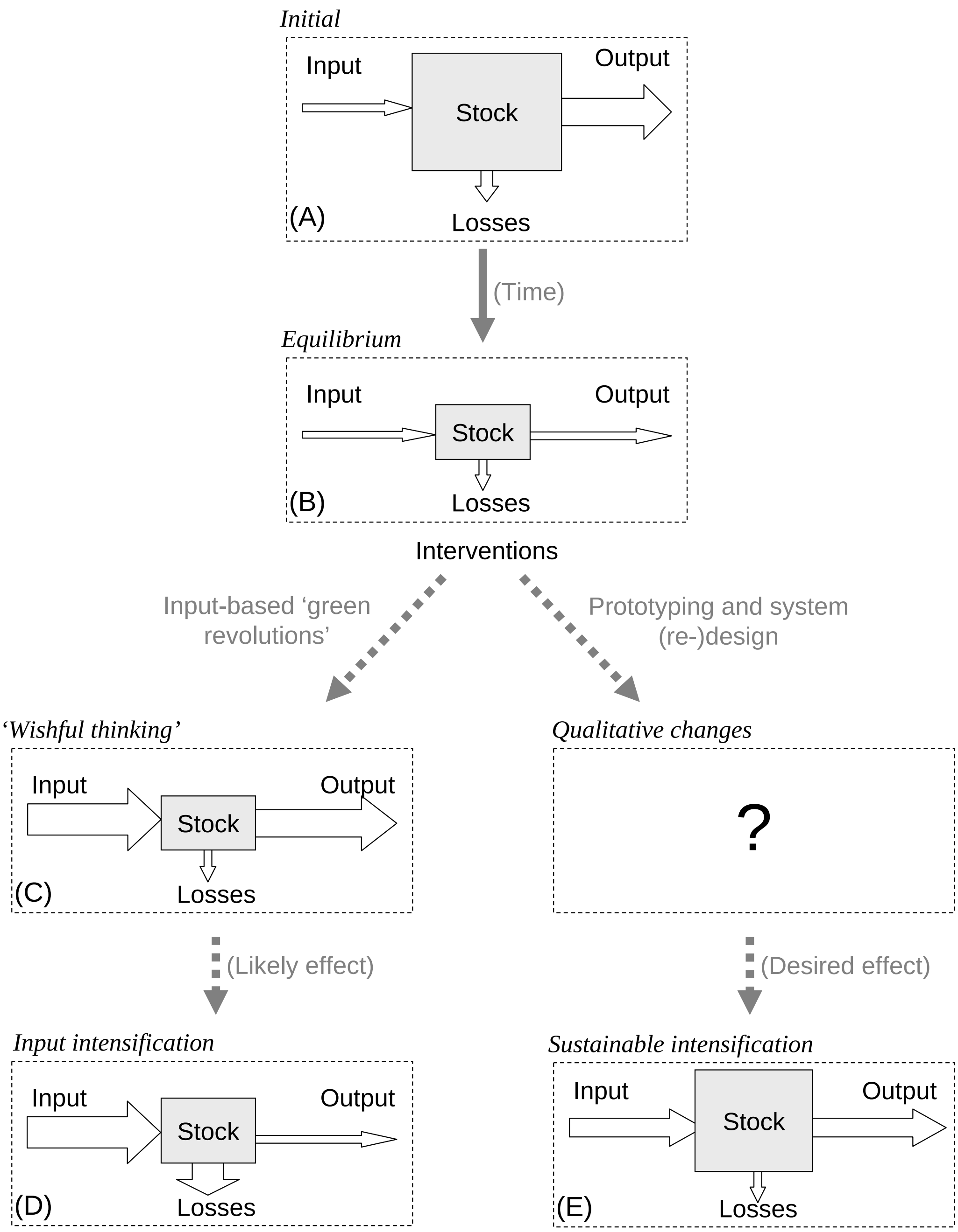

Figure 6: Visions on intensification of smallholder farming systems. See text for explanation.

8. Outline of the thesis

The various chapters of this thesis have been grouped in four parts, following approximately the DEED methodology steps. In step 1 (Describe), the farming systems under study are characterised and compared, with particular attention paid to the biophysical, socioeconomic and managerial drivers of soil heterogeneity across sites. This is done in Chapter 2 for different agricultural systems of the East African highlands and in Chapter 3 (an addendum to Chapter 2) in more detail for western Kenya, where most of the work reported here has been conducted. In the second step (Explain), the factors behind the commonly observed spatial variability in crop yield, resource use efficiency and crop response to fertilisers within smallholder farms are analysed. This is done in Chapter 4, using statistical models to explain the observed variability in maize yields within heterogeneous farms, and in Chapter 5, looking at the effect of soil heterogeneity on nutrient use efficiencies and crop responses to mineral fertilisers. In the third step (Explore), the analysis done in Chapter 6 attempts to understand how operational, day-to-day farmers' management decisions contribute to the creation of farm heterogeneity and the nature of the tradeoffs that farmers face when deciding on the allocation of their scarce resources. In Chapter 7, the strategic allocation of resources for integrated soil fertility management within heterogeneous farms is analysed considering long-term horizons. The fourth step (Design) is partly covered in Chapter 8, which is a contribution to the design of sustainable farming systems taking reference on *ideal farms* designed by smallholder farmers through participatory prototyping. Finally, the implications of the findings of this thesis to the design of sustainable farming systems are discussed in Chapter 9. In many parts, this thesis summarises work that has been published or is under review for publication. While the methodology has been described in sufficient detail to understand the results presented in each chapter, specific methodological details can be found in the publications referred to.

Chapter 2

Drivers of farm heterogeneity in agricultural systems of the East African highlands†

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† This chapter is a summary of:

Tittonell, P., Muriuki, A.W., Shepherd, K.D., Mugendi, D., Kaizzi, K.C., Okeyo, J., Verchot, L., Coe, R., Vanlauwe, B., 2007. Soil heterogeneity in smallholder farms of East Africa. I. Biophysical and socioeconomic drivers at regional and local scales. Agriculture, Ecosystems and Environment, in prep.

Tittonell, P., Muriuki, A.W., Shepherd, K.D., Mugendi, D., Kaizzi, K.C., Okeyo, J., Verchot, L., Coe, R., Vanlauwe, B., 2007. Soil heterogeneity in smallholder farms of East Africa. II. Spatial patterns of resource allocation and their interaction with landscape variability. Agriculture, Ecosystems and Environment, in prep.

Abstract

Technological interventions to address the problem of poor soil fertility in smallholder agricultural systems must be designed in the context of diverse and spatially heterogeneous farms and farming systems. This chapter presents a study based on comparative quantitative and qualitative evidence from six districts in Kenya and Uganda, designed to understand cross-scale interactions between the major determinants of diversity and heterogeneity of farming systems. Analysis of the variance of soil fertility indicators across 250 randomly-selected farms (i.e. 2607 fields) revealed that the variation in soil organic C and total N was mostly related to differences in the inherent properties of the soils across sites and the landscape, while available P, K and pH had larger residual variability in the model, which was associated with spatial soil heterogeneity within farms. Wide diversity was generally observed in socioeconomic (e.g. 4 months year^{-1} of food self sufficiency in Vihiga vs. 10 in Tororo) and management (e.g. fertiliser use by 95% of farmers in Meru South vs. none of the farmers in Mbale) factors across and within districts. Across districts, all the households with less than 3 months year^{-1} of food self-sufficiency had a land:labour ratio (LLR) < 1, and all those with LLR > 1 produced enough food to cover their diet for at least five months. Households with LLR < 1 were also those who generated more than 50% of their total income outside the farm. The dependence on off-/non-farm income was one of the main factors explaining socio-economic variability, and is a key determinant of household diversity. The reason for some farmers to do casual work outside their farms was, literally "because I am unemployed". Based on resource endowment, dependence on off-farm income and production objectives, different households were grouped into five Farm Types: 1. Farms that rely mainly on permanent off-farm employment; 2. Larger, wealthier farms growing cash crops; 3. Medium resource endowment, food self-sufficient farms; 4. Medium to low resource endowment relying partly on non-farm activities; and 5. Poor households with family members employed locally as agricultural labourers by wealthier farmers. Although the five livelihood strategies were identified in the six districts, the relative distribution of households into different farm types varied across districts. These farm types differed in land, labour and financial resources and potential nutrient availability (e.g. animal manure) which affect land use and soil fertility management. However, the five farm types differed more in the degree of soil heterogeneity than in their average soil fertility status at farm scale. In general, variability in soil fertility was larger in farms (and sites) with poorer soils and smaller in farms owning livestock. In allocating nutrient resources, farmers prioritised the fields they perceived as most fertile. Due to multiple interactions between site-specific factors, farm resources and objectives, landscape variability and history of land use and management, the variability in soil fertility indicators often observed within individual farms could not be summarised in consistent, generalisable patterns of spatial heterogeneity.

Keywords: Sub-Saharan Africa; Farm typology; Resource endowment; Soil fertility gradients; Food security; Land:labour ratios

1. Introduction

Smallholder farming systems in sub-Saharan Africa occur within diverse biophysical and socioeconomic environments. Rural communities develop different livelihood strategies driven by opportunities and constraints encountered in such environments. Agroecology, markets and local cultures determine different land use patterns and agricultural management practices across regions. Within localities and villages, households differ in resource endowment, production orientation and objectives, ethnicity, education, past experience and management skills, determining diversity of natural resource management strategies (Crowley and Carter, 2000). At the scale of individual farms, resource limitation forces farmers to preferentially allocate the available labour and nutrient resources to certain fields, which contributes to the creation of spatial variability in soil fertility within their farms; i.e. soil fertility gradients (Tittonell et al., 2005c). Thus, due to cross-scale interactions between biophysical, socioeconomic and management factors, smallholder farms are diverse and heterogeneous: within a certain locality, different farm types may be identified and within these, spatial and temporal patterns of heterogeneity may be recognised.

Recognising variability within and among farms and across localities is an important step in the design of policies to help poor farmers (Ruben and Pender, 2004). Farm heterogeneity and diversity are key determinants of the adoptability and performance of new technologies. For example, the adoption of certain soil-management technologies by farmers may be limited by the availability of land (e.g. improved fallows), labour (e.g. biomass transfer), or cash (e.g. mineral fertilisers). The performance of technologies may also be highly variable within spatially heterogeneous farms, further hampering their adoption. Improved understanding of the main drivers of diversity and heterogeneity of smallholder systems, and ability to categorise patterns of variability, should help to better target technologies to specific socio-ecological niches (e.g. Ojiem et al., 2006). To improve use efficiency of production factors – an important principle underlying integrated soil fertility management strategies (Vanlauwe et al., 2002) – management technologies must be designed considering the various determinants of farm heterogeneity operating at different scales.

In the region of study, comprising the populated highland and midland humid zones of East Africa, wide variability in these factors have resulted in different land use systems that range from strongly market-oriented smallholder coffee, tea and dairy systems, through semi-commercial cereal/legume-based systems, to subsistence oriented systems based on starch crops (Braun et al., 1997). In general, continuous cropping with few or no nutrient inputs coupled with removal of crop residues from the fields has led to a general poor fertility status of the soils (Shepherd et al., 1996). Earlier studies in the region also showed that rural livelihood strategies to cope with limited access to (land, labour, monetary) resources were not only restricted to alternative methods of farm management and/or choice of production activities; off- and non-farm opportunities provide alternative or complementary livelihood strategies, with household surveys revealing that up to 80% of the interviewed families had some external income (e.g. Tittonell et al., 2005b). However, labour markets and non-farm job opportunities also differ across localities, strongly affected by land use (e.g. by the presence of labour-demanding cash crops such as tea) and by proximity to urban areas. Finally, farmers' attitude towards risks and their mechanisms for risk avoiding or coping are also elements of household diversity in the region (Salasya, 2005)

Impact of household resource endowment or access to alternative income sources on farm (and specifically soil) management has been reported for case study farms in the region (e.g. Nkoya et al., 2004; Tittonell et al.,2005b and c; Barret et al., 2006). Household categorisation is thus not only necessary to target (development or technology) interventions to families with varying livelihood strategies, but also to understand how such strategies may affect resource allocation. Previous studies in East Africa used various criteria and methods to categorise households for specific purposes: e.g. soil fertility research (Carter, 1997), agroforestry interventions (Shepherd and Soule, 1998), econometric and/or policy analysis (Kruseman et al., 2006), etc. A common denominator in most household clustering exercises is the use of wealth or resource endowment indicators, which are also used when farmers classify themselves through participatory wealth rankings (e.g. Mango, 1999). While all these constitute examples of structural household typologies, functional typologies that consider also the dynamics of production orientations and livelihood strategies may improve the categorisation of households, depending on the objectives of the analysis (Mettrick, 1993).

This chapter presents the results of research conducted to understand cross-scale interaction between the major determinants of diversity and heterogeneity of farming systems, from region to individual households. Our objectives were (1) to identify and categorise the diversity of biophysical and socioeconomic drivers of farm heterogeneity operating at different scale in areas with moderate to high agricultural potential of East Africa; and (2) to analyse their influence on rural livelihood strategies and their potential effect on current soil fertility status and its variability at farm scale. The major drivers of soil heterogeneity were grouped as: (i) regional differences in soils and climate; (ii) biophysical differences between and within localities (landscape variability); (iii) socioeconomic diversity between farms (and across the region); (iv) management-induced variability within farms, and its interaction with (i), (ii) and (iii). The analysis was performed on a sample of households from six districts in Kenya and Uganda, which were selected through spatial randomisation to avoid household selection biases and to account for variability due to soil-landscape associations.

2. Materials and methods

2.1 Selection of study sites and farms

The selection of study sites was done using a hierarchical approach, designed to identify sites with markedly different market opportunities and agricultural potential (Table 1). The six study sites were located in Meru South and Mbeere districts in Central Kenya, Vihiga and Siaya districts in Western Kenya, and Tororo and Mbale districts in Eastern Uganda (Figure 1 A). The rainfall distribution across the whole region is bimodal, characterised by a long and a short rainy season that allow two cropping seasons per year (Table 2). The sites at Meru South, Vihiga and Mbale districts are located in areas considered to have the highest agricultural potential within East Africa, due to their inherently fertile soils and ample rainfall (Jaetzold and Schmidt, 1982; Wortman and Eledu, 1999).

Table 1: Sampling scheme from region to field indicating the various units at each geographical scale (A) and the criteria followed for site selection (B)

(**A**)

Scale	Total number of units	Description
Region	3	Sub-regions within East Africa: Central Kenya, Western Kenya, Eastern Uganda
District*	6	Two districts per sub-region: Meru South, Mbeere, Vihiga, Siaya, Tororo, Mbale
Locality**	24	Four Y-sampling frames per site or district, corresponding each to a Sub-location in Kenya or to a Parish in Uganda
Farm	240	Each Y-sampling frame comprising 10 farms, selected as explained in main text
Field	2607	All fields within a farm (number varying between 4 and 18 fields per farm)

(**B**)

Sub-region	District	Access to major urban markets	Agricultural potential
Central Kenya	Meru South	Relatively good	Relatively good
	Mbeere	Relatively good	Relatively poor
Western Kenya	Vihiga	Intermediate	Relatively good
	Siaya	Intermediate	Relatively poor
Eastern Uganda	Tororo	Relatively poor	Relatively poor
	Mbale	Relatively poor	Relatively good

*The term ‘District’ is used here to designate study sites; however, the 4 localities selected within each district are representative but not necessarily similar to the full range of variability aggregated at district scale, as presented e.g. in governmental district surveys

**The term ‘Locality’ is generically used to indicate political/administrative divisions that receive a different name across borders

Population densities are high in Vihiga and Meru South, consequently with small farm sizes (Table 2). Both lack communal areas for livestock grazing and thus intensive livestock systems prevail. The population density in Mbale is about the highest in Uganda, due to migrations from the central parts of the country at the beginning of the 20th century. Coffee is extensively grown as a cash crop in Mbale and Meru South, where tea is also cultivated. The area under cash crops in Vihiga (tea), Siaya (cotton), Mbale (coffee) and Tororo (cotton, tobacco) has decreased during the past decades. Ox-ploughing is more commonly observed in Mbeere, Siaya and Tororo, due to the larger size of the fields.

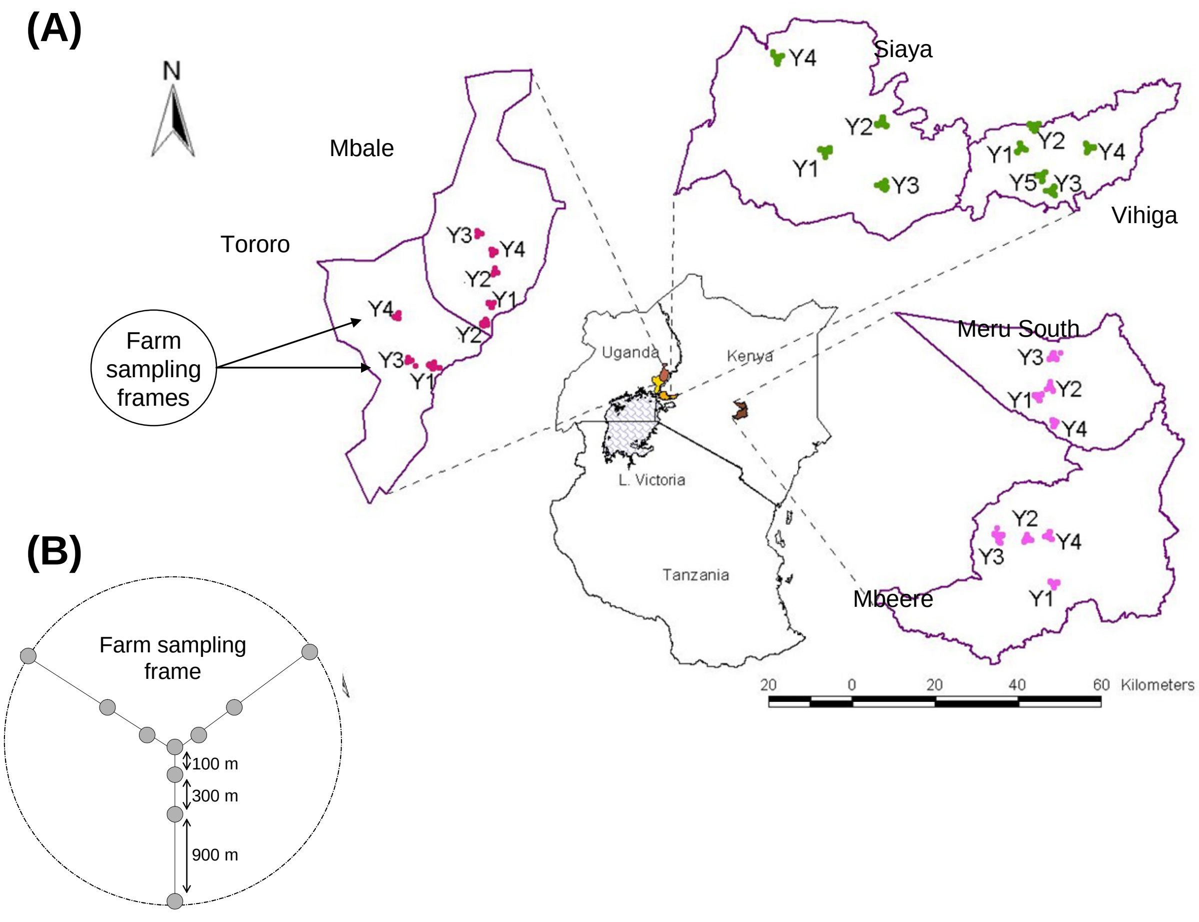

Figure 1: (A) Map of the region, districts and location of the Y sampling frames. (B) Details on the Y sampling frame used for farm selection, indicating the position of the selected farms (grey circles) and the distance between them.

Within each of the six study sites[‡] four different localities were selected (totalling 24 - cf. Table 1; Figure 1 A), corresponding to different administrative units of the districts considered.

[‡]Although probably more ambiguous, the term 'site' was preferred over 'district' to designate the six study areas. The use of district would imply that the sites chosen are representative of the full range of variability for entire district, which is not necessarily the case.

Table 2: Main characteristics of the selected sites in three sub-regions of East Africa

	Central Kenya		Western Kenya		Eastern Uganda	
Characteristic	Meru South	Mbeere	Vihiga	Siaya	Tororo	Mbale
Biophysical						
Altitude (masl)	1500	1100	1600	1200	1100	1600
Annual rainfall (mm)*	1600	700	1800	1400	1100	1200
Dominant soil types (FAO)	Nitosols, Ferralsols	Lixisols, Arenosols	Nitosols, Ferralsols	Ferralsols, Acrisols	Acrisols, Vertisols	Ferralsols, Acrisols
Landscape	Strongly undulating, slopes up to 45%	Fairly flat to gently undulating to, slopes < 5%	Gently undulating, slopes 5 to 20%	Fairly flat, slopes < 3%	Fairly flat, slopes < 3%	Gently undulating, slopes up to 30%
Socioeconomic						
Population density (km^{-2})	800	400	1000	350	250	350
Farm sizes (ha)	0.5 – 3	1 – 10	0.3 – 2	0.5 – 5	1 – 8	0.5 – 5
Distance to major urban areas**	Close	Close	Close to medium	Medium to far	Medium to far	Far
Production activities						
Major food crops	Maize, beans	Sorghum, cowpeas	Maize, beans	Maize, cassava	Cassava, sorghum	Bananas, beans
Major cash crops	Coffee, tea	Khat, groundnuts	Tea, coffee	Sugar cane, cotton	Cotton, tobacco	Coffee
Livestock system	Zero grazing dairy systems and cultivation of fodder crops; improved cattle	Free ranging local zebu (traction) and goats; night corralling	Tethered cattle grazing in compound fields, zero grazing	Free grazing and tethered local cattle, used for traction	Free grazing in communal grasslands; local zebu used for traction	Zero grazing of cattle (traction) and goats; donkey used for transport

* In all sites rainfall is distributed bi-modally (i.e., long and the short rains seasons)
**This takes into account not only the physical distance but also infrastructure for transport and communication

GIS layers for soils, agro-ecological zones and sub-locations (Kenya) or parishes (Uganda) were overlaid for each district. Soils considered to be of little agricultural importance were discarded, and the four localities were selected randomly from all sub-locations (in Kenya) or parishes (in Uganda) present in the six districts. Within each locality 10 farms were selected within a 1200 m diameter radius using a Y-shaped sampling frame (Figure 1 B). The sampling frame was designed to include those characteristics considered to occur at random (e.g. elevation, parent material, climate, landscape position) and 'fixed effects' considered under farmers' control (e.g. soil management, land use history). One farm was located at the centre of the 'Y' and three in each of the randomly oriented arms separated at constant distances from the central farm (at 100, 300 and 900 m). The 'Y' sampling frame was considered to be the most efficient way to avoid sampling bias while obtaining information on spatial correlation with fewest possible sampling points, allowing for further analysis of spatial correlation using geo-statistical models[§] (Stern et al., 2004). Four Y-frames per district led to a final sample of 240 farms; an extra Y-frame was sampled in a fifth locality at Vihiga to include a previous benchmark site where research on soil fertility issues had been conducted, giving a total of 250 farms. The Y-frames were prepared using ARC-GIS software to obtain the exact geographical location of each farm. Farms were geo-referenced using a Global Positioning System (GPS) device.

2.2 Household surveying and categorisation

The selected farms were surveyed during the first (long) rain season of 2003 (March – July). Survey questionnaires were designed to capture biophysical, socio-economic and managerial aspects of each farm and national teams trained to administer them. Socioeconomic and farm management information included characteristics of the household head (name, age, gender and marital status) and family structure, labour availability, sources of income, a map of the farm, land use patterns, use of/ access to agricultural inputs, food security, livestock system, links to nearby markets, and production orientation. The different fields of each farm were identified with the aid of a map drawn by the farmer and the centre and perimeter of each field geo-referenced by means of a GPS. The surface area of each field was determined with a differential GPS. Biophysical information was collected on a field-by-field basis and included field characteristics (e.g. slope, landscape position, flooding, erosion, hard-setting, rock/stone cover, etc.) and management (e.g. the practice of fallow, nutrient input use, soil conservation measures, farmer soil fertility assessment, etc.).

During the short rains season of 2003, participatory wealth ranking and resource flow mapping exercises were implemented to delineate wealth classes, identify livelihood strategies and categorise household diversity. From the information gathered we derived wealth indicators (e.g., land availability, livestock ownership), the occurrence

[§] No further explored in this thesis

of certain production units (e.g., tea fields, zero-grazing cattle), farmers' goals, priorities and indicators of soil fertility and proper farm management. Wealth indicators selected by farmers were used together with wealth indicators derived from the survey data to define household resource endowment classes (poor, medium, high). Households were categorised considering resource endowment plus criteria representing orientation of production activities (market, self-consumption), main type of constraints to agricultural production (as determined by land:labour ratios and cash availability), position of the household in the 'farm developmental cycle' (Crowley, 1997 – Chapter 1) and main sources of income for the household (Table 3). Principal component analysis (PCA – see later) was used to identify non-correlated socioeconomic indicators to use as proxies for the categorisation criteria described in Table 3. The frequency distribution of such indicators was studied for each site individually, and cut-off values (e.g. n-*quantiles*) were arbitrarily chosen, in consultation with the local surveying teams, to cluster households into relatively homogeneous categories (e.g., while the distribution of farm sizes was extremely asymmetrical and often the median could be used as cut-off, age of the household head was normally distributed and thus 3-quantiles could be used to represent the three stages in the farm developmental cycle – cf. Chapter 1).

Table 3: Functional typology for household categorisation applied in western Kenya by Tittonell et al. (2005b).

Farm type	Resource endowment* and production orientation	Main characteristics**
1	Predominantly high to medium resource endowment, mainly self-subsistence oriented	Variable age of the household head, small families, mostly constrained by land availability (lack of family labour compensated by hiring-in). Permanent sources of off-farm income (e.g. salary, pension, etc.)
2	High resource endowment, market-oriented	Older household head, numerous family (starting land subdivision), mostly constrained by labour (hired-in) due to large farm areas; cash crops and other farm produce are the main source of income
3	Medium resource endowment, self subsistence and (low-input) market-oriented	Young to mid-aged household head, young families of variable size in expansion, mostly constrained by capital and sometimes labour, farm produce and marketable surpluses plus complementary non-farm enterprises
4	Predominantly low to medium resource endowment, self-subsistence oriented	Young to mid-aged household head, variable family size, constrained by availability of land and capital, deriving income from non-farm activities (e.g. ox-plough service, handicrafts)
5	Low resource endowment, self-subsistence oriented	Variable age of household head, variable family size, often women-headed farms constrained by land and capital, selling their labour locally for agricultural practices (thus becoming labour-constrained)

*Referring to assets representing wealth indicators (i.e. land size, livestock ownership, type of homestead, etc.).
**Referring to the family structure, position of the household in the 'farm development cycle' (see Chapter 1), to the main constraints to agricultural production faced by the household, and to the main source of income.

2.3 Soil sampling and analysis

Within each field, soil was sampled within a 5 x 5 m quadrat located to avoid sampling bias and under- or over-sampling of edge effects on small fields. Within each quadrat, soil was sampled at three points along the slope, at 0.5 m, centre, 2.5 m and 4.5 m from the edge of the quadrat. Soil samples were taken using a soil auger of 5.3 cm diameter at 0-20 depth (composite of three samples) and 20-50 cm depth (central location only). A total number of 2,607 geo-referenced composite topsoil samples were taken from the 250 farms. These were air-dried, weighed and passed through a 2 mm sieve. Soil fines (< 2 mm) were also weighed. Visible-near-infrared diffuse reflectance spectroscopy (0.35 to 2.5 µm) was used to characterize the air-dried samples, which were scanned in Duran glass Petri-dishes using a FieldSpecTM FR spectroradiometer using the optical setup described by Shepherd et al. (2003).

A subset of 20% (n = 430) of the soil samples were selected for wet chemistry analyses using standard methods described by Shepherd and Walsh (2002), except that total C and N were determined by combustion using a CN analyser. The samples were selected on the basis of a principal components model of the first derivative reflectance values. Soil properties were calibrated to the first derivative spectra using partial least squares regression implemented in The Unscrambler (Camo Inc). The analytical procedures for calibration and validation of predicted soil properties were described by Shepherd et al. (2003). The predicted soil properties for all samples were used in subsequent statistical analyses. Hold-out-one cross-validated root mean square error of the transformed values, respectively, were as follows: organic C, 0.49 Sqrt g kg^{-1}; total N, 0.14 Sqrt g kg^{-1}; exchangeable Ca, 0.52 Ln $cmol_c$ kg^{-1}; exchangeable Mg, 0.73 Ln $cmol_c$ kg^{-1}; extractable K, 0.60 Ln $cmol_c$ kg^{-1}; extractable P, 0.68 Ln mg kg^{-1}; sand 0.66 Sqrt %; silt 0.75 Sqrt %; clay 0.63 Ln %.

2.4 Categorising variability in soil fertility within farms

Criteria to classify fields with similar characteristics into groups or types included the dominant type of land use (commercial, subsistence), or classes based on: (i) the slope of the fields; (ii) their position in the landscape – closely associated with local soil names; (iii) their history of use (years under cultivation); (iv) their relative distance to the homestead; and (v) the fertility of the soils as perceived by the farmer. These criteria were evaluated by examining the frequency distribution of the number of fields sampled and their average area in each category, to obtain comparable field typologies across sites. A relative distance from the homestead was calculated to allow comparisons across farms of different size, by dividing the absolute distance from the homestead to the centre of a field by the distance to the farthest field in the farm. Only the classifications by landscape position (ii) and farmers' perception of soil fertility (iii) are presented here, since they produced the most consistent categorisation of soil variability.

2.5 Data analysis

2.5.1 Magnitude and distribution of soil variability

The structure of the variance in soil fertility status was analysed using a mixed model ANOVA approach, with random and fixed terms. For our purpose, we focused only on the random components: region, site, locality and farm (cf. Table 1). This analysis was done on soil properties pertaining to individual fields (n = 2,607), expressed as the spectral predictions of soil organic C, total N, available P, exchangeable K, Ca and Mg, pH, and sand, silt, and clay contents in a composite sample from each field plot, transformed as necessary (log or square root) to ensure normality in their distribution.

2.5.2 Socioeconomic diversity

Comparisons across sites and household categories in terms of socioeconomic and land use and management indicators were done through calculation of descriptive statistics and analysis of variance, with the explanatory factors Site (or 'District' – see Table 1), household category (or 'Farm Type' – see later) and their interaction. A principal component analysis was conducted using the socioeconomic data (previously log or square root transformed, and standardised for comparable ranges) to identify proxy indicators for the main drivers of livelihood strategies across sites.

2.5.3 Soil fertility status and its variability at farm scale

To analyse soil fertility status and its variability at farm scale we aggregated soil properties measured on the various fields of a farm into farm-scale weighted averages, and calculated the coefficient of variation and an index of range amplitude at farm scale for each soil fertility indicator. Weighted average soil fertility indicators at the farm scale were obtained by adjusting the predicted soil properties of each individual field according to the proportion of its area relative to total farm area, as follows:

$$SFS_{(X)} = \sum_{i=1}^{n} SF_{(X)i} \times (FA_i / TFA) \quad (1)$$

where:

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

$SF_{(X)i}$ = Soil fertility status (i.e. stock, availability) as predicted from the spectral soil analysis for each field in the farm (1 to n fields)

$FA_{i,}$ = Area of each particular field (1 to n fields) [ha]

TFA = Total farm area [ha]

After having categorised households into farm types of different wealth and production orientation, the variability associated with differences between fields within single farms was estimated according to the residual variance term in the generic statistical model:

$$C_{ijk} = W_i + F_{ij} + P_{ijk} \quad (2)$$

Where, the value of the predictor of a certain soil property (C_{ijk}) is the result of the effects of farm type (W_i, i = 1 to number of farm types in the categorisation) and of each particular farm (F_{ij}, j = 1 to number of farms per site); the unexplained or residual variance term P_{ijk} (k = 1 to number of plots per farm) was used as an estimator of variability due to soil heterogeneity within farms. This variance term was used to calculate the coefficient of variation (CV) for each farm and soil fertility indicator. Alternatively, an index that reflects the amplitude in the differences in soil fertility indicators between the best and the worst field of each individual farm was calculated as:

$$I_{(X)j} = [(X_{best\ field} - X_{worst\ field}) / X_{farm\ average}]_j \times [(k-1)/k]_j \quad (3)$$

Where, the index of amplitude for the soil property X for the j^{th} farm is equal to the full range for that particular property within the farm (i.e. the maximum minus the minimum values of X) divided by its mean and corrected by the number of fields or plots (k) in that particular farm. Similar to the CV, this index is a ratio between a measure of dispersion and the value of the mean. The index of amplitude is by definition more sensitive to extreme values than the CV, and since it may be influenced by analytical error it should be interpreted in combination with the CV.

The values of the average, coefficient of variation and the index of amplitude for each soil fertility indicator were (log or square root) transformed to normalise distributions prior to analysis of their variance. All analysis and calculations were performed using GenStat Version 8.

3. Results

3.1 The magnitude of soil variability at different scales

The average value of main soil fertility indicators varied across districts, following the major biophysical gradients (Figure 2). Soil organic C and total N contents were greater in areas with finer-textured soils and higher rainfall; available P was higher in soils developed on the foot slopes of Mt. Kenya (Meru South) and Mt. Elgon (Mbale); the concentrations of exchangeable bases were higher in the heavier clayey soils of Siaya, while the highly weathered soils of Meru South and Vihiga had lower pH. While the farms sampled in Meru South had the largest average soil C contents varying within a narrow range between farms, those from Mbeere and Tororo had smaller average values and larger variability (Figure 2 A and B). Large inter-quartile variation in the farm-scale, weighted average P and K status was observed in Mbale, probably due to wide soil-landscape variability, while farms of Vihiga and Tororo had the smallest average values.

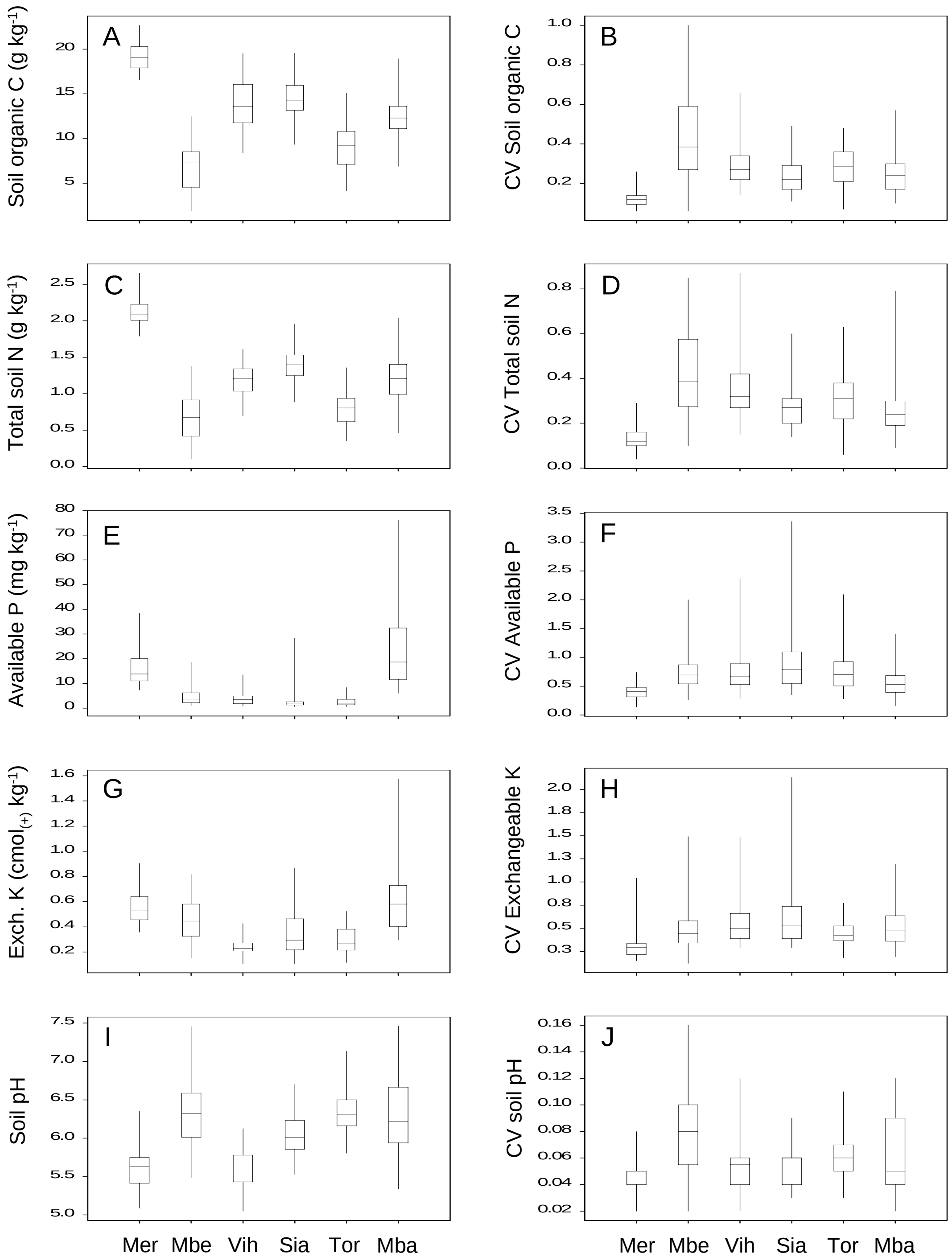

Figure 2: Variability in soil fertility status across sites. The left panes are box-and whisker plots indicating the variation in farm-scale weighted average soil organic C, total N, available P and exchangeable K+ and pH; the right panes show the dispersion in the coefficient of variation of these indicators across the 250 farms sampled. The box-and-whisker diagrams include the range of 50% of the samples (rectangle), the median (cross bar) and the maximum and minimum values (extreme of the lines). Exch. K: exchangeable K; CV: coefficient of variation. Site abbreviations: Mer = Meru South, Mbe = Mbeere, Vih = Vihiga, Sia = Siaya, Tor = Tororo, Mba = Mbale.

Within individual farms, the largest relative variability was observed for available P, with extreme values for the coefficient of variation (up to 300% variability) between the different fields of farms in Vihiga and Siaya. Exchangeable K was also highly variable within farms, with CV > 1 in extreme cases. The CV of soil organic C between fields was in most cases < 0.3 and for soil pH < 0.1-0.2.

Differences between districts accounted for the largest proportion (60%) of the total variance in soil C and total N for the entire sample population (n = 2,607), whereas little of the variance was explained by differences between localities and farms (Table 4). The remaining (20-25%) was due to residual variance associated with variability within farms. Most of the variability in available P and exchangeable K was associated with variation within farms and less with inherent differences across sites. Part of the variation in exchangeable Ca and Mg was explained by differences between localities and farms, presumably due to soil-landscape covariance and the presence of different landscape units within larger farms (see later). The site and within-farm (residual) components explained most of the variation in pH. Thus, the proportion of total variance in soil fertility explained by the factor 'site' differed for the various soil indicators, with substantial variation within localities and farms for some of them. In the following sections we describe the various factors that contribute to explain the distribution of the variance in Table 4 for different soil indicators. At regional scale, soil organic C (and associated total N) and available P were uncorrelated and showed contrasting patterns of variation across and within sites. Since both indicators are also associated with availability of the major nutrients N and P, they were often important in characterising soil variability.

Table 4: Relative proportion of the total variance explained (%) by different random components of mixed-models performed for different soil fertility indicators at field scale.

Random term	% of variation explained by the random model terms for each soil fertility indicator						
	Soil organic C	Total soil N	Available P	Exch. K	Exch. Ca	Exch. Mg	pH water
Site	60	56	19	13	6	12	36
Locality	7	11	12	9	18	25	10
Farm	8	10	6	8	29	31	16
Residuals	25	23	62	69	47	32	38

Exch.: Exchangeable

3.2 Inherent biophysical factors

3.2.1 Regional and local variability

The six sites differed in the dispersion and range of variability in clay+silt, soil organic C and P availability (Figure 3). Within each sub-region the amount of soil C tended to increase as the clay+silt fraction increased (Figure 3 A, C, E), but this was less clear within each individual site. Soil C was highest and least variable in Meru South, contrasting with Mbeere in central Kenya, where soil texture varied more and coarser-textured soils had less organic C. The number of fields sampled in Meru S. (n = 555) was much larger than in Mbeere (n = 224), reflecting different patterns of land use and spatial fragmentation within farms. For both sites of western Kenya the number of fields sampled and the magnitude of the variation in soil C were comparable, the latter being larger than the variation observed for the other four sites. Most fields in the eastern Uganda sites of Mbale and Tororo had soil C < 20 g kg^{-1}, with larger average values for Mbale and a larger number of fields sampled in Tororo.

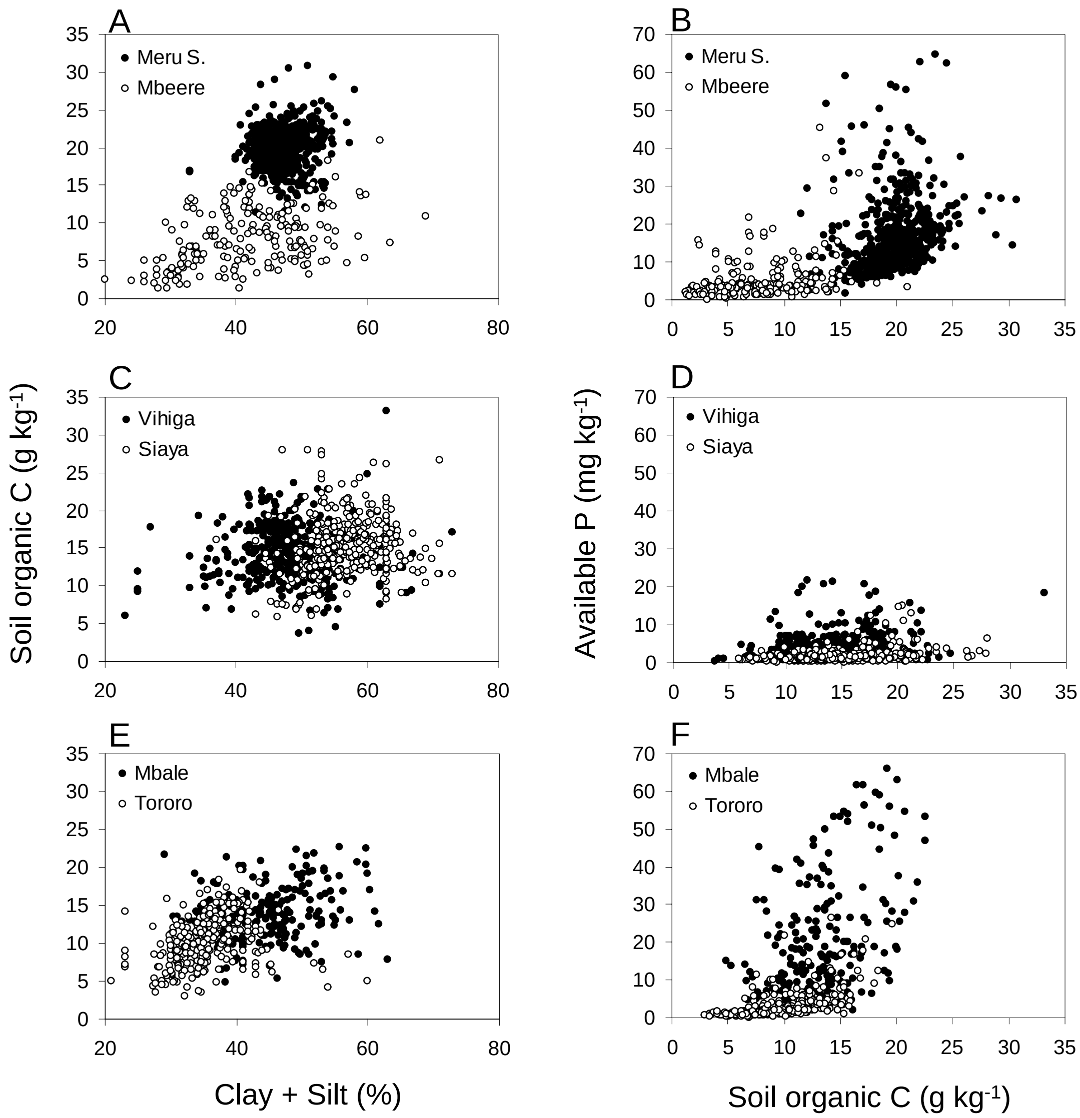

Figure 3: Relationship between the silt+clay fraction and the content of soil organic C (A, C, E), and between soil organic C and available P (B, D, F) for all the fields sampled in the six study sites (n = 2,607 fields).

The average value and the variation in available P differed strongly across sites (plotted against soil C in Figure 3 B, D and F). Except for Mbale and Meru S., most soils had < 10 mg kg^{-1} of available P with a few observations above that level. Despite the wide differences across sites, higher P availabilities (> 10 mg kg^{-1}) were only measured in soils with higher organic C (ca., > 10 g kg^{-1}). Part of the variability observed in soil texture, organic C and available P could be ascribed to differences between locations (Y-frames) within each site, as illustrated in Appendix 2.1.

3.2.2 Landscape variability

Toposequences of soil types characteristic of each individual site were associated with traditional names used by farmers to identify the various soil-landscape units. In Meru South, Vihiga and in the higher areas of Mbale, relatively narrow and long farms are located along the typical topographic profiles of these sites (Appendix 2.2). Larger farms may include all soil-landscape units of a typical catena within their area. Roads normally run on top of the ridges, with farms located in between the roads and streams in the valley bottoms. The different field plots of a large farm may occupy the flat upslope zones (ridges), the midslopes (breaking slopes and footslopes) and the valley bottom land alongside the water courses. In sites of flatter topography such as Mbeere, Siaya and Tororo, where the homesteads tend to be placed in the middle of the farm land, large farms do not necessarily include all the soil-landscape units occurring in their area. The entire sample of farms (n = 250) included cases that differed in their land area and their position in the landscape, in six sites with markedly different topography. To analyse soil properties as influenced by their position in the landscape, all fields sampled (n = 2607) were grouped into classes representing major landscape units (Table 5). This categorisation was done independently for each site, since e.g. the flatter upslopes in Meru South had the same topographic slope (%) as the midslopes in Siaya. Most of the fields sampled fell in the midslope category – or the equivalent convex areas in Mbeere, with average slopes ranging from 3 to 24%. Fewer fields were found in the 'accumulation' areas categorised as valley bottoms, drainage ways, concave areas or marshland borders, although their average area tended to be larger. In sites with more abrupt topography there was closer association between distance from the homestead and soil-landscape variability. Some (average) soil properties tended to vary more than others across the landscape (Table 5). The average soil organic C was similar for all landscape positions in Meru South and Tororo, whereas it decreased towards the lower positions in Siaya and Mbale. Average available P decreased towards lower positions in Vihiga and Mbale although, given the smaller farm sizes in these intensively cultivated areas, this decline may be mostly the result of increasing distance from the homestead (see Section 3.5). Soils in the lower parts of the landscape in Mbeere, Siaya and Tororo had higher average Ca^{2+} and Mg^{2+} concentrations (associated with their higher electric conductivity – Jaetzold and Schmidt, 1982). This grouping brought together fields with different history of land use belonging to farms of different resource endowment (e.g. livestock owners vs. non-livestock owners), and thus clear-cut differences in average soil fertility between landscape units cannot be expected.

Table 5: Average slope, area, distance to the homestead and soil properties of fields located in different positions of the landscape across the six sites; soil properties were predicted using near infrared diffuse spectral reflectance.

Site		Slope	Area[1]	Distance[2]	Particle size (%)			SOC	Av. P	Exchang. bases ($cmol_+ kg^{-1}$)			pH water
Landscape unit	*n*	(%)	(ha)	(m)	Clay	Silt	Sand	($g kg^{-1}$)	($mg kg^{-1}$)	K^+	Ca^{2+}	Mg^{2+}	(1:2.5)
Meru S.													
Upslope	180	4.5	0.06	39	20	26	54	20.3	15.6	0.64	5.6	1.5	5.8
Midslope	299	23.9	0.08	93	23	25	52	19.7	17.2	0.54	4.9	1.4	5.6
Footslope	43	5.0	0.06	138	22	25	53	19.1	21.2	0.53	4.8	1.3	5.5
Valley bottom	4	2.2	0.19	220	24	27	49	20.3	24.6	0.56	4.4	1.4	5.3
Mbeere													
Convex areas	199	8.8	0.20	73	23	18	59	7.9	5.8	0.52	5.0	1.2	6.4
Concave areas	10	6.7	0.16	169	34	21	45	5.9	3.3	0.43	16.2	2.6	6.9
Vihiga													
Upslope	47	7.6	0.09	50	23	26	51	16.5	6.3	0.33	4.4	1.4	5.8
Midslope	288	14.3	0.07	63	24	26	50	14.4	5.0	0.29	4.2	1.3	5.7
Footslope	44	12.1	0.07	132	26	22	52	12.6	4.0	0.19	3.2	1.1	5.4
Drainage way	6	1.9	0.09	128	27	26	47	14.1	2.7	0.23	2.4	1.1	5.1
Siaya													
Upslope	12	3.0	0.24	95	27	31	42	18.4	2.6	0.41	7.1	2.5	6.0
Midslope	283	4.4	0.12	87	29	30	41	15.5	4.9	0.45	6.9	2.7	6.1
Footslope	53	6.9	0.13	169	32	29	39	13.5	1.6	0.25	11.5	3.7	6.0
Marshland border	11	2.4	0.08	190	33	29	38	13.0	1.6	0.20	23.8	5.3	6.4
Mbale													
Upslope	5	9.9	0.13	16	18	20	62	16.9	55.2	0.82	7.9	1.6	6.4
Midslope	175	20.8	0.18	48	23	22	55	13.8	25.9	0.68	6.5	1.6	6.3
Footslope	8	2.6	0.12	78	24	22	54	10.9	12.3	0.43	6.3	2.1	6.5
Valley bottom	5	3.4	0.09	82	21	22	57	14.5	25.6	0.48	5.5	1.2	5.8
Tororo													
Upslope	127	1.2	0.22	76	18	17	65	10.2	2.9	0.34	3.9	1.3	6.3
Midslope	179	3.0	0.19	62	19	16	65	10.1	3.5	0.38	5.2	1.5	6.5
Marshland border	10	2.1	0.64	155	23	16	61	10.3	3.5	0.21	15.9	2.9	6.7

[1]Average area of all fields within each category
[2] Average distance from the centre of the fields to the homestead

3.3 Socioeconomic factors

3.3.1 Land, labour and food security

In spite of the differences in average farm sizes across districts (cf. Table 2), most of the farms surveyed (156 out of 250) had less than 1.35 ha, with a median of 1.29 ha and with an average of 1.66 ha (Figure 4 A). Farmers in the Ugandan sites of Tororo and Mbale districts often doubled the area they used for cropping by annexing (hiring, buying) other pieces of land scattered around the villages. As a result, households in Tororo achieved almost 10 months year^{-1} of food self sufficiency on average, compared with less than 4 month year^{-1} in the densely populated localities of Vihiga (Table 6 A). The average size of the households and the total number of cattle owned did not differ significantly between sites, while the number of family members working full time on the farm was significantly larger in Siaya than in other sites with closer access to off-/non-farm labour opportunities such as those in Meru South or Mbeere. A distinction was also made with respect to the type of livestock owned by the farmers; e.g., while the total number of cattle per farm was larger in Tororo, the number of improved dairy cattle was the largest in Meru South (Table 6 B). Livestock densities (which indicate potential manure availability per area cropped) also varied across sites, with more cattle per area of cropland in highly populated areas.

Households were then categorised into classes in terms of the number of months of food self-sufficiency; Table 6 C shows the frequency of households achieving 12 months of self-sufficiency and those with less than 3 months of self-sufficiency. In Tororo, 45% of the households were food self-sufficient, and those with less than 3 months of food sufficiency derived most of their income from off-farm activities (as in Mbale), mainly working for other farmers. In about 60% of the households interviewed in Vihiga all the food produced on the farm lasted less than 3 months, whereas in Meru South, Mbeere and particularly in Siaya, most of the households interviewed fell within intermediate classes of food self-sufficiency (i.e. between 3 and 11 months). With the exception of Tororo and Meru South, households that achieved 12 months of food self-sufficiency owned almost twice the area of land owned by the food insecure. However, when land availability was expressed as per family member the differences between food sufficiency classes was not as wide, particularly in Vihiga (0.16 compared with 0.14 ha family member^{-1}) and Siaya (0.19 compared with 0.27 ha family member^{-1}).

Significant ($P < 0.05$) differences between sub-regions were observed for the land:labour ratio (LLR, in ha person^{-1}; i.e., the number of adults working on the farm over the area of land available per family), but not between sites within sub-regions (Figure 4 B). At individual farm scale (Figure 4 C) LLR showed wide variability within sites, illustrating the value of this indicator for household categorisation. Small

LLR's indicate land limitation, whereas large values may indicate labour limitation, particularly when land preparation is done by hand-hoeing.

Table 6: (A) Socioeconomic indicators; (B) Details on livestock ownership and average densities across sites; (C) Indicators per class of food self sufficiency, considering both extremes: less than 3 and 12 month year^{-1}

(**A**)

	Land holdings (ha)			Family members		Food security	Total number of cattle per farm*
Site	Owned	Farmed	Annexed	Total	Labour*	(months)	
Meru S.	1.6	2.3	0.7	6.5	2.2	7.7	2.2
Mbeere	2.4	2.9	0.5	6.2	2.3	7.0	1.9
Vihiga	0.9	1.0	0.1	7.6	2.9	3.9	2.3
Siaya	1.4	1.7	0.3	8.0	3.3	7.4	2.2
Tororo	2.1	3.8	1.9	7.1	2.7	9.6	3.2
Mbale	1.9	4.1	2.1	7.4	2.2	8.2	2.3
Mean	1.7	2.6	0.9	7.1	2.6	7.2	2.3
SED	0.34	0.64	0.58	0.76	0.36	0.63	0.71
Significance	0.001	0.010	0.002	ns	0.013	0.010	ns

(**B**)

Indicator	Site						*SED*
	Meru S.	Mbeere	Vihiga	Siaya	Tororo	Mbale	
Cattle owned (# TLU farm^{-1})							
Local races	0	1.4	1.7	1.7	2.3	1.7	*0.10*
Improved	2.1	0.1	0.6	0	0.2	0.1	*0.21*
Oxen	0.1	0.4	0	0.5	0.7	0.5	*n/a*
Total	2.2	1.9	2.3	2.2	3.2	2.3	*0.71*
Cattle density (# TLU ha^{-1})							
Area owned	2.0	0.9	3.3	1.8	1.7	1.4	*0.53*
Cropped area	1.4	0.7	2.9	1.3	0.9	0.6	*0.36*

*Working full time on the farm; SED: standard error of the differences

(**C**)

Site	Frequency (%)		Farm size (ha)		Off-farm income (%)		Livestock owned*	
	<3 months	12 months	<3 months	12 months	<3 months	12 months	<3 months	12 months
Meru S.	15	28	0.7	1.2	13	17	2.0	2.4
Mbeere	20	23	2.0	3.5	44	38	2.1	3.7
Vihiga	61	2	0.8	1.6	33	20	1.0	5.9
Siaya	5	5	0.5	1.2	20	21	0.0	6.1
Tororo	3	45	2.3	2.6	62	19	4.2	3.8
Mbale	8	24	0.8	2.9	50	9	1.3	4.9

*In tropical livestock units (1 TLU is equivalent to an animal of 250 kg)

Food self-sufficiency, however, was achieved in households with LLR ranging widely from very low (0.02) to almost 5. All the food-insufficient households (e.g. < 3 months year^{-1}) had LLR values < 1 and all those with LLR > 1 produced enough food to cover their diet for at least five months (Figure 4 D). Households with LLR < 1 were also those generating more than 50% of their total income outside the farm (Figure 4 E). The relative number of households per district with LLR > 1 and their average LLR was: 11/40 in Meru South (LLR: 2.9), 14/40 in Mbeere (LLR: 2.2), 3/50 in Vihiga (LLR: 1.5), 7/40 in Siaya (LLR: 1.7), 20/40 in Tororo (LLR: 3.2) and 24/40 in Mbale (LLR: 2.7). The relationship between LLR and the number of livestock heads per farm was less clear and, as with the other indicators, only weak trends were found at this scale of analysis.

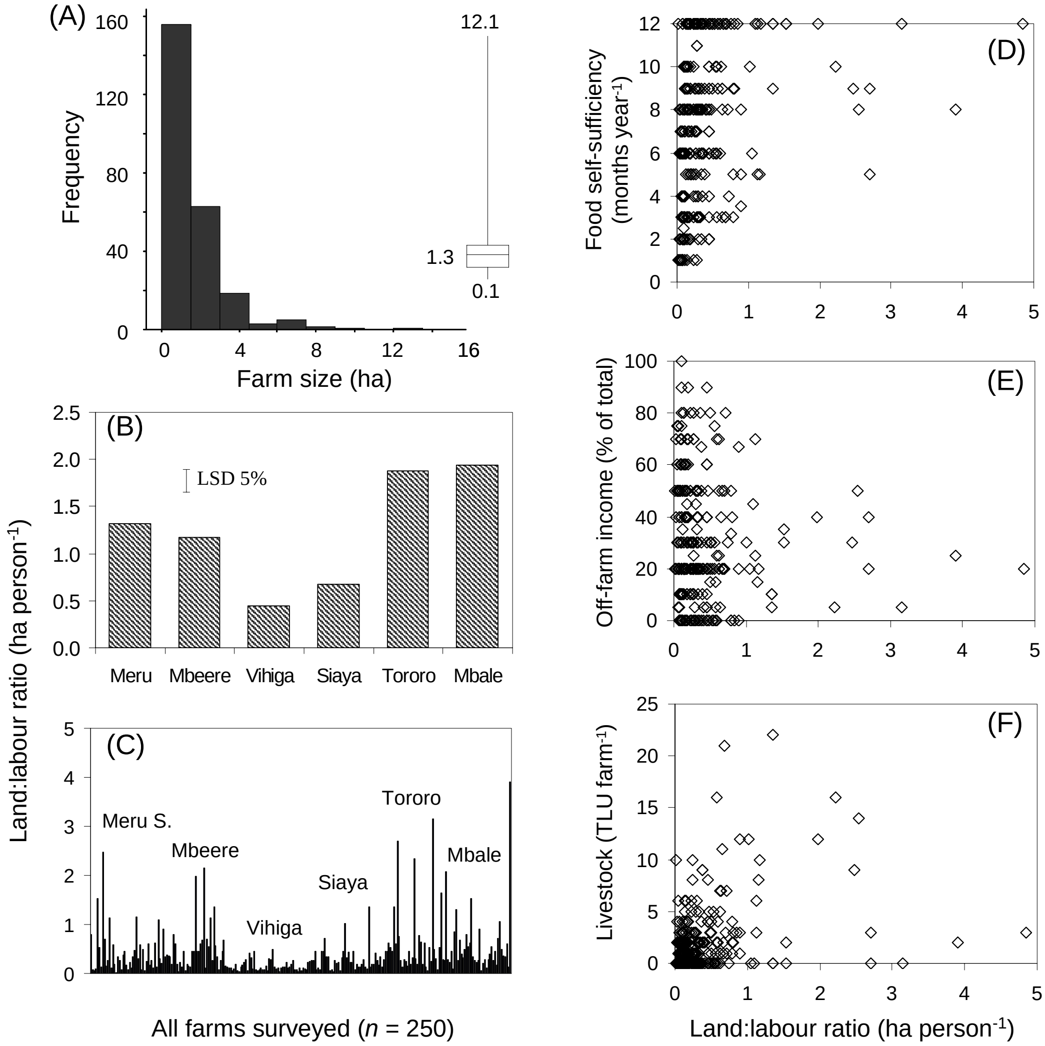

Figure 4: Land, labour and socio-economic indicators. (A) Frequency distribution of farm sizes (inset: box-and-whisker plotting of farm sizes, indicating the median, close and extreme outliers, and figures indicating average, maximum and minimum values); (B and C) land:labour ratios per site (average) and per farm (n = 250), respectively; (D, E and F) the relationship between land:labour ratios and months of food self-sufficiency, percentage of off-farm income and livestock ownership, respectively. TLU: tropical livestock units.

3.3.2 Production activities, land use and management

The number of farmers growing cash crops and the number of crop types and species grown per farm varied across districts (Table 7), related to agroecological conditions and market opportunities, and less to land availability. The number of fields occupied by cash crops was by far the largest in Meru South – 190 fields in the 40 farms interviewed, as a result of the good agricultural potential and proximity to large urban markets (i.e. the populated towns of Meru, Embu, Thika and Nairobi city). Lower frequencies of fields with cash crops were recorded in Siaya and Tororo (respectively 5 and 21 fields in the 40 farms interviewed).

Table 7: Indicators of production activity and resource allocation across sites

Indicator		Site: Meru S.	Mbeere	Vihiga	Siaya	Tororo	Mbale
No. of fields with cash crops		190	48	40	5	21	77
% area with cash crops		27.1	11.0	4.8	0.8	4.0	22.4
Crop types cultivated (No. of fields)							
Cereals		145	116	204	168	116	11
Legumes		121	146	167	133	82	8
Roots and tubers		97	20	100	74	140	70
Vegetables		19	3	45	40	15	14
Fodder crops		90	15	110	79	12	16
Bananas		155	19	66	30	34	95
Fruit and timber trees		21	37	88	42	20	16
Fallow		10	34	22	79	82	36
Av. No. of fields farm^{-1}		13.3	6.3	9.6	8.9	7.9	4.8
Av. Area of the fields (ha)		0.2	0.5	0.2	0.3	0.5	0.3
Av. No. of crop types farm^{-1}		4.3	3.4	4.4	4.4	3.8	5.2
Av. No. of crop species farm^{-1}		21	11	17	16	13	9
Tot. No. of crop species grown		30	25	27	20	25	19
Ranking of consumption crops	1st	Maize	Maize	Maize	Maize	Cassava	Banana
	2nd	Beans	Beans	Beans	Sorghum	F. millet	Maize
	3rd	Banana	Cowpea	Banana	Beans	Maize	S. Potato
Ranking income-generating crops	1st	Coffee	Khat	Tea	Peanuts	Vegetables	Coffee
	2nd	Banana	Beans	Maize	Beans	Cotton	Banana
	3rd	Banana	Cowpea	Beans	Cassava	Maize	Beans
Use of nutrient resources (% of farmers)							
Farmyard manure or compost		93	80	96	63	58	53
Mineral fertilizers		95	45	80	23	5	0
Green manures and biomass transfer		15	20	6	8	8	3

Av. No.: average number; Tot. No.: total number

Cereals and legumes were the main crop types grown in the Kenyan districts, whereas cassava dominated in Tororo and cooking bananas in Mbale (Table 7). A larger proportion of households achieving food self-sufficient in Tororo and Mbale (cf. Table 6) may be in part also the result of local food habits: perennial crops such as cassava and bananas that can be harvested more evenly throughout the year.

Crop production was ranked as the main income-generating activity by 63% of the farmers interviewed across sites (*n* = 250), followed by off- and non-farm activities (24% of the farmers) and by livestock-related activities (14%of the farmers). In farms owning dairy cattle, however, livestock activities were mostly ranked as the most important income-generating activity (i.e, by 61% of the farmers who owned livestock). Selling of food crops such as maize or beans (not necessarily surpluses) was ranked first among the income generating activities (by 69% of all farmers interviewed), followed by crops grown only for sale such as cotton or tea (31%) and occasional selling of fruits such as mangoes, bananas and avocados (13%). In most cases maize was the main consumption crop followed mainly by beans, cooking bananas and cassava, reflecting differences in the dominant staple crops and food habits across sites (Table 7). When all farm activities were considered, not only crops, the ranking in Vihiga was: first tea, second milk and third timber as income-generating activities. Virtually all farmers indicated regular or occasional use of fresh or composted farmyard manure in Meru South and Vihiga – corresponding with the higher densities of cattle in these areas (Table 7). A large number of farmers in these districts also occasionally or regularly used mineral fertilisers. Fewer farmers used fertilisers in Mbeere and Siaya, and a few or none in the Ugandan study sites. Farm yard manure was applied exclusively to food crops on most farms in Mbeere, Vihiga, Siaya and Tororo, whereas farmers in Meru South and Mbale farmers did not allocate fertilisers preferentially to specific crops. Most of the farmers using fertilisers in Mbeere, Vihiga and Siaya applied them exclusively to food crops. Green manure and/or biomass transfer technologies were practiced by 15 – 20% of farmers in Central Kenya, and by less than 10% of farmers in the other districts.

3.3.3. Livelihood strategies

Farmers were grouped into those who focused mainly on producing enough food for the household and those who prioritised production for the market. Farmers falling in each category varied across districts and, interestingly, a larger number of months of food self-sufficiency was achieved by predominantly market-oriented farmers (Table 8 A). About 70% of the farmers were predominantly subsistence-oriented in Vihiga, whereas 80% were market-oriented in Mbale. Earning off-farm income represented an important livelihood strategy in all districts; the percentage of households having some kind of off-/non-farm income varied from 60% in Mbale to 96% in Vihiga (Table 8 B). Farmers in Vihiga estimated that almost 40% of the annual household income was generated by off- and non-farm activities, on average. In Meru South, closer to urban markets (cf. Table 1), more than 70% of the total income was generated by cash crops grown on the farm.

Table 8: Indicators of livelihood strategies: (A) production orientations; (B) income sources and labour allocation to off- and non-farm activities across sites; and (C) reasons given by farmers to decide on selling their family labour to other farmers as casual agricultural workers (e.g. for land preparation, weeding, livestock feeding, etc.).

(A)

	Predominantly self-subsistence		Predominantly market-oriented	
District	% of farms	Months of food self-sufficiency	% of farms	Months of food self-sufficiency
Meru South	42	7.0	58	8.4
Mbeere	50	5.8	50	8.0
Vihiga	66	3.5	34	4.7
Siaya	48	6.9	52	7.9
Tororo	37	9.7	63	9.4
Mbale	20	9.0	80	8.1

(B)

	District					
Indicator	Meru S.	Mbeere	Vihiga	Siaya	Tororo	Mbale
Proportion (%) of households that have some kind of off/non-farm income	90	93	96	88	88	60
Farmers' estimations of the % of total family income derived from off/non-farm activities	28	34	39	23	28	17
Proportion of households in which one or more family member:						
- works temporarily or permanently off-farm	80	68	82	68	78	43
- is employed in non-farm activities	48	43	68	38	55	20
- sells his/her labour to other farmers	48	35	42	48	35	28

(C)

Reasons to decide on selling labour locally	% of farmers answering[I]	Districts with the higher frequencies for each of the answers
Families who sell their labour		
"Because I am unemployed"	14	Meru S. (68%)
To increase family income[II]	64	Siaya (89%), Tororo (86%), Mbale (82%)
For necessity[III]	12	Mbeere (36%)
For need of cash income	9	Vihiga (43%)
Families who do not sell their labour		
Lack of time	63	Mbeere (96%), Siaya (86%), Vihiga (79%)
No need[IV]	16	Tororo (42%), Mbale (24%)
Unable due to health condition	19	Mbale (41%), Meru (24%)
No or few opportunities/ badly paid	3	Totoro (12%)

[I] Out of 250 household interviewed, 98 families sold their labour and 152 did not; percentages were calculated on these values, respectively; [II] In this case, income generated from farming and/or other income-generating activities was enough for subsistence; [III] This answer implied that income generated by other activities, including farming, was insufficient for subsistence; [IV] No need due to enough income generated from farming and/or other non-farm activities

Off/non-farm income sources ranged from remittances by members of the extended family living in cities, through petty trading or food aid to employment outside the farm. In most households in all districts at least one family member was temporarily or permanently working off-farm, and in about half of the cases family members were engaged in non-farm activities. Farmers sold their labour locally to other (wealthier) farmers to increase their family income (Table 8 C) and, particularly in Meru South, their reason to do casual work outside their farms was, literally “because I am unemployed”.

3.4 Categorising and describing household diversity

3.4.1 Formal and ‘farmer-derived’ indicators

A principal component analysis (PCA) on the socioeconomic data for the entire sample of farms (n = 250) indicated that roughly 80% of the household variability explained by the first two principal components (PC), which had respectively high positive and negative loadings with respect to the proportion of the total family income generated from off/non-farm activities and with the age of the household head (Figure 5). The third PC, more weakly associated with the commonly-used wealth indicators: total area farmed and number of livestock, explained virtually all the remaining variability; the contribution of the fourth and fifth PC’s (family size, months of food self sufficiency) explained only little of the remaining variation. While the %off/non-farm income is a general indicator of livelihood strategies, age of the household head indicates the position of the family in “the farm developmental cycle” and it is normally associated with resource endowment (households undergo a phase of expansion of their resource base from establishment to maturity – Crowley, 1997; cf. Chapter 1). Being orthogonal and thus independent, these two dimensions may be considered as starting points for a consistent categorisation of households across study sites.

Farmers selected ‘wealth’ and ‘farm management’ indicators that were not always the same across districts and localities. However, indicators such as food security, cash crops, livestock, labour and input use and timely crop management (closely associated with labour availability) were selected in four localities of western Kenya (Table 9). Land availability, income sources and commitment to farm work were alternatively selected in three of the four localities, whereas access to information, educational level, family size and the type of housing, among other broadly-used indicators, were less consistently selected. Therefore, the participatory categorisation of households based on these criteria was different for each locality: the proportion of households in the wealthier class varied from 5 to 13% across sites, but in the poorest class ranged from 30 to 80%. Although some of the criteria that farmers selected represent drivers of social diversity (e.g. availability of land and labour), others were simply a consequence of differences between households as induced by such drivers of diversity (e.g. timely weeding, use of hybrid seeds or veterinary services), and were highly correlated with each other.

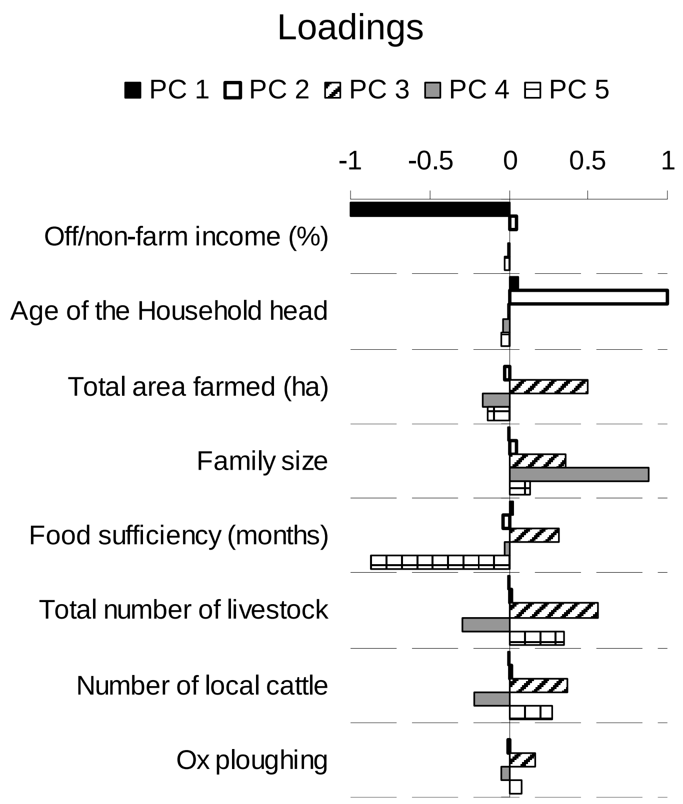

Figure 5: The loadings of different socioeconomic variables included in a principal component analysis with respect to the first five principal components (PC). The first two PC's were dominated by the % off/non-farm income perceived by the household and by the age of the household head; the third PC was associated with the 'classical' wealth indicators total farm area, livestock ownership (positively correlated with number of local cattle breeds and ox-ploughing) and food self-sufficiency.

3.4.2 A functional farm typology

Considering the main criteria that drive livelihood strategies (cf. Table 3) and using proxy indicators derived from the PCA (Figure 5) and participatory wealth ranking (Table 9), five farm types were defined based on indicators of resource endowment, main sources of income and production orientation (Table 10). This typology of households is essentially the same as that derived by Tittonell et al. (2005) in western Kenya, and represents distinct household livelihood strategies that can be identified across the region. In Figure 6, the five household categories or Farm Types are represented in relation to resource endowment and dependence on off-farm income. While Farm Types 2, 3 and 5 had more clearly defined livelihood strategies, Farm Types 1 and 4 showed wider variation in terms of resource endowment and income strategies, respectively. Market orientation increased from low or medium to high resource endowment farms, particularly for households generating most of their income by farming.

Table 9: Farmers' criteria to classify households in relation to resource endowment and farm management during participatory wealth rankings in Vihiga (Ebusiloli and Emusutswi) and Siaya (Nyabeda and Nyalugunga) districts, western Kenya, and distribution of households within three wealth classes based on these indicators in the four localities.

Criteria	Key indicators/ levels
Selected by farmers in the 4 localities	
1. Food security	Months of food self sufficiency (8-12 Class I; 3-5 Class II; 0-2 Class III); having food surplus to market
2. Labour availability	Depending exclusively on family labour, complemented with hired labour or using exclusively hired labour
3. Cash crops	Presence and acreage of tea plantations (> or < 1 acre); presence of tobacco, sugar cane, tomatoes; level of input use and maintenance
4. Livestock	Type and number of livestock heads owned (e.g. 3-5 improved dairy cows in Class I) and management system (stall fed, free grazing)
5. Use of fertilisers	Regular, occasional or no use of organic and/or mineral fertilisers; applied in most fields or only in homegardens; only basal or basal plus topdressing applications
6. Timing of farm operations	Timely planting and weeding, ownership/ capacity to hire oxen for ploughing vs. hand hoeing; labour hired for timely weeding
Selected by farmers in 3 of the 4 localities	
7. Land availability	Farm size (variable acreages across localities); hire-in, use own or hire-out land for cultivation
8. Use of quality seed	Use of certified seeds, maize hybrids; use certified in long rains and local seeds in the short rains
9. Income	Annual income (e.g. KSh 80,000-100,000; 30,000-50,000 or <10,000 for Class I, II and III, respectively, in Nyabeda); main source of income (on-farm vs. non/off-farm); permanent vs. intermittent off-farm income
10. Commitment to work	Hardworking vs. idlers; need to work for other farmers or commit to other occupations
11. Soil conservation	Presence and maintenance of permanent or semi-permanent (grass strips) soil conservation measures
Selected by farmers in 2 of the 4 localities	
12. Access to information	Having regular or sporadic access to agricultural information and knowledge, seeking extension services
13. Planting method	Planting in lines using oxen furrows or ropes vs. broadcasting
14. Weeding frequency	Weeding once or twice in the season or not at all, in all the fields vs. a few of them
Selected by farmers in only 1 of the 4 localities	
15. Type of house	Permanent brick houses vs. huts, tin roofing vs. thatched, maintenance
16. Transport means	Ownership/ hiring wheelbarrow, bicycle, wheel carts
17. Veterinary services	Contracting veterinary services vs. using herbal treatments
18. Household nutrition	Number of meals a day (1, 2 or 3) throughout the year, balanced diets vs. starchy diets, meat consumption
19. Family size	Small families vs. large, polygamous families
20. Education level	Level of education (primary, secondary) completed plus additional training; well educated and informed
21. Postharvest storage	Presence of storage facilities (permanent) or use of drums, pots, sacks; use of chemicals vs. traditional methods for preservation

*Relative proportion of households in each class**

Locality	Class I	Class II	Class III
Ebusiloli	49 (10%)	277 (60%)	138 (30%)
Emusutswi	19 (5%)	58 (16%)	285 (79%)
Nyabeda	32 (13%)	125 (49%)	97 (38%)
Nyalugunga	29 (9%)	180 (53%)	132 (39%)

*Class I: wealthier households, good farm managers; Class II: moderately endowed, regular farm managers; Class III: poor households, poor farm management.

Type 2 farms represent wealthier farmers owning relatively large farms, growing cash crops and keeping a larger number of livestock, who rely mostly on income generated by farming. Type 3 farms have similar income generation strategies but are less endowed in land and/or capital, and some family members may engage sporadically in off-farm activities to cover expenditure (e.g. school fees). Type 5 farms constitute the poorest category depending largely on off-farm earnings, in which often more than one household member is locally employed as a labourer by wealthier farmers. Type 1 represents a category of households that relies mostly on off-/non farm activities – as much as Type 5 – although such activities represent permanent employment and/or more-skilled jobs. Type 1 farmers are able to invest in sustaining or reproducing their resource base, and in achieving households needs (food security, education). Type 4 includes households with poor to medium resource endowment in which, next to farming, a varying range of off- and particularly non-farm strategies can be observed. Normally, they engage in activities which require less skill or are poorly remunerated (e.g. petty trading, providing oxen or transport services, manufacturing handicrafts, etc.).

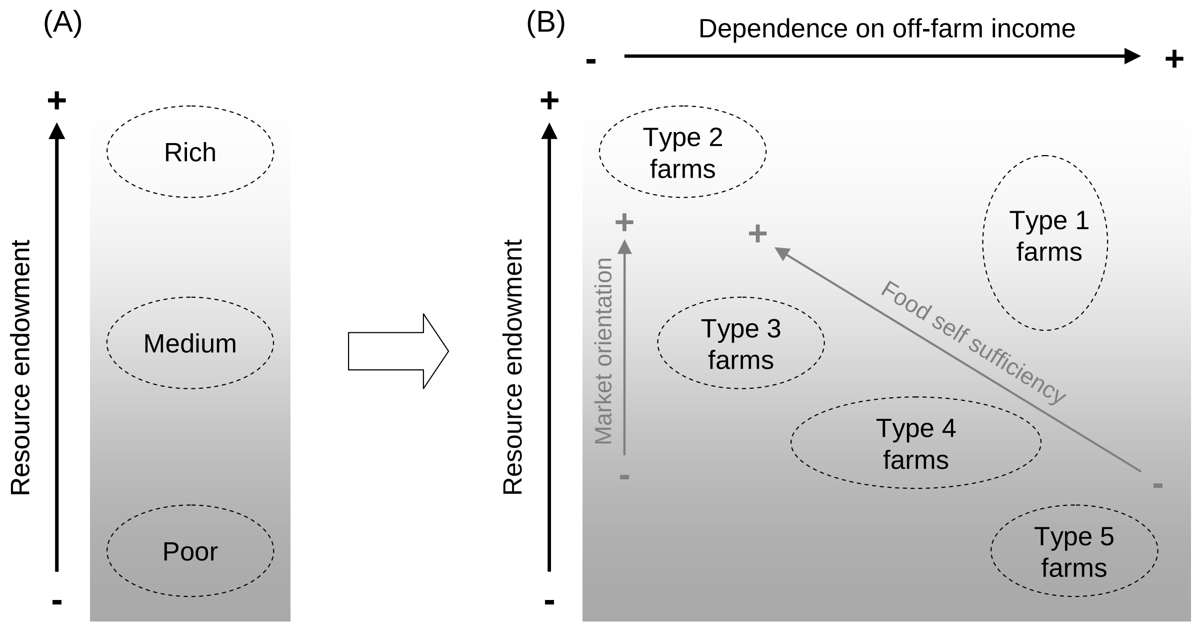

Figure 6: Scheme indicating the conceptual framework for generating the farm typology, from (A) an approach based exclusively on the household's level of resource endowment to (B) a multidimensional approach considering the main source of income and production orientation. The intensity of shading roughly indicates of the distribution of households in a community. The farm types are encircled in dotted lines indicating that there are no actual clear-cuts between types but rather diffuse transitions between them. Types 1 and 4 showed wider variation in terms of resource endowment and income strategies, respectively (represented by their shape).

Table 10: Household categorisation and key resource endowment and livelihood indicators for the five Farm Types across sites; distribution of households in each category, total land area and cattle ownership, land availability per family member and land:labour ratio*, proportion of off/non-farm income perceived by the household and months of food self-sufficiency per year

Site	Farm type	Distribution of households (%)	Total area owned (ha)	Owned cattle (TLU)	Land available (ha) per family*		Off/non-farm income (%)	Food self-sufficiency (months)
					member	labour		
Meru S.	1	23	1.3	2.4	0.45	0.99	33	7.7
	2	13	4.0	5.6	1.13	3.40	16	9.4
	3	20	2.3	2.0	0.46	1.93	18	8.9
	4	20	0.8	1.4	0.23	0.44	36	5.8
	5	25	0.7	0.9	0.15	0.43	40	7.3
		SED (Farm Type)	*0.7*	*0.9*	*0.21*	*0.76*	*11*	*1.9*
Mbeere	1	28	1.7	2.1	0.46	1.33	46	7.1
	2	10	8.8	4.5	1.62	3.74	22	11.3
	3	25	1.9	2.7	0.36	0.75	17	6.9
	4	25	1.5	0.6	0.41	0.96	47	6.0
	5	13	1.1	0.4	0.31	0.48	61	5.6
		SED (Farm Type)	*0.7*	*1.9*	*0.23*	*0.49*	*12*	*1.6*
Vihiga	1	24	1.0	2.7	0.19	0.52	58	4.0
	2	8	2.0	5.4	0.30	0.69	30	7.6
	3	24	0.9	2.5	0.13	0.45	29	3.5
	4	26	0.5	1.8	0.11	0.39	42	3.2
	5	20	0.5	1.0	0.10	0.28	52	3.5
		SED (Farm Type)	*0.2*	*0.7*	*0.05*	*0.18*	*12*	*1.4*
Siaya	1	10	1.6	2.5	0.44	1.52	35	7.3
	2	13	3.2	7.2	0.59	1.10	12	8.6
	3	28	1.4	2.5	0.34	0.71	16	8.7
	4	30	1.0	1.0	0.20	0.41	26	7.2
	5	20	0.7	0.1	0.16	0.32	31	5.3
		SED (Farm Type)	*0.4*	*1.7*	*0.15*	*0.31*	*9*	*1.2*
Tororo	1	23	1.6	1.2	0.80	1.86	39	10.7
	2	20	4.1	9.5	1.19	4.33	11	10.4
	3	28	2.1	2.9	0.66	1.48	14	9.9
	4	18	1.4	0.9	0.26	0.73	27	8.1
	5	13	0.9	0.2	0.25	0.43	36	7.4
		SED (Farm Type)	*0.8*	*2.1*	*0.51*	*1.42*	*13*	*1.3*
Mbale	1	13	1.6	1.8	0.44	0.93	29	10.4
	2	15	3.6	9.0	1.67	4.74	9	11.0
	3	38	2.2	1.4	0.45	1.65	10	8.2
	4	20	0.9	0.8	0.37	1.68	33	7.5
	5	15	0.8	0.5	0.26	0.69	47	4.5
		SED (Farm Type)	*0.6*	*1.6*	*0.27*	*0.78*	*10*	*1.2*
		SED (Sites)	*0.4*	*0.6*	*0.33*	*0.11*	*5*	*0.6*
	Significance (P values)							
		Site (S)	<0.001	Ns	<0.001	<0.001	<0.001	<0.001
		Farm Type (FT)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
		Interaction S × FT	<0.001	Ns	0.085	Ns	0.078	Ns

*Calculated as land cropped over the total number of family members or the number of those working on the farm, respectively.
SED: Standard error of the differences; Ns: not significant.

Although the five strategies were identified across the six sites – albeit with different thresholds in the various livelihood indicators – the distribution of households falling in each category varied across between them (Table 10). This is due partly to the procedure for the sampling of households, but fundamentally to the regional variability of the main criteria used for stratification. For instance, the occurrence of Farm Types 1 and 4 is determined by the characteristics of labour markets and the existence of non-farm opportunities at each site.

3.5 Farmer-induced soil heterogeneity within farms

In general, the weighed-average soil indicators at farm-scale did not show a consistent pattern of variation between farm types across the six districts. For example, no significant difference between farm types were observed for soil C, available P and K contents in most cases (Appendix 2.3). However, different farm types exhibited a different degree of variability in soil fertility indicators. Soil organic C was most variable between fields in Mbeere (CV's between 0.3 and 0.5) and least in Meru South (0.1 – 0.15). The widest amplitude of variation in soil C was observed for farms of Type 5 in Mbeere, with an index of range amplitude (I_{SOM}) of 0.8 (i.e., the range between the best and worst field was about 80% of the value of the average soil C at farm scale). Available P and K were more variable and showed wider amplitude between the best and the worst field of each individual farm than soil C, in agreement with the wider inter-quartile ranges in the CV shown earlier (cf. Figure 2). In Vihiga, Siaya and Tororo larger farms belonging to Type 2 had both greater CV and indices of range amplitude $I_{Av.P}$ and $I_{Ex.K}$ Thus, different farm types differed more in the degree of variability than in the average status of these soil indicators.

In general, the greater average value of soil C and available P at farm scale, the smaller their variability within the farm (Figure 7). Although this pattern of variation was driven by the regional biophysical variability, the trend was also confirmed by the variation within districts. Variability of soil C and available P tended to decrease with farm area and was larger for farms with intermediate numbers of fields per farm, which indicates the degree of land fragmentation (Figure 8). At both ends of the scale, small farms with a few fields and large farms with many fields exhibited less soil variability. Higher densities of cattle population (i.e., the number of heads per area of land cropped) were associated with less variability and narrower ranges of soil C and available P between the best and worst fields of each farm (Figure 8). Considering the number of cattle irrespective of the area of land cropped, farms with 1 or 2 cattle exhibited more variability in soil C and available P than those without cattle or with more than 2 cattle in Meru South, Mbeere and Vihiga (where a larger proportion of farmers used manure – cf. Table 7). Soil variability was also associated to different degrees with other variables representing household diversity.

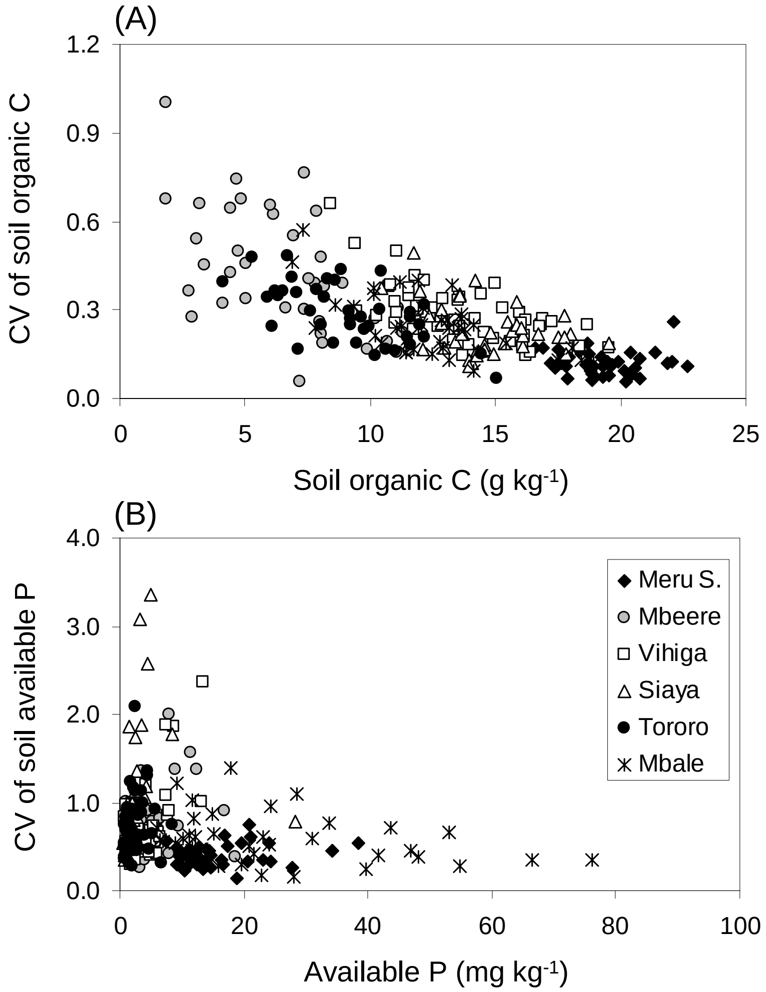

Figure 7: Average soil organic C and available P and its variability within farms. (A) Farm-scale weighted average soil C and (B) available P plotted against their respective coefficient of variation at farm scale, site by site.

Within farms, there was more variability in soil organic C and available P between fields located closer to the homestead (Figure 9). To gain graphical detail, and since most farms sampled were small in size, the few fields located at more than 60 m from the homestead were not plotted in Figure 9. In the case of available P, the largest values were generally measured in the close fields, except in Meru S. and Mbale. Part of the observed variability may have resulted from having considered farms of different size and resource endowment. For individual farms, however, gradients of decreasing soil fertility at increasing distances from the homestead and variability among fields located on different landscape positions were often observed. For example, in a farm presented as a case study in Appendix 2.4, soil organic C and available P contents tended to decrease towards the footslope (F8), with the homestead located on the breaking slope (F1). However, soil C contents in all fields were rather small for soils of this texture, and P availability was in all cases below the threshold for crop responses to P application in the area (Vanlauwe et al., 2006).

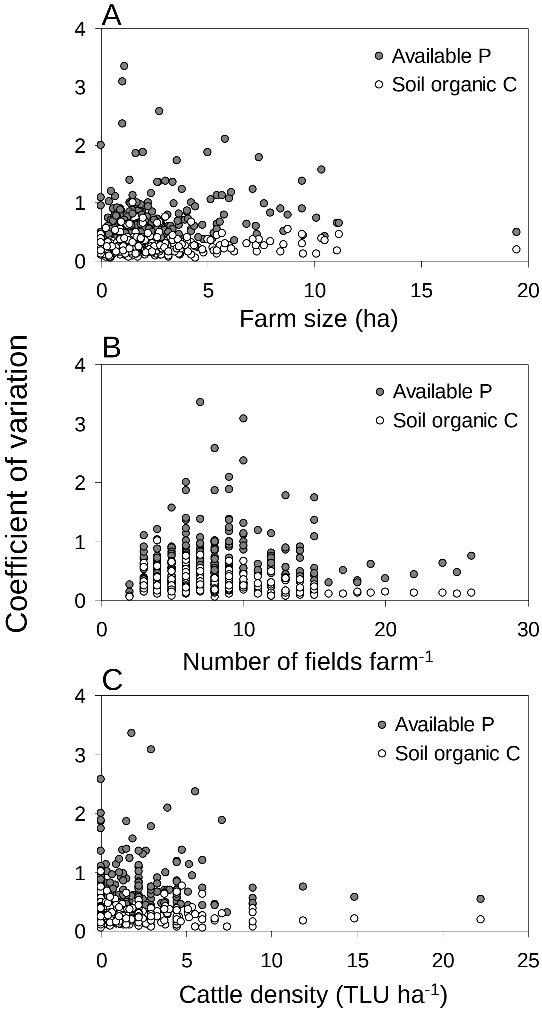

Figure 8: The coefficient of variation of soil C and available P at farm scale as a function of (A) farm size, (B) land fragmentation (i.e. the number of plots per farm) and (C) the density of cattle population for all sites plotted together. TLU: tropical livestock units.

3.6 Resource allocation and perceived soil fertility

When making decisions on resource allocation, farmers prioritised the fields they perceived as more fertile. Across sites, farmers preferentially applied manure and fertilisers to the 'good' fields over those perceived as medium or poor (Figure 10). In Meru South, Mbeere and Vihiga, manure was applied on 60 to 70% of the fields perceived as fertile, but also on around 30% of those perceived as poor, in stark contrast with the remaining sites. The use of mineral fertilisers was in general more restricted; in Meru South and in Vihiga up to 30% of the fields within different soil fertility classes received fertilisers, and none in Mbale. These figures on mineral fertiliser use, however, do not distinguish fertiliser types or application rates. Farmers classified their fields as poor, medium or good according to the perceived quality of their soils. This was done by each farmer individually, without contrasting them with their neighbour's fields, and the criteria to classify fields varied from site to site. In general, soil fertility classes perceived by farmers were weakly related to visual indicators of soil degradation and physical impediments, and moderately related to the slope of the fields and/or their position in the landscape (Appendix 2.5).

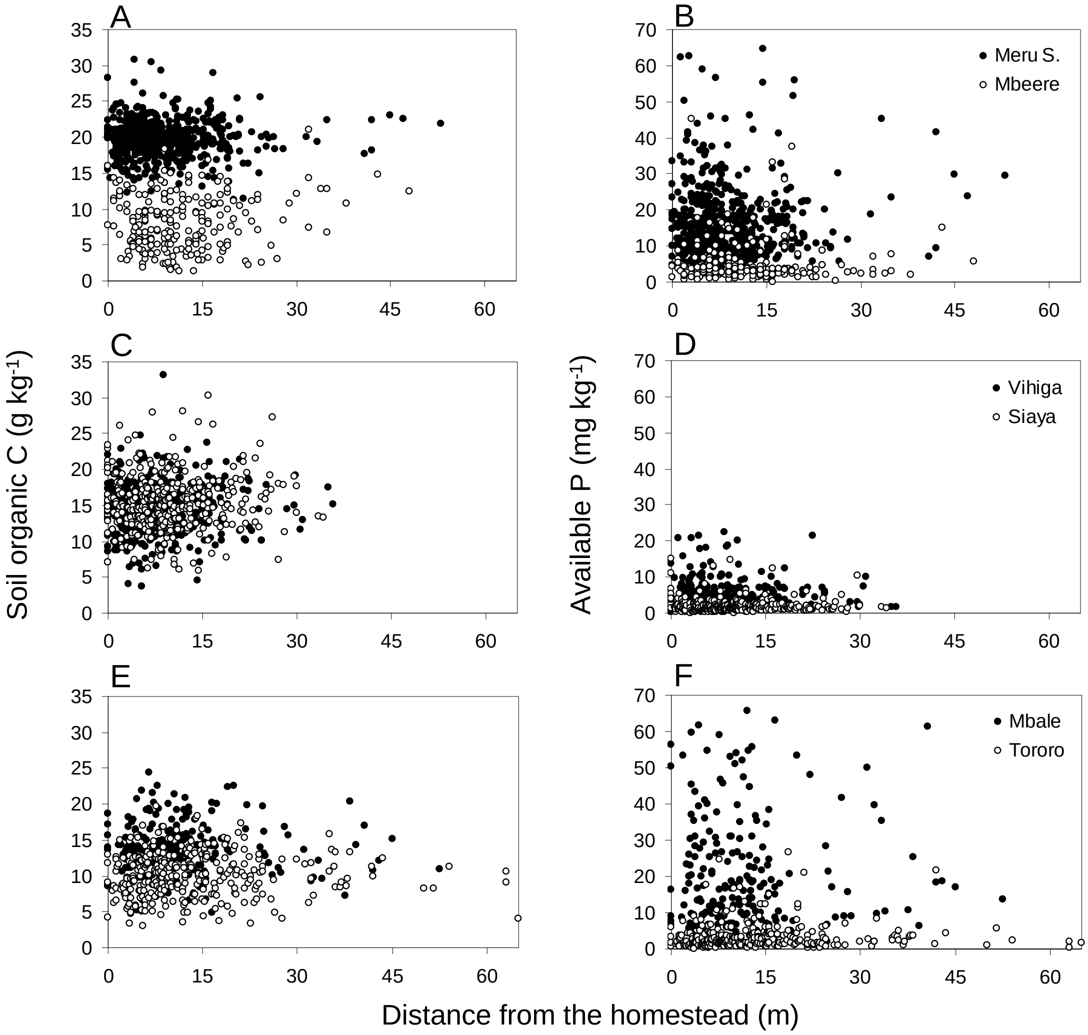

Figure 9: Soil organic C and available P plotted against the absolute distance from each field to the homestead (m) for each of the six study sites (n = 2,607 fields). A few fields farther than 60 m from the homestead were not included.

Across sites, most fields (40 to 60%) fell into the category ‘medium soil fertility’, followed by the category ‘poor’ (Table 11). The proportion of fields perceived as fertile ranged between 10 and 20% in the Kenyan sites, compared with 34 and 26% in the Ugandan sites (Tororo and Mbale, respectively). In the highland sites with an undulating topography (Meru South, Vihiga and Mbale) the perceived fertility of the fields was clearly associated with their slope and, since the homestead is normally placed in the higher (and flatter) positions of the landscape, poor fields tended to be on steep slopes far from the homestead. In the remaining sites, characterised by flatter landscapes, there was a less clear association between soil quality perception and slope or distance from the homestead. In Siaya, however, fields perceived as fertile were mostly those having ‘black soils’, associated with swampy areas and therefore located far from the homestead.

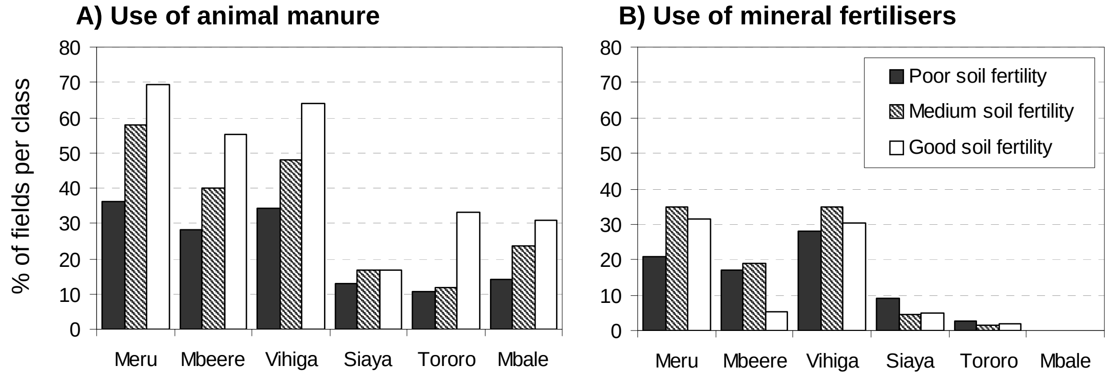

Figure 10: Relative frequency (%) of fields receiving animal manure and mineral fertilisers grouped according to their soil fertility status as perceived by farmers (poor, medium, good). Farmers classified their fields individually, and thus the criteria to define poor or good fields often varied from on farmer to the next.

Table 11: Farmers’ classification of the fields within their own farm according to their perceived soil fertility; distribution of fields in each class and their average slope, area, distance from the homestead and period under cultivation across the six sites

Site	Farmers’ soil fertility classification	*n*	Distribution (%)	Slope (%)	Area (ha)	Distance (m)	Relative distance	Years under Cultivation*
Meru S.	Good	122	22	9.0	0.06	54	0.33	43
	Medium	240	43	14.3	0.07	68	0.47	43
	Poor	193	35	21.3	0.08	110	0.62	41
Mbeere	Good	41	18	9.9	0.21	70	0.40	23
	Medium	106	47	9.6	0.23	65	0.53	12
	Poor	77	34	7.1	0.15	97	0.61	15
Vihiga	Good	54	14	11.4	0.09	57	0.36	37
	Medium	169	44	10.6	0.07	64	0.42	48
	Poor	163	42	15.9	0.07	82	0.62	45
Siaya	Good	42	12	3.9	0.13	134	0.59	60
	Medium	216	60	4.3	0.12	82	0.51	58
	Poor	102	28	5.7	0.12	134	0.54	55
Tororo	Good	106	34	2.1	0.23	65	0.44	27
	Medium	135	43	2.3	0.23	67	0.50	25
	Poor	75	24	2.3	0.18	84	0.57	36
Mbale	Good	56	26	16.4	0.17	44	0.39	31
	Medium	95	43	17.5	0.19	50	0.49	31
	Poor	68	31	24.3	0.13	51	0.58	29

*As indicated by interviewed farmers

Poor fields were generally located at a relative distance of 0.6 with respect to the homestead, while relative distances were more variable for the fertile and medium fields across sites. The average area of the fields and their history of use (years under cultivation) differed across sites but not between soil quality classes. A clear exception was Mbeere, where farming started more recently, and where cultivation started earlier on fields that are now perceived as poor.

4. Discussion

Soil heterogeneity resulted from complex interactions between the inherent geology and geomorphology, socioeconomic differences between households that affect land use and management, and by preferential resource allocation to fields perceived as most responsive within individual farms. The effects of these three groups of factors shape different patterns of variability for different soil indicators across the region. The structural analysis of the variance of soil fertility indicators across 250 farms (i.e. 2,607 fields) in central and western Kenya and eastern Uganda revealed that the variation in soil organic C and associated total N was mostly related to differences in the inherent properties of the soils across sites and the landscape, while available P, K and pH had larger residual variability in the model, which was associated with spatial soil heterogeneity within farms. The latter variables are thus more informative of impacts of land use history and past soil management. Yet part of the spatial soil heterogeneity within-farms was also explained by soil-landscape variability when different ‘soilscape’ units occur within an individual farm, when soil erosion takes place, and/or when farmers preferentially allocate resources to some of such units. Differences in soil properties across the region were expected from the selection of study sites on the basis of regional biophysical gradients (i.e. rainfall, geology). Socioeconomic drivers such as farm size, availability of labour and resource endowment (through, for example, manure availability or access to mineral fertilisers) reinforced such variability.

4.1 Agroecological potential and market opportunities

Higher rainfall and cooler average temperatures at higher altitudes, and the larger capacity of finer-textured soils to protect C physically determined the variation in average soil C and N contents in the soils of the region. Climatic and biotic factors regulate the rates of C inputs and outputs into/from the soil, while soil texture and particularly the proportion of the clay and silt fractions determine the capacity of the soils to retain (physically protect) organic C. Feller and Beare (1997) showed that the amount of organic C protected by the 0 – 20 μm fraction of a certain soil fluctuates within a characteristic range that is wider for finer-textured soils. Knowing such thresholds, and within a certain band of rainfall, the average soil organic C content can be used as a good proxy for the agricultural potential of an area. The agroecological potential and the prevailing socio-economic and cultural conditions influence soil management indirectly, through resource allocation decisions. Such influences are represented by availability of land for fallow, or labour for biomass transfer (e.g. mulching) or erosion control, presence of cash crops that may justify investments in nutrient inputs, use of mineral and organic fertiliser and/or adoption of soil improving technologies as influenced by access to markets, knowledge and financial resources. Their consequence is mostly reflected by spatial variability in soil available P and K that results from concentration of nutrient resources such as mineral fertilisers, ash or animal manure in certain fields of the farm.

4.2 Diversity of livelihood strategies

Based on resource endowment, dependence on off-farm income and production objectives, smallholder farms in the region were grouped into five 'Farm Types' (Figure 6): 1. Farms that rely mainly on permanent off-farm employment; 2. Larger, wealthier farms growing cash crops; 3. Medium resource endowment, food self-sufficient farms; 4. Medium to low resource endowment relying partly on non-farm activities; and 5. Poor households with family members employed locally as agricultural labourers by wealthier farmers. This categorisation extends the stratification of households in wealth classes to a multidimensional conceptualisation of household diversity that includes livelihood strategies (cf. Tittonell et al., 2005b). An important difference between the analysis presented here and that of Tittonell et al. (2005b) is that in the earlier exercise 'case-study' farms were selected with key informants in three localities within western Kenya (60 farms in total), whereas here we selected a larger number of farms (n = 250) through spatial randomisation in six districts of Kenya and Uganda. In the earlier study of Tittonell et al. (2005b and c) on a more restricted number of farms the interrelationships between household diversity, nutrient management and soil fertility status were more clearly recognised. Here, the five different farm types did not differ in their average soil fertility status at farm scale, but they exhibited widely different variability in soil indicators such as available P and K between their most fertile and poorest fields.

Household diversity and livelihood strategies, however, have implications for the design of technology interventions to target smallholders and in the relative impact of changes in policy. For example, farms categorised as Farm Type 1 are not very dependent on agriculture, and probably less likely to benefit from outputs of agricultural research/development. They tend to operate as in semi-urban settings, where most of the family income is generated by permanent employment of the household head. Although their better financial situation may allow this type of farmers to invest in land, labour and/or agricultural inputs, other investments that represent strategic pathways out of poverty (e.g. higher education) are given more priority. In farms of Type 5 multiple constraints in terms of resources, education and health – which had been often faced for more than one generation, limit the possibilities and motivation of these subsistence farmers to engage in technological innovation. This is often reflected in their lack of participation in agricultural extension activities (Misiko, 2007). Social security programmes designed to remove or alleviate permanent constraints faced by this type of households are a pre-requisite to allow them to implement soil-improving technologies. Often, the on-farm income-based strategies pursued by Farm Types 2 and 3 means they are focused on increasing productivity, are often more innovative and their earlier adoption and adaptation of technologies may serve as example for other farmers within a certain locality. This may facilitate the further dissemination of technologies within the community.

Resource limitation may often induce a shift in livelihood strategies towards a higher dependence on off-farm income. This has an effect on decision-making and farming practices (Crowley and Carter, 2000). Engagement in off-/non-farm activities was observed in a large number of the farms visited, to the extent that farmers in Meru South felt 'unemployed' when they spent their time on their own farms. These strategies are more clearly exposed by functional rather than structural household typologies. Brown et al. (2006) arrived at comparable household categories for Kenya as those presented here using cluster analysis. Mbetid-Bessane et al. (2002) using a similar categorisation approach based on household strategies found comparable household categories in areas of central Africa, for systems that differ considerably in terms of farming and socio-cultural aspects. Farmers' self-categorisation through participatory wealth rankings, which is often practiced in agricultural research/extension (e.g. Baijukya et al., 2005), may help gaining insight in their goals, priorities and indicators of success. However, the causes (e.g. farm size, assets) and consequences (e.g. timely crop management, use of manure) of household diversity are often confounded in such exercises (cf. Table 6) and extra attention should be paid to identifying key drivers of livelihood strategies that influence the potential impact of interventions.

4.3 Targeting resource-poor, heterogeneous farming systems

All the farms included in our study can be considered to be resource-poor smallholders. The indicators for the main household categorisation criteria, namely: resource endowment (e.g. farm size and number of livestock), sources of income (e.g. number of family members working off-farm and % of income generated on-farm), degree of market orientation and fulfilment of food security through on-farm production, varied consistently between farm types across sites (cf. Table 10). The observed socioeconomic variability across the region was also consistent with the poverty maps for Kenya and Uganda (e.g. Thornton et al., 2006; Woldemariam and Mohammed, 2003; www.worldbank.org/research/povertymaps/). While the maps for

Uganda indicate that 25 to 35% of the population in the sampled sites in Tororo and Mbale district are below the poverty line, the sites in Kenya correspond to areas where 40 to 50% (Meru South and parts of Vihiga), 50 to 70% (Vihiga and Siaya) and more than 70% (Mbeere and parts of Siaya) of the population are below the poverty line. Although for the purpose of targeting interventions we differentiate farmers that are relatively 'wealthier or poorer', the actual differences in resource endowment between these classes is generally narrow – indeed 60 to 70% of the households are below the poverty line. The observed values for socioeconomic indicators were also within the range of those presented in population surveys (e.g. IEA, 2002 – www.ieakenya.or.ke; MFPED, 2001 - www.popsec.or.ug). Unfortunately, although a large number of projects conducted baseline farm surveys in the region, their results are not publicly available.

Across sites, the five farm types differed more in their degree of soil heterogeneity than in the average status of soil fertility indicators at farm scale. This may have different explanations: (i) The spatial randomisation of the sampling of farms (the Y-frame, cf. Figure 1) led to larger farms having a greater chance of being captured by the sampling grid. While this sampling allows good representation of the biophysical variability at landscape scale, it does not necessarily lead to a fair representation of the distribution of farms of different resource endowment. (ii) In heavily dissected landscapes such as those of Meru South, Vihiga or Mbale, small (poor) farms located on top of the ridges may even have better *average* soil properties than larger (wealthier) farms which cover both ridge and slope land. (iii) In the various sites analysed agriculture has been practiced for varying periods of time, with different intensities of land use, and soils have undergone different types and degrees of degradation. This also applies to different farms sampled within a certain site. (iv) Better endowed farmers have access to larger amounts of organic (C) and nutrient resources (and labour) that can be more evenly distributed across their farms. Differences in farmer-induced soil heterogeneity are largely due to the differential availability of nutrient resources, in particular manure, between farm types.

Animal manure is a key resource for nutrient management, and farmers create zones of soil fertility by preferential allocation of this resource – especially when it is in short supply. Farmers tended to apply manure more frequently to the fields closer to the homestead and less in the outfields, due to the requirements of labour to carry bulky materials to distant fields, because more valuable crops were planted close to the homestead to prevent theft, or simply due to 'convenience' (Misiko, 2007). Within individual farms, resources were also allocated in relation to the perceived fertility of the different fields (Table 11, Figure 10). However, the amounts of manure applied (and their average C content) are often insufficient to induce large differences in C content in soils of finer texture (cf. for example, compare Meru South with Mbeere in Figure 3 A). The effect of preferential allocation was less evident from the pattern of variation of soil C than frequently observed in other regions of Africa with coarser-textured soils (e.g. Zingore et al., 2007a; Samaké et al., 2006). In our case, the variability in both soil C and available P decreased as their farm-scale weighed average value increased (Figure 7), which is consistent with the trend observed of decreasing soil C and available P variability in farms that have larger numbers of livestock (cf. Figure 8). The association between labour needs and distance from the homestead varies also across sites with different topography; i.e., fields located far from the homestead are also less easily accessible (while carrying manure) in the highland areas. A consequence of concentration of manure and other organic material in certain fields is the observed relationship between soil organic C and available P. Poor P availabilities were measured across the full range of soil C, while high P availability tended to correspond with soils that had larger organic C contents (Figure 3 B, D and F). The origin of such farmer-induced patterns of soil variability can be better understood considering the dynamics of farming systems, and soil improving technologies should also be designed to target fields in different positions along chronosequences of soil degradation.

5. Conclusions

Regional biophysical and socio-economic drivers shape the environment for different farming and livelihood opportunities, and define the general scenarios to which major policy/technology interventions should be targeted. The patterns of variability across scales observed in these agricultural areas of East Africa can be summarised as follows:

- The magnitude of soil variability differed across districts and for the different soil quality indicators within districts. While variability in soil organic C or total N was mainly associated with the existence of regional gradients of soil types and climate, variability in available P and K levels was larger within localities and farms, and could be ascribed partly to differential historical management of the various fields within farms.
- Farm types differed in land, labour and financial resources and potential nutrient availability (e.g. animal manure) which affect land use and soil fertility management. The dependence on off-/non-farm income was one of the main factors explaining socio-economic variability, and is a key determinant of household diversity.
- The categorisation of households based on livelihood strategies and constraints indicated that major drivers of farm heterogeneity can be generalised consistently across districts. However, the proportion of households falling within each category may be expected to vary for different districts and this has implications for poverty alleviation, implying the need of different policy/technology interventions in each case.
- The average soil fertility status of the farms did not vary consistently across farm types, owing partly to the coexistence of soil-landscape variability within

individual farms. In general, more variability in soil fertility was observed in farms (and districts) with poorer soils, and less in farms owning livestock.

- Due to multiple interactions between site-specific factors, farm resources and objectives, landscape variability and history of land use and management, the variability in soil fertility indicators often observed within individual farms could not be summarised in consistent, generalisable patterns of spatial heterogeneity.

Proper characterisation of within-farm variability, and its causes, requires further analysis at a more detailed scale, considering also the dynamics of the systems, their context, and the resulting spatio-temporal patterns of resource allocation.

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Chapter 3

Characterisation of smallholder farming systems in western Kenya[†]

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

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

Tittonell, P., Misiko, M., Ekise, I., Vanlauwe, B., 2005. Feeding back the result of soil research: the origin, magnitude and importance of farmer-induced soil fertility gradients in smallholder farm systems. Report on the discussion meetings at Emanyonyi Farmer Field School, Vihiga, western Kenya. Tropical Soil Biology and Fertility Institute of the International Centre for Tropical Agriculture (TSBF-CIAT), Nairobi, Kenya, 23 pp.

1. Introduction

The western Kenya region is one of the most densely populated areas of sub-Saharan Africa, due to large initial human settlements that were attracted by its high agroecological potential for crop production: a bimodal rainfall regime and relatively deep soils dominated by clay and loam textures, which were inherently fertile. Due to high population in the subsistence smallholder sector, average farm sizes tend to be very small (from 0.5 to 2.0 ha, on average). Being an area of high human population density and intense soil degradation, western Kenya represents a prospective demographic scenario for other tropical highland regions with comparable climate and soil types. There is also ample variability in rainfall regimes and soil-landscape types across the region, which leads to different land use systems. Thus, western Kenya is an interesting and strategic case study region, as it offers wide gradients in altitude, rainfall, topography and soil types as well as differences in population, ethnic groups, in access to markets and the diversity of land use systems (e.g., most major annual crops grown in sub-Saharan Africa are also grown in this region, livestock systems range widely, and commercial agriculture coexists with smallholder farming). The most acute effects of human population density and consequent resource degradation within western Kenya are found in the highlands (Vihiga and Kakamega districts), with more than 1000 inhabitants per km^2 in certain rural areas.

For all the reasons expressed above, much of the work in this thesis has focused on western Kenya and particularly in the highland sites. To complement the analysis presented in the subsequent chapters, this chapter offers a brief description of farming systems in the region and of the context in which they operate, based on several previously-published studies. Further details can be found in the references provided throughout the text.

2. Agroecological potential and current soil fertility

The highland and midland zones of western Kenya encompass a wide gradient of agroecological zones, ranging from a heavily dissected rolling landscape with deep brown and red soils receiving up to 2000 mm $year^{-1}$ rainfall in the East and North, to gently undulating landscapes with heavy clayey soils and less rainfall (c. 1200 mm $year^{-1}$) towards the Southwest, and sandy flatlands with intermediate rainfall (c. 1500 mm $year^{-1}$) towards the Northwest. Farming systems vary along this gradient, from intensive smallholder mixed dairy-maize systems in the highlands, through sugar cane, commercial maize schemes and tea plantations, to cassava and sorghum-based systems where communal areas for livestock grazing are still present (South and West). Throughout western Kenya maize (*Zea mays* L.), sorghum (*Sorghum* bicolor (L.) Moench), finger millet (*Eleusine coracana* L.), cassava (*Manihot esculenta* Crantz) and sweet potato (*Ipomoea batatas* L.) are the major starch crops, common beans

(*Phaseolus vulgaris* L.), groundnuts (*Arachis hypogaea* L.), cowpeas (*Vigna ungiculata* (L.) Walp.) and secondarily soyabean (*Glycine max* (L.) Merr.) and greengram (*Vigna radiata* (L.) R.Wilczek) are the most common legumes. Bananas (*Musa* spp.), mangoes (*Mangifera indica* L.), avocados (*Persea americana* Mill.) and guava (*Psidium guajava* L.) are the most common fruits. Cash crops range from tea (*Camelia sinensis* O. Kuntze), coffee (*Coffea arabica* L.) and sugar cane (*Saccharum officinarum* L.) to smaller areas of tobacco (*Nicotiana tabacum* L.) cotton (*Gossypium hirsutum* L.), rice (*Oryza sativa* L.), sunflower (*Helianthus annuus* L.) and chilli pepper (*Capsicum* spp.). Vegetables, Napier grass (*Pennisetum purpureum* Schumach) and milk are also important marketable items.

Rainfall is bimodal, allowing two cropping seasons a year: the long rains from March to July and the short rains from August to November, with differences in the amount and distribution across the region (Figure 1 A). Rainfall is highest around Kakamega forest (Shinyalu – 2145 mm on average; 0° 12’ N; 34° 48’ E), followed by the central highlands of Vihiga (Emuhaya – 1850 mm; 0° 4’ N; 34° 38’ E), the area along the border with Uganda, Teso and Malaba districts (Aludeka – 1463 mm; 0° 35’ N; 34° 19’ E) and the midlands north of lake Victoria shores (Nyalgunga – 1265 mm; 0° 2’ N; 34° 26’ E).

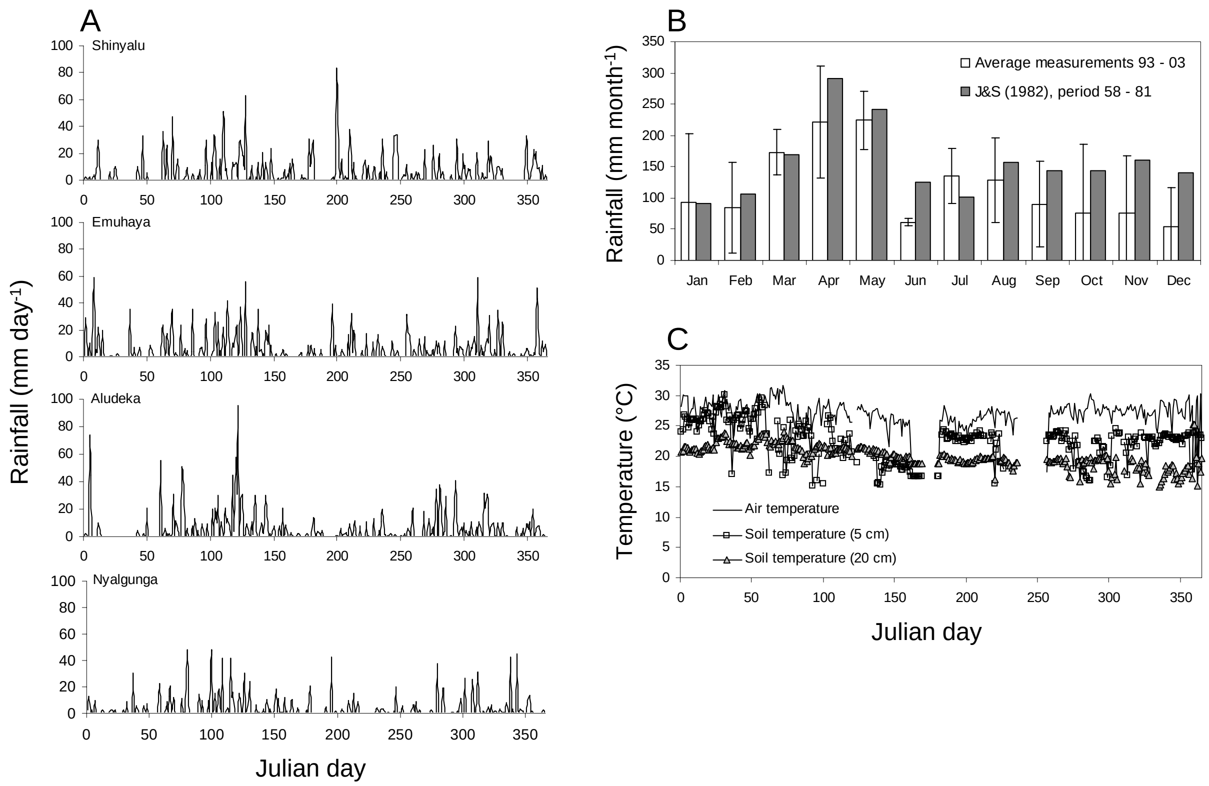

Figure 1: (A) Daily rainfall records for the year 2002 at four sites in western Kenya; (B) Monthly rainfall at the experimental site of TSBF in western Kenya (Ochinga) as measured between 1993 and 2003 and published for the period 1958 to 1981; (C) Mean air and soil temperatures at different depths at Ochinga (Dystrol-mollic Ferralsol).

While prospective rainfall scenarios indicate a net increase in rainfall for the region, through with a trend towards uni-modality (i.e., it is predicted that the short rains may disappear – Thornton et al., 2006), farmers in the area complain about the increasing frequency of season failures. To illustrate this, two long-term datasets were used to characterise the intra-annual rainfall distribution, the 23-year average monthly rainfall published by Jaetzold and Schmidt in 1982, and the average of the 1993-2003 records at the experimental field of Tropical Soil Biology and Fertility Institute of CIAT (Figure 1 B). During the 1990's, the average annual rainfall was 30% less and particularly the short rains were less conspicuous compared to the 1970-80s. Figure 1 C illustrates, for the same experimental site, the variation in mean air and soil temperatures throughout the year.

Western Kenya covers an area of 99,420 km^2, 68% of which is considered of high agricultural potential. In the various agroecological zones of western Kenya the dominant soil types include Nitosols, Ferralsols, Acrisols, Lixisols and localised Arenosols and Vertisols (Jaetzold and Schmidt, 1982; Andriesse and Van der Pouw, 1985). Typical toposequences of soil types in different villages of western Kenya were described by Tittonell et al. (2005b), including the match between FAO soil classes and local soil names used by farmers. In Vihiga, for instance, soils on the upper flatland and breaking slope positions are locally known as *Ingusi* (brown soils), followed by the *Ipulu* on the abrupt midslopes (red soils), and the *Ethri* soils in the valley bottoms (black soils); around scattered rock outcrops the sandier *Oluyekhe* soils develop. Despite their original fertility, most soils in the area are now degraded, as a consequence of long term cultivation with no or little carbon and nutrient inputs (Table 1). Cultivation is believed to have started in the area with massive colonisation at the end of the 19th century. Accounts of 19th century travellers to the area already indicated signs of severe land degradation (Crowley and Carter, 2002).

Table 1: Soil properties measured in and around Kakamega forest reserve, one of the areas with the highest agroecological potential in western Kenya

Source	Clay + Silt (%)	Bulk density (kg dm^{-3})	Soil organic C (g kg^{-1})	Total soil N (g kg^{-1})	Extr. P (mg kg^{-1})	Exch. K (cmol$_{(+)}$ kg^{-1})	pH (water 1:2.5)
Forest reserve A	77.5	-	120.0	12.9	37.0	0.40	5.5
Forest reserve B	59.0	0.76	118.7	10.8	-	-	5.9
KARI research station	76.0	-	31.0	3.6	8.0	0.53	5.5
Farmers' fields							
Homefields	76.4	0.95	21.8	2.1	11.6	0.44	5.3
Midfields	78.3	1.18	18.5	1.6	4.4	0.27	5.4
Outfields	76.2	1.09	16.1	1.1	2.6	0.14	5.2

Forest reserve A: Jaetzold and Schmidt (1982); Forest reserve B: Solomon et al. (2007); KARI research station: FURP report (1994); Farmers' fields: Tittonell (2003).

Nowadays, families farm small pieces of land that is degraded, land is rarely kept as fallow in densely populated areas, a few farmers use fertilisers in limited amounts, and the lack of communal grazing areas prevents the inflow on nutrients to the system via livestock. As a consequence, even the most fertile soils of the region exhibit fertility indicators that are far from their potential under forest or controlled conditions in most of the farming area, except the home gardens.

3. Markets

In a survey conducted in 10 different urban and rural markets in western Kenya, five to six vendors per market were interviewed about the average sale price of their produce, during times of scarcity (highest price) and immediately after harvest (lowest price) (TSBF, 2006). Input suppliers and food retailers were interviewed as well. During the same exercise, farmers were requested to indicate prices paid for transport, wages paid to casual agricultural labourers, and the cost of renting land. The price of certain commodities such as maize or milk varied little across the markets surveyed – with slight differences between rural and urban markets, whereas the price of beans (and cassava, sweet potato, finger millet – not shown) was more variable (Table 2). While the latter were normally produced and traded locally, maize was often also brought from other production areas dominated by commercial farming (e.g. Kitale, in north-western Kenya). Fertilisers were more expensive in certain markets of Siaya district, which are far from the main road networks, and calcium ammonium nitrate (CAN) was not sold at all in such markets. The local unit of trading of mineral fertilisers is not the 50 kg-bag but much smaller amounts, e.g. 1 or 2 kg bags, with prices per kg increasing considerably.

Labour costs were also variable. Information was collected on daily wages paid, amount of hours comprising a man-day, whether workers were offered meals (reducing the amounts paid in cash) and whether different wages were paid for female and male labour. All these variables differed across localities, but to allow comparisons average values in KSh $hour^{-1}$ were calculated (Table 2). However, the problem of pricing labour is complex and average values expressed per hour may not reflect actual agricultural labour costs in the region at different times of the year. Transport costs were highly variable, depending on the infrastructure, but also the frequency of transport differed widely between rural and urban markets. The price of rented land was expressed in acres, the locally used unit. When more than 1 acre was rented (e.g. 1 ha), or for more than one season, the unit price decreased. Land rents were clearly more expensive in areas of higher population density.

Table 2: Selected results from a survey conducted in 10 markets in Vihiga and Siaya districts, western Kenya

District/ Market*	Maize grain (KSh kg^{-1})		Common beans (KSh kg^{-1})		Milk (KSh L^{-1})	Fertiliser (KSh bag^{-1})		Dairy meal (KSh bag^{-1})	Labour (KSh h^{-1})	Transport (KSh km^{-1})		Renting land (KSh acre^{-1})	
	Min	Max	Min	Max		DAP	CAN			Bicycle	MTV	‘old’	‘new’
Vihiga													
Esibuye[R]	9	20	15	35	30	1900	1750	280	4.0	7.0	5.0	2500	3000
Mbale[R]	10	20	30	60	30	1800	1500	n/a	5.0	3.8	3.1	3000	4000
Kilingili[R]	10	21	15	30	30	1850	1700	n/a	4.0	n/a	n/a	2000	2500
Luanda[U]	13	23	25	60	35	1850	1600	300	4.0	6.0	2.8	2000	3000
Chavakali[U]	13	24	30	60	30	1900	1700	270	5.0	n/a	n/a	2500	3000
Majengo[U]	12	23	25	50	30	1700	1450	250	4.2	5.9	2.9	2500	4000
Siaya													
Ugunja[R]	10	20	25	50	25	1950	1800	272	5.0	n/a	n/a	1000	1500
Ngiya[R]	12	22	30	75	30	2200	n/a	n/a	6.7	n/a	n/a	600	600
Yala[U]	10	23	15	50	23	1950	1600	300	10.0	n/a	n/a	1000	2000
Siaya town[U]	13	18	30	65	30	2200	n/a	285	3.3	n/a	n/a	1500	2000

*R; rural, U: urban; markets located in towns > c. 10,000 people were considered urban

Maize and beans prices calculated from the price of a *goro-goro* (a local measure unit, +/- 2 kg). Fertiliser price per bag of 50 kg; Dairy meal price per bag of 20 kg; MTV: motor vehicle; DAP: di-ammonium phosphate; CAN: calcium-ammonium nitrate; ‘old’ and ‘ new’ land used locally to indicate poor and good soil quality, or time since last fallow.

1 acre = 0.45 ha; 1 KSh = 0.72 US$ at the time of the survey.

4. Socioeconomic diversity and farm typology

Poverty mapping in western Kenya indicates that the number of households falling below the poverty line of 1239 KSh month^{-1} ranges between 40 and 60% for most of the region to more than 60% in some of the highland areas (www.worldbank.org/research/povertymaps/). The average exchange rate at the time of the survey was 75 KSh US$$^{-1}$. The same mapping exercise indicated that the contribution of livestock to total household income was larger for households that are better off, with maximum levels of 50% and 68% for households below and above the poverty line, respectively. In a demographic and health survey that clustered households based on health indicators more than 50% of the households in the highlands fell in the two poorest quintiles (NCPD, 1999). Estimates of human population density in western Kenya are variable, depending on the source, the year, and the area considered[‡]. From the least populated areas to the west up to the highlands in the east, densities of 300 to 1300 inhabitants km^{-2} are reported (e.g., Kenya Ministry of Agriculture and Rural Development, 2004).

In spite of facing similar stresses originating from high population densities, resource degradation, poor infrastructure and market development – or as a consequence of these – farming systems in western Kenya are highly diverse. Such diversity is represented by different livelihood strategies, which result from differences in opportunities and constraints facing rural households. Across sites and regions, rural livelihood strategies can be characterised by key indicators pertaining to the following

[‡] I.e., the region defined here as western Kenya comprises almost the entire West Kenya Province plus areas of Nyanza province, to the north of Lake Victoria; governmental surveys often only consider West Kenya Province.

drivers (cf. Chapter 2): household resource endowment, production orientation, access/ dependence on off-farm income and family structure (i.e., size, age composition and position on the farm developmental cycle – Chapter 1). A distinction between rural livelihood strategies is important, as they affect resource allocation decisions. The diagrams in Figure 2 are generic representations of resource allocation patterns by farms of Type 1 to 5 (cf., the typology of households described in the Chapter 2) that were derived from participatory resource flow mapping in Mutsulio village, Kakamega district (further details in Tittonell et al., 2005b). In brief, these strategies can be characterised as: Type 1 – subsidised; Type 2 – self-sufficient; Type 3 – expanding; Type 4 – subsisting; Type 5 – dependent.

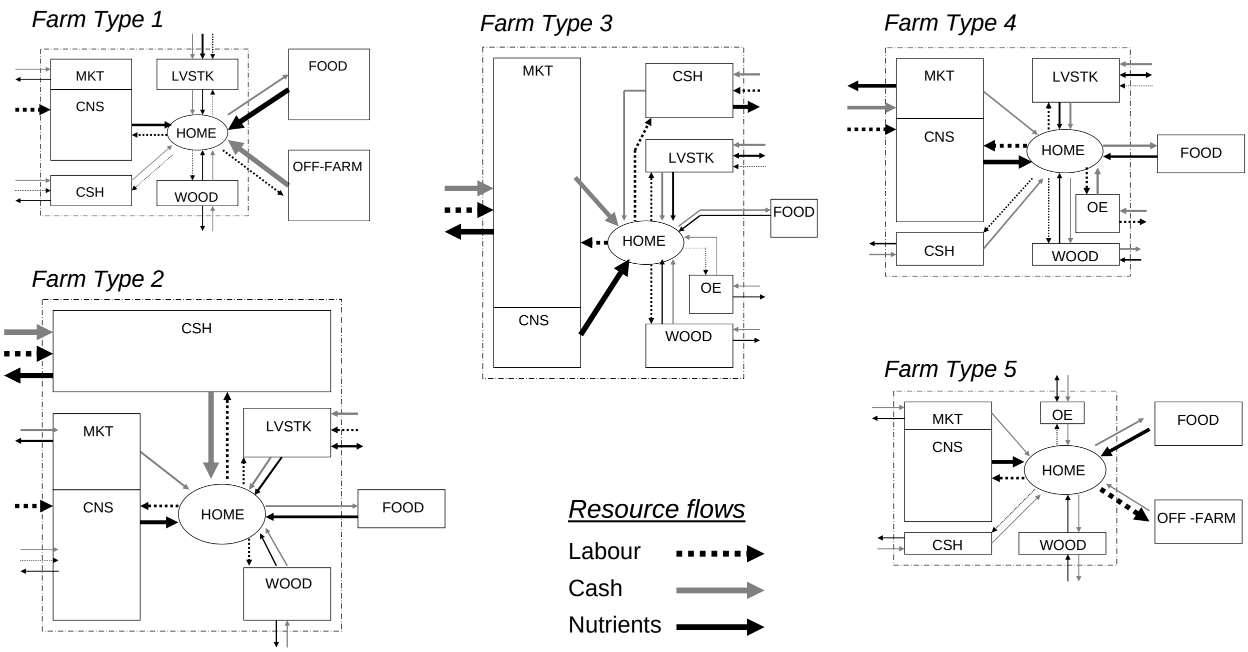

Figure 2: Schematic, generic representation of resource allocation patterns in Farm Types 1 to 5. The sizes of the components as well as of the system boundaries indicate their relative size and/or importance in reality (e.g. the size delimited by the boundaries indicates land size). The weight of the arrows indicates the relative importance of the flows they symbolise. For simplicity, not all possible flows are included. HOME: household (family size); CNS: food crops consumed by the household; MKT: surplus of food crop produce sold on the market; CSH: cash crops; LVSTK: livestock; WOOD: woodlot, mainly for fuel; FOOD: external source of food items (market); OFF-FARM: external source of income; OE: other enterprises, which comprise income-generating activities that involve on-farm production factors (e.g. honey bees, ox-ploughing services, etc.). (Adapted from Tittonell et al., 2005b).

5. Integrated smallholder crop-livestock systems in the highlands

On a typical farm in the highlands of western Kenya, maize intercropped with beans represents the major cropping system, occupying c. 75% of the area of smallholder farms; individual banana stools and local vegetables are found in the home gardens, while sweet potatoes are planted in fields of poor soil quality often far from the homestead. Communal grasslands are virtually absent, except for the grass growing in the roadsides and/or on small patches in the public market places. Napier grass is the main fodder crop grown and represents also a cash crop, particularly during the drier months of the year. Milk production is the major income-generating livestock activity for those farmers who own dairy breeds, while zebus are kept as mid-term investments and/or to pay dowries, contribute to funerals or other social obligations. Animal traction is rarely used for land preparation in the highlands due to the small plot areas and the pronounced slope of most fields. In the compound fields around the homestead, local zebu cattle, sheep and goats are often tethered to graze. Kikuyu grass (*Pennisetum clandestinum* Hochst. ex Chiov.) and secondarily scutch grass (*Cynodon dactylon* (L.) Pers.) are the main species growing on these compound fields. Cross bred and/or improved cattle breeds (e.g. Frisian, Gernsey, Ayrshire) are kept either in the compound fields or in zero-grazing units (feeding stalls), or alternating between both, and kept during the night in a roofed 'boma'. Zebus are more often seen grazing on the roadsides, herded by a boy. Biomass from the thinning of maize, maize stover (during thinning and harvesting times, respectively), sweet potato vines, weeds and grasses cut from different places within and outside the farm area, and concentrates such as dairy meal are used as feed to complement Napier grass. Average nutrient composition and quality parameters for the main types of fodder used in western Kenya are presented in Table 3.

Table 3: Dry matter (DM), crude protein (CP), metabolisable energy (ME), neutral detergent fiber (NDF) and organic matter digestibility (OMD) content of selected feedstuffs used in western Kenya expressed in g kg^{-1}, except ME, in MJ kg^{-1}.

Feed type	DM	CP	ME	NDF	OMD
Napier grass, fresh	144	122	8.9	536	791
Napier grass, mature	197	60	7.1	608	607
Maize stover, dry	939	50	6.8	738	538
Maize stover, fresh	294	70	6.6	645	n/a
Maize dry ears	896	87	n/a	234	n/a
Kikuyu grass, dry	945	191	7.0	n/a	558
Banana leaves, fresh	94	10	n/a	557	522

Source: International Livestock Research Institute, Nairobi, Kenya

The interaction between crops and livestock through feeds and manure takes place at different points in the year according to the cropping calendar (Figure 3). Collected fresh manure is stored in a compost pit or piled together with crop residues and other organic (plant) materials throughout the season. At planting time, the matured manure is removed from the storage and applied to the crops normally into the planting holes. Thus, the period of maturation extends throughout the season, being slightly longer during the long rains. During the maturation period continuous or intermittent (depending on the system – see below) additions of fresh manure to the pit or heap take place. Since three months of maturation are locally recommended to ensure good quality manure (Jaetzold and Schmidt, 1982), the actual maturation periods appear to be excessive. Crop residues are normally fed to cattle for some time after harvest and the refusals of these, not eaten by the animals, are added to the manure pit or heap. Some farmers may remove manure three months of storage, when they judge it is mature, to be used in vegetable gardens or sold to other farmers who produce vegetables for the market. Both manure and crop residues have often other competing uses within the farm, such as the use of cattle dung for plastering or dry crop residues used as fuel for cooking.

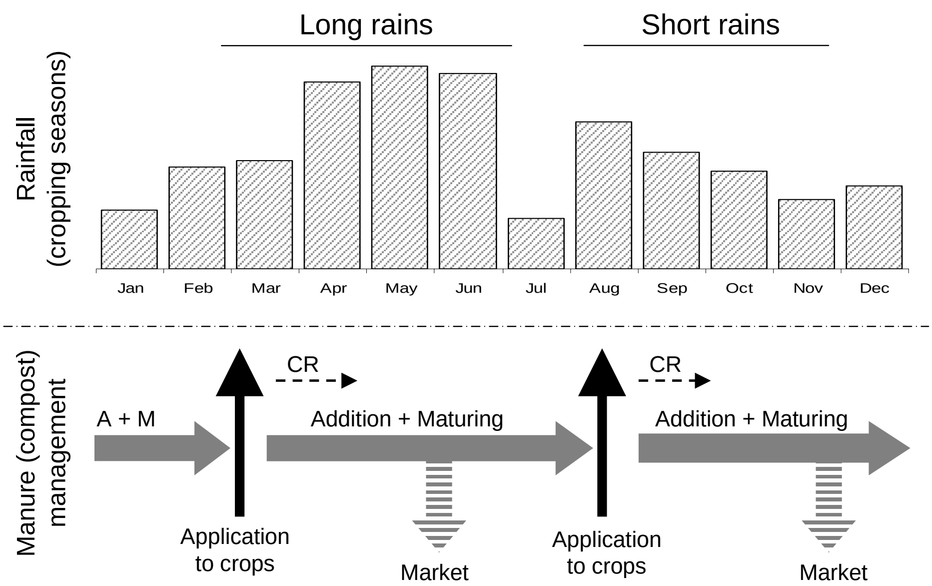

Figure 3: Schematic representation of the approximate duration of manure composting periods in smallholder farms of western Kenya. The dotted lines indicate the periods shortly after harvest during which crop residues (CR) are added to the compost; however, addition of other plant materials take place throughout the compost maturation period.

On different farms, the interactions between crops and livestock take place following three major patterns:

- Pattern I: Wealthy, market-oriented dairy farmers keep improved cattle breeds in roofed and hard-floored zero grazing units, where Napier grass is fed in combination with concentrates and fresh crop residues. Farmers in this group tend to be self sufficient in fodder production. Fibrous, dry crop residues are used as bedding material. Manure plus urine (slurry) are normally channelled into a collecting pit dug next to the feeding stall. These farmers often also have zebu cattle grazing in the compound fields.
- Pattern II: Mid-class, semi-commercial farmers often keep their cross-bred or local animals tethered in the compound, where they complement their grazing with Napier grass and surplus crop materials. In times of scarcity, poor quality fodder such as dry maize stover or banana leaves are offered to the animals. Feed refusals plus cattle dung are frequently (from daily to weekly) collected

and thrown into a compost pit or heaped together with other farm yard organic materials of poor fodder quality. Zebus are also common and normally treated as a separate feeding group.

- Pattern III: Poor, subsistence-oriented farmers that can afford to own cattle have normally local zebu breeds of small frame (+/- 200 kg body weight) tethered in their compound, grazing standing crop residues in the crop fields or herded around to graze in communal patches of grass. Manure, when collected, is either thrown directly on the gardens around the homestead without incorporating it in the soil, heaped around the base of banana plants or heaped/pitted together with the little crop residues or feed refusals available (residues are mostly used for fuel in this type of households).

Intermediate situations and/or combination of the above systems are of course common. These three patterns of crop-livestock interaction take place on different farm types. The first pattern is more common in Farm Types 1 and 2; the second pattern is typical of Farm Type 3, although it may be also found nuanced with pattern II in some farms of Type 1 and 2. The third pattern corresponds to farm Types 4 and 5, the poorest categories, but it may also happen in farms of Type 3. It must be noted that in some cases, although livestock ownership is positively correlated with wealth, households that derive most of their income from off-farm employment or growing tea may not necessarily invest in intensive livestock management systems or improved breeds.

Table 4: Carbon, nutrient and ash content of farm yard manures collected in four case study farms representing types 1 to 4 in Vihiga, western Kenya

Farm Type	Content (%)				
	C	N	P	K	Ash
1	30.2	1.24	0.32	1.97	44
2	29.0	1.01	0.30	1.55	41
3	25.5	1.01	0.12	0.64	57
4	22.7	0.48	0.10	0.59	69

To illustrate with examples of how resource flows corresponding to these patterns may look like in reality, four case study farms were selected in Ebusiloli, Vihiga district, that represented approximately Farm Types 1 to 4 (only few Type 5 farmers own cattle), and were quantitatively characterised (Karanja et al., 2006; Casellanos-Navarrete, 2007) (Figure 4). In Farm Type 1 milk was the major source of income and nutrients entered the system as concentrates and fertilisers applied to crops. Farm Type 2 was self sufficient in Napier grass and had surpluses to market. Farm Type 3 sold some milk and manure and sporadically brought fertilisers and extra Napier grass from the market. Farm Type 4 relied on vegetation growing in fences or alongside the roads of the village to maintain their cow. To prevent theft, Farms Types 1 and 2 could engage night guards or built secure cattle sheds, whereas 3 and 4 kept their cattle inside their homestead during the night. As a result of diverse management systems, frequency of manure collection and duration/conditions of storage, manure qualities vary widely across farm types within the same village (Table 4). Smallholder farms in the highlands are clearly integrated crop-livestock systems, although the type and magnitude of the flows defining such interactions vary between farm types.

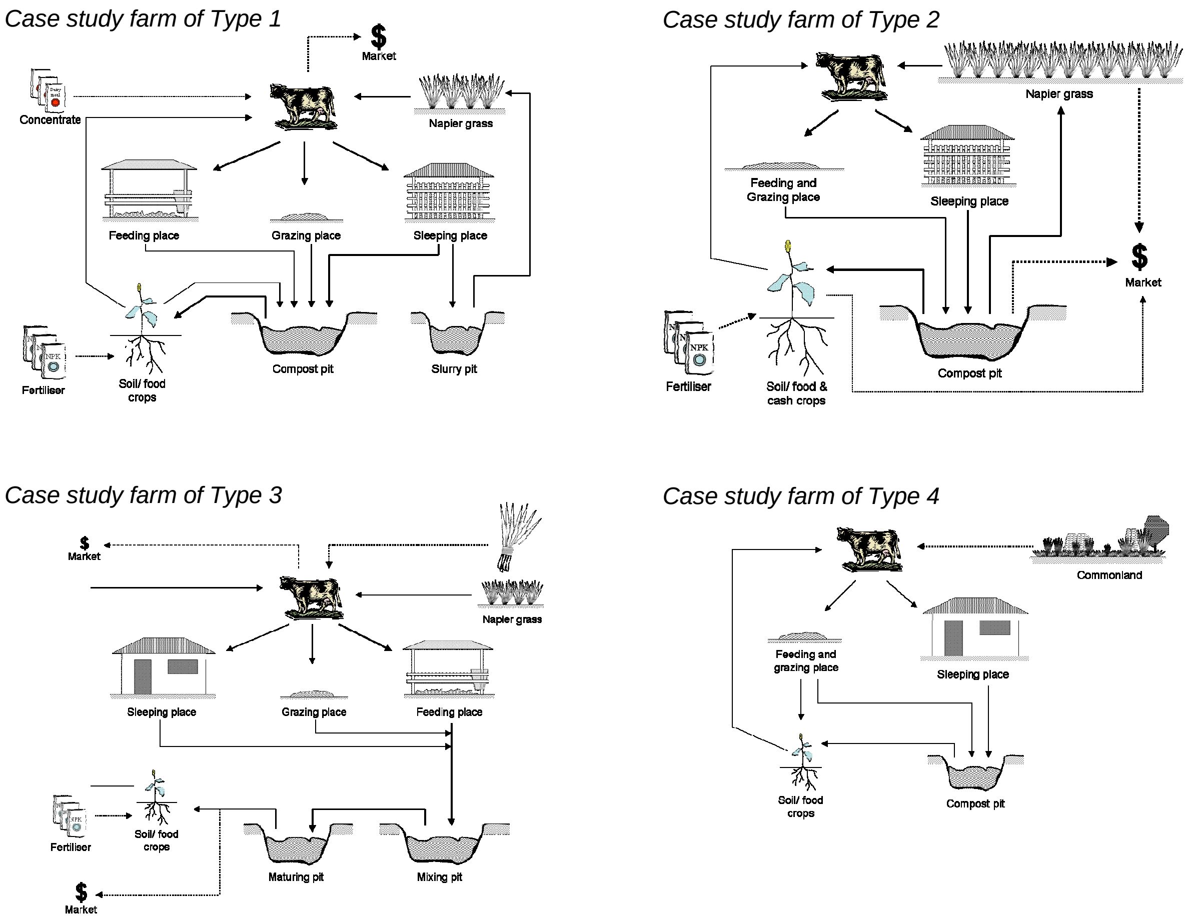

Figure 4: Four examples of multiple crop-livestock interactions and resource flows taking place in four case-study farms of Ebusiloli, Vihiga district representative of Farm Types 1 to 4 (different resource endowment and household objectives) in the typology of households of Tittonell et al. (2005b) (cf. Chapter 2). The size of the components is indicative of their relative importance (e.g., the '$' sign).

6. Resource allocation and spatial soil heterogeneity

Resource allocation patterns and allocation of production activities were derived from analysing resource flow maps drawn by farmers (Figure 5). Current soil fertility is poor due to water erosion and to continuous cultivation with few or no C and nutrient inputs, leading to high heterogeneity in crop production within individual farms (Tittonell et al., 2005c). Resource flow mapping revealed low rates of nutrient application in organic and mineral fertilisers due to poor availability of or limited access to these resources (Table 5 A and B). For farmers owning cattle, potential manure application rates varied (on average, 0.9 to 4 t fresh weight ha^{-1}) across farms of different resource endowment and across localities where different livestock management systems prevail (e.g. free grazing vs. stall feeding).

Table 5: Nitrogen use in farms from different wealth classes in western Kenya as derived from resource flow analysis (adapted from Tittonell, 2003). (A) Potential availability of manure and C, N and P for application to crops; (B) Use of mineral N fertiliser and proportion of the cropped area that could receive recommended N rates on 11 case-study farms

(**A**)

Village*	Resource endowment	Land cropped (ha)	Livestock heads (TLU's)	Potential manure availability (t year^{-1})	Potential application rates (kg ha^{-1})** C	N	P
Ebusiloli	High	2.1	4.0	8.4	960	38	6.1
	Medium	1.1	2.2	3.6	785	31	5.0
	Poor	0.5	0.8	1.1	528	21	3.3
Among'ura	High	2.3	2.3	3.5	212	8	1.3
	Medium	2.2	2.0	2.9	218	9	1.4
	Poor	1.0	1.7	2.0	408	16	2.6

(**B**)

Resource endowment	Total amount of fertiliser N used (kg N year^{-1})	Land cropped (ha)	Actual application rate (kg N ha^{-1})	% of cropped land receiving N fertilizer	% or cropped land that could receive 60 kg N ha^{-1}
Lower	4	1.0	14	8	2
.	5	1.4	7	51	6
.	7	1.3	16	33	9
.	13	1.9	92	7	11
.	15	0.9	27	62	28
.	15	1.7	38	23	14
.	18	2.0	18	53	16
.	19	5.5	33	10	6
.	20	0.8	35	71	42
.	29	4.1	66	11	12
Higher	93	2.6	82	44	60

*Ebusiloli (Vihiga district) is located in a highly populated area (ca. 1000 Inhabitants km^{-2}), closer to urban centres with easier access to markets; intensive (zero grazing, Friesian) livestock production systems predominate. Among'ura (Teso district) area is less populated (200-300 Inhabitants km^{-2}), land is available for fallow, markets are far, and the local (zebu) livestock graze in communal land.
**Calculated over the total area of cropped land, assuming optimum manure handling and an average dry matter content of 80%, C content 30%, N content 1.2% and P content 0.19%

In spite of the scarcity of animal manure only a relatively small number of farmers use mineral fertilisers and in limited amounts. In the case of N, the wealthiest farmers applied rates of 60-80 kg N ha^{-1} only in small portions of their cropped land (Table 5 B). The poorer farmers, among those using fertilisers, would be able to fertilise less than 10% of their land area with an N application rate of 60 kg ha^{-1}. To guarantee food security, farmers tend to concentrate C and nutrient resources in certain fields of their farm, inducing soil heterogeneity in the long term.

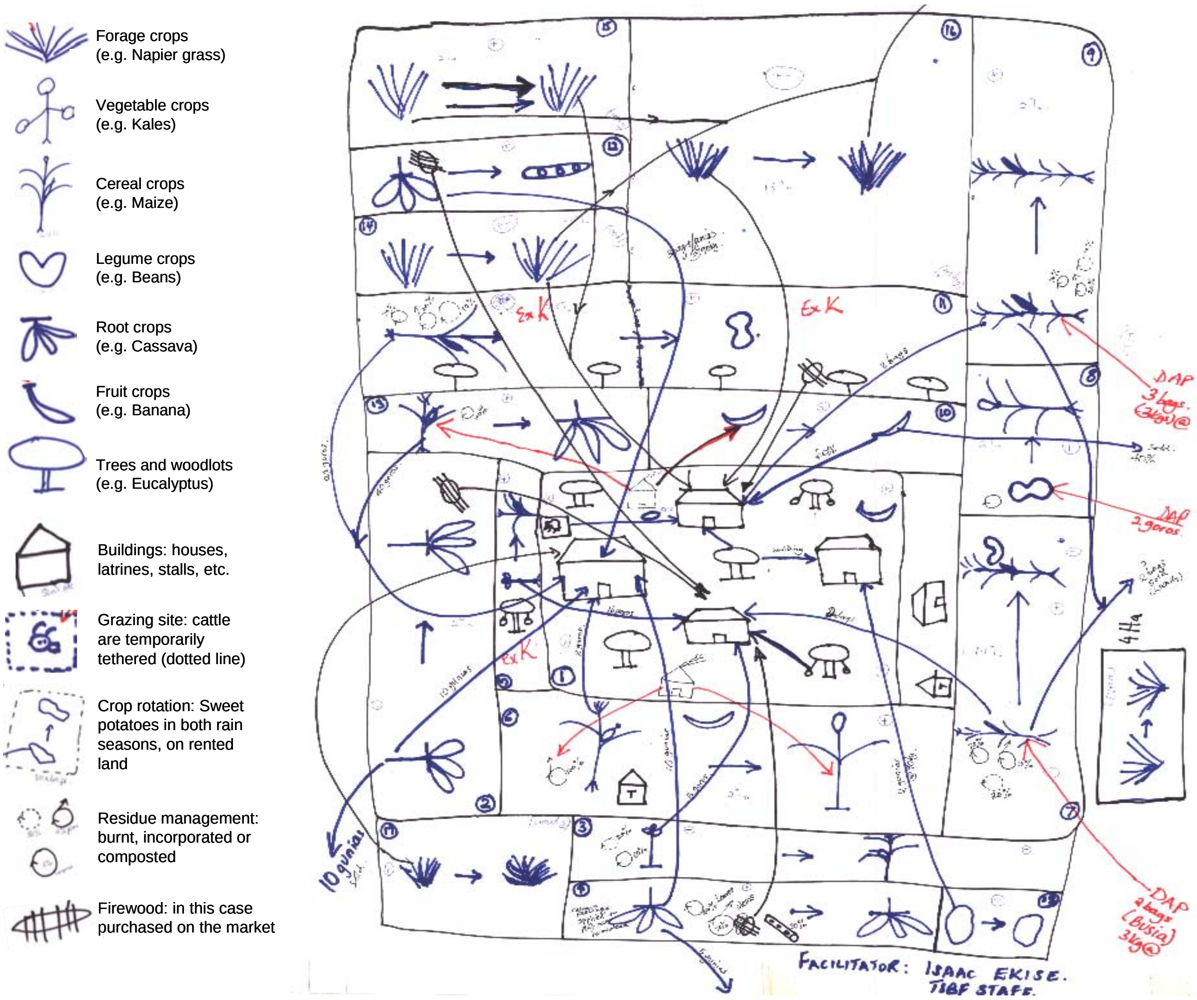

Figure 5: An example of a resource flow map drawn by a farmer (Type 2) in Likolisi, Teso district of western Kenya. For each of the production units (fields) the crops grown in the long and in the short rains season are indicated. Some of the symbols used are enlarged in the key to the left of the graph. While drawing the map red markers are used to indicate input flows (e.g., DAP fertiliser); output and internal flows are drawn in blue.

Such heterogeneity is often manifested as a gradient of decreasing soil fertility with increasing distance from the homestead. The fact that farmers concentrate most resources around the homestead is partly due to labour constraints. Nutrient applications take place at planting time, when different activities are concentrated (Figure 6). However, in-depth community studies have also indicated that sometimes farmers adopt certain practices simply prioritising *convenience*, and not necessarily as a consequence of labour constraints (Misiko, 2007). As a result of such spatial allocation patterns, nutrient balances tend to be positive in fields close to the homestead, at the expense of negative balances in most of the other fields of the farm (an example for N is presented in Figure 7).

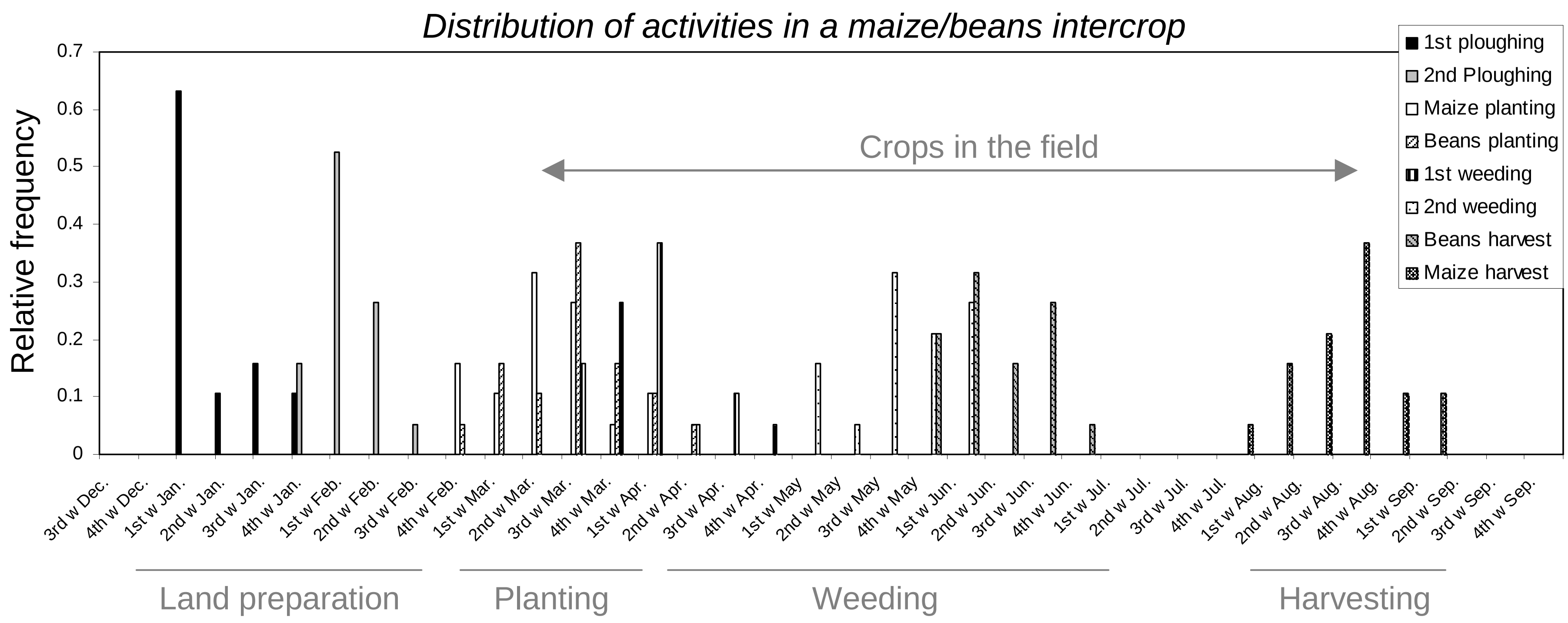

Figure 6: The distribution of activities for a maize/ beans intercrop, combining labour calendars obtained in 20 farms of Mutsulio village, Kakamega district of western Kenya; e.g., more than 60% of the farmers that were visited started with land preparation on the first week of January and about 40% of them harvested beans and maize on the 4th week of August.

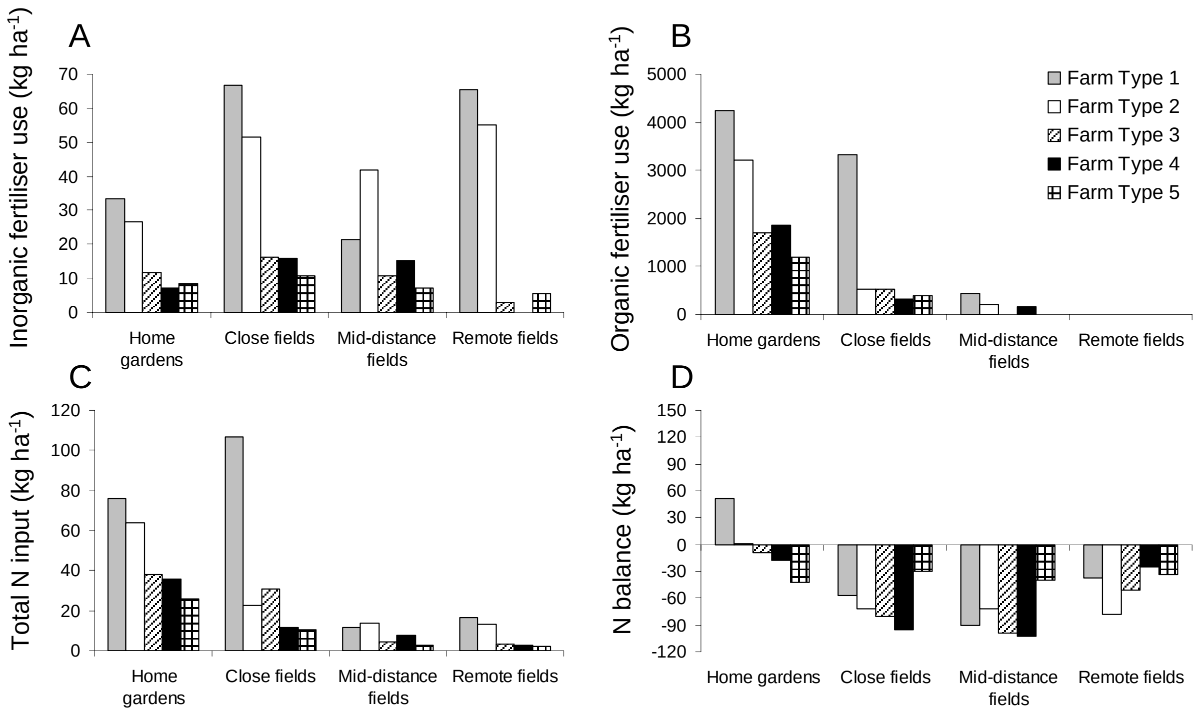

Figure 7: Nitrogen input and balances at field scale in smallholder farms of western Kenya (Tittonell et al., 2005c). Use of (A) inorganic and (B) organic fertilisers; (C) total N inputs to the soil applied in mineral and organic fertilisers; and (D) partial N balances for the different field types of case study farms of Types 1 to 5 at Shinyalu, western Kenya. Estimations considering organic and mineral fertilisers, residue management and harvests from each field type according to the results of the resource-flow maps. The estimations of total N inputs (C) used to calculate N balances (D) included mineral and organic fertilisers (A and B), plus N in crop residues (when they were incorporated) and in other organic sources (e.g. kitchen wastes). Note the important differences in the scales of the y-axes.

This heterogeneity induced by human agency interacts with the inherent variability of soil types across the landscape creating very complex spatial patterns, particularly in the highlands of western Kenya (i.e., homesteads are placed on top of the ridges and the most remote fields often correspond to valley bottom land) (Figure 8 A). An extra element of complexity is management intensity: since farmers allocate more resources and effort in the fields perceived as more fertile, soil heterogeneity induces ‘resource use efficiency gradients’ that are visually evident through large variability in crop performance within a single farm (Tittonell et al., 2007a).

7. Farmers’ indicators

When farmers classified fields according to their perceived soil quality they used criteria such as crop growth performance, history of use, slope, texture or distance from the homestead (Tittonell et al., 2005c). Results of soil analysis tended to match farmers’ classification of fields into ‘poor’, ‘average’ and ‘fertile’ (translated from

Swahili: *rotuba kidogo*, *rotuba kadiri* and *rotuba sana*, respectively) (Figure 8 A). There was also agreement between 'field types' and perceived soil quality, with *esilundu* fields being perceived as more fertile, *hakari* fields as intermediate and *mwbanda* fields as poor. However, each farmer classified his/her own field independently from their neighbours and often using different criteria. Subjectivity in soil classification prevents its use in fine-tuned soil management recommendations to target specific field types.

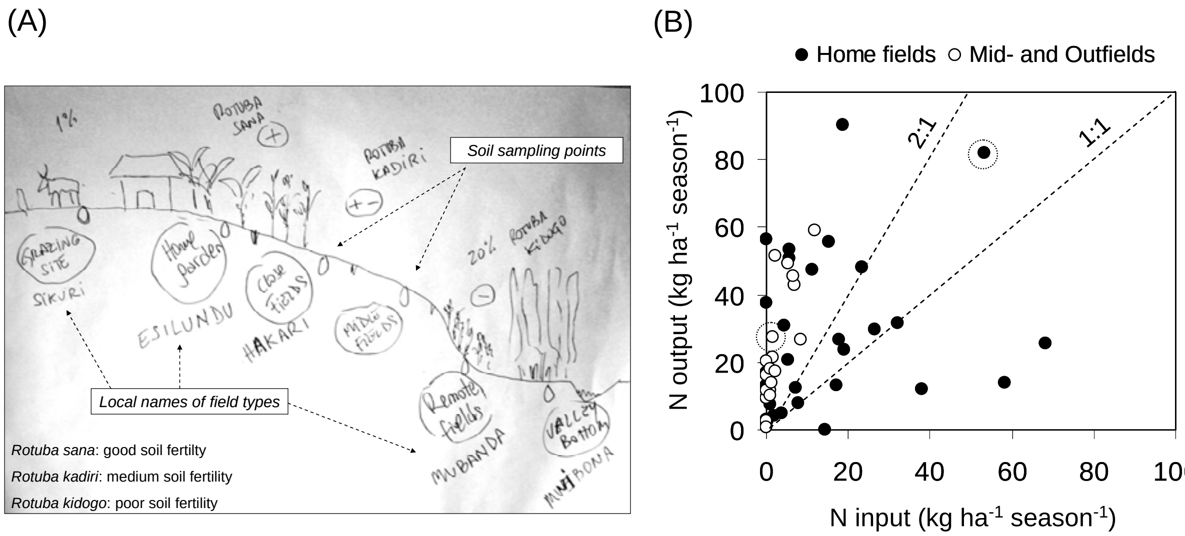

Figure 8: (A) A typical transect of a smallholder farm in Vihiga, western Kenya drawn during discussion sessions on soil variability at Emanyonyi Farmer Field School, indicating areas of fertile and poor soils and field types; (B) Outputs of N in crop harvests versus inputs of N as organic and mineral fertilisers in the home- and outfields of 15 farms of western Kenya, with two encircled points indicating a similar value of -22 kg ha^{-1} season for the N balance.

On the other hand, scientists' indicators are sometimes meaningless to farmers. For instance, Figure 8 B shows partial N balances corresponding to home and outfields from 15 farms in western Kenya. Alarmingly, in most fields N outputs were larger than N inputs, and in most outfields they were twice as large. But although soil fertility management varied widely between infields and outfields, both points encircled in Figure 8 B had a balance of -22 kg N ha^{-1}. The implications of negative nutrient balances may be easy to foresee and communicate to farmers. But, since the most negative balances correspond to the best yielding fields of the farm, and *vice versa*, farmers participating in field schools in Vihiga strongly questioned the validity and meaning of nutrient balances as indicators (Tittonell et al., 2005b). When nutrient stocks in the soil are large, strongly negative balances may represent minimum changes in the soil; e.g. nutrient balances of -16.0 and -17.1 kg N ha^{-1} represented relative changes in the soil N stock of -2.6 and -14.6 % for close and remote fields in western Kenya, respectively (Tittonell et al., 2007a). Under an over-simplistic assumption, a relative annual change of -2.6 % in the N stock implies that farming may continue at the same rate of extraction for almost 40 years – close to the lifetime of a rural family (Crowley and Carter, 2000).

8. Summary and conclusions

Counteracting the processes that lead to resource degradation and in particular soil fertility decline is not an easy task in such a highly populated region as western Kenya. For years when the land was first settled, rural families farmed their land without fertilisers, relying on fallow periods and nutrient inputs through manure to restore soil fertility. Nowadays, farm sizes have dwindled and communal grazing and wood lands virtually disappeared. The current number of cattle per household is low and the resources to feed them are scarce, restricting their contribution to the maintenance of soil productivity via manure. The amount and the quality of manure available are insufficient, and farmers concentrate this resource in certain fields of the farm at the expense of the fertility of the rest of the farm. Rather than livestock driving productivity of the cropping systems, in most farms in western Kenya the livestock system *depends* on crop residue, thinnings and weeds used as feeds, further accelerating nutrient extraction rates.

Some of the problems associated with poor farm productivity originate from management decisions that are conditioned by the perception of soil quality and determined by household objectives and long-term livelihood strategies. People from western Kenya have a long tradition in agriculture and extensive knowledge and innovation capacity. The region has ample agroecological potential that allows a wide range of cropping and livestock systems, with bimodal rainfall and inherently fertile soils. Farms in the highlands are closely integrated crop-livestock systems that can exploit synergies to improve nutrient cycling efficiencies and minimise risks. Although current soil fertility is poor, high potential to fix atmospheric C into crop biomass (two cropping seasons a year) and predominantly fine-textured soils offer ample scope for restoring the productivity of farming systems in the region through integrated soil fertility management.

Acknowledgements
The following farmers from Emanyonyi Farmer Field School, Emuhaya (western Kenya), are thankfully acknowledged for their enormous contribution to our understanding of their farming system: Alice Andwati, Refa Oluchina, Boaz Okwala, Sofia Agoy, Jairus Lusuli, John Muhando, Joash Mukora, Mildred Otsembo, Titus Katembo, Susan Ogola, Morrison Opiayo, Doricas Nakaya, Lucia Musumba, Weeliff Inyangala, Sarah Mukabi, Gideon Omito, John Ogola, John Obwamu, Anne Muhando and Christine Walla. Thanks in particular to Isaac Ekise and Michael Misiko for the long days spent in the field together.

Chapter 4

Unravelling the effects of soil and crop management on maize productivity[†]

[†] Adapted from:
Tittonell, P., Shepherd, K.D., Vanlauwe, B., Giller, K.E., 2007. Unravelling the effects of soil and crop management on maize productivity in smallholder agricultural systems of western Kenya – an application of classification and regression tree analysis. Agriculture Ecosystems and Environment 123, 137-150

Abstract

To guide soil fertility investment programmes in sub-Saharan Africa, better understanding is needed of the relative importance of soil and crop management factors in determining smallholder crop yields and yield variability. Spatial variability in crop yields within farms is strongly influenced by variation in both current crop management (e.g. planting dates, fertilizer rates) and soil fertility. Variability in soil fertility is in turn strongly influenced by farmers' past soil and crop management. The aim of this study was to investigate the relative importance of soil fertility and crop management factors in determining yield variability and the gap between farmers' maize yields and potential yields in western Kenya. Soil fertility status was assessed on 522 farmers' fields on 60 farms and paired with data on maize-yield and agronomic management for a sub-sample 159 fields. Soil samples were analysed by wet chemistry methods (1/3 of the samples) and also by near infrared diffuse reflectance spectroscopy (all samples). Spectral prediction models for different soil indicators were developed to estimate soil properties for the 2/3 of the samples not analysed by wet chemistry. Because of the complexity of the data set, classification and regression trees (CART) were used to relate crop yields to soil and management factors. Maize grain yields for fields of different soil fertility status as classified by farmers were: poor, 0.5 – 1.1; medium, 1.0 – 1.8; and high, 1.4 – 2.5 t ha^{-1}. The CART analysis showed resource use intensity, planting date, and time of planting were the principal variables determining yield, but at low resource intensity, total soil N and soil Olsen P became important yield-determining factors. Only a small group of plots with high average grain yields (2.5 t ha^{-1}; $n = 8$) was associated with use of nutrient inputs and good plant stands, whereas the largest group with low average yields (1.2 t ha^{-1}; $n = 90$) was associated with soil Olsen P values of less than 4 mg kg^{-1}. This classification could be useful as a basis for targeting agronomic advice and inputs to farmers. The results suggest that soil fertility variability patterns on smallholder farms are reinforced by farmers investing more resources on already fertile fields than on infertile fields. CART proved a useful tool for simplifying analysis and providing robust models linking yield to heterogeneous crop management and soil variables.

Keywords: Near infrared spectroscopy, Local soil quality indicators, Soil fertility variability, Maize yield, Sub-Saharan Africa

1. Introduction

It is widely recognized that major investments in improving soil and crop management are required to raise agricultural productivity in sub-Saharan Africa. The evidence base is widespread negative nutrient balances on smallholder farms and the large yield gap between potential and actual yields, both observations being causally related (Vanlauwe and Giller, 2006). To help target investment programmes, a better understanding is needed of the relative importance of soil and crop management factors that limit smallholder crop yields and cause large variability in yields within farms. Crop growth potential at a given location is determined by genotype and climate, whereas actual crop yields result from the interactions of local growth-limiting and growth-reducing factors (De Wit, 1992). The variability in crop growth performance within individual farms therefore reflects the effects, interactions and spatial distribution of these factors, many of which are directly influenced by management decisions. Both long-term and current soil management decisions influence the prevailing soil quality, spatio-temporal patterns of resource allocation, and the timing and effectiveness of agronomic practices (e.g. time of planting, weeding).

Crop growth variability within African farming systems has been attributed to: soil properties (e.g. van Asten, 2003); agronomic practices (e.g. Mutsaers et al., 1995); farmers' resource allocation decisions (e.g. Nkonya et al., 2005); or combinations of these (e.g. Samaké et al., 2006). In western Kenya, agronomic management decisions play an important role in determining resource use efficiency and consequently crop productivity (Tittonell et al., 2007). The gap between potential and actual maize yields is principally caused by limiting factors such as N and P availability, and by growth-reducing factors such as *Striga* infestation (Tittonell et al., 2005b). Water availability may also be limiting under conditions of pronounced soil physical degradation, extraordinarily dry years and/or mid-season droughts, resulting in substantial yield losses especially for crops grown on steeply sloping fields subject to run-off (Braun et al., 1997).

In most of these studies, linear regression and correlation techniques have been used to relate crop yield variability to agronomic factors. We hypothesise that the different components of crop growth variability are interdependent, and that their interaction often leads to reinforcing synergistic effects; e.g. when crops are planted late on sloping remote fields of a farm, bare soil surfaces are exposed to erosion, which further degrades the soil. We can expect thresholds to exist in relationships between yield and management or soil fertility variables, leading to non-linearities. Analysis of such interactions requires application of multivariate analysis methods and an ability to deal with non-linear relationships. Farm survey data sets are normally characterized

by a mixture of continuous and categorical variables, highly skewed data, and large numbers of missing observations, adding to the complexity of the analysis.
Classification and regression tree (CART) analysis has increasingly been used in different fields of research for analysis of problems of this nature, as it has a number of advantages over alternative methods, such as multivariate logistic regression (Tsien et al., 1998). Since CART is inherently non-parametric, no assumptions are made regarding the underlying distribution of values of the predictor variables. Thus, CART can handle numerical data that are highly skewed or multi-modal, as well as category predictors with either ordinal or non-ordinal structure. CART has been extensively applied in medical research, as it is ideally suited to the generation of clinical decision rules (e.g. Crichton et al., 1997), and to develop risk assessment tools (e.g. Steadman et al., 2000). CART analysis has rarely been applied in agricultural research. Shepherd and Walsh (2002) used classification trees to relate soil fertility case definitions to reflectance spectra for an extensive library of African soils. CART analysis has also been used to characterise the habitat structure of termites in agroforestry systems (Martius, 2004).

In analysing crop yield variability at farm scale, the use of CART may help to stratify such variability into classes that reflect interactions between crop management and soil fertility, and thus may have practical use for targeting soil and crop management interventions and advice to farmers. For example, the relation between input use and yields (i.e. crop response) has been shown to vary for different soil quality classes (Vanlauwe et al., 2006). These classes can be related to local farmers' soil quality indicators to assist in efficient targeting of resources through fine-tuned decision making. However, the analysis of a sufficiently large number of cases to establish reliable explanatory models requires time-consuming and costly soil analyses, which are rarely feasible. To overcome this limitation, we propose the use of soil analysis by infrared diffuse reflectance spectroscopy (IR) in combination with spectral calibration to conventional wet chemistry methods; soil reflectance itself can also be used as a soil fertility indicator (Shepherd and Walsh, 2002; 2007). With this technique, soil fertility properties can be characterized on about 400 samples a day at low cost.

Our objective was to determine the main environmental and agronomic management factors that determine maize yields on farmers' fields across a range of conditions of soils, climate, population density, and market access in western Kenya. Understanding the relative importance of these factors was deemed a necessary step in contributing to the design of technical interventions to reduce yield gaps for maize, the major food crop in western Kenya. We used CART to unravel the relationships between environmental and agronomic management factors and determine their relative importance as explanatory variables for crop yield variability.

2. Materials and methods

2.1 The study area

The study included three sites in the highly-populated region of western Kenya: Aludeka division in Teso district (0° 35’ N; 34° 19’ E), Emuhaya division in Vihiga district (0° 4’ N; 34° 38’ E) and Shinyalu division in Kakamega district (0° 12’ N; 34° 48’ E), covering an area of 99,420 Km^2 (68% of which is considered of high agricultural potential). Gradients in altitude, rainfall, topography and soil types as well as differences in population density, ethnic groups, access to markets, and land use were observed between these sites, which encompass much of the variability found in the region. Average farm sizes are small (from 0.5 to 2.0 ha); population density in the rural areas ranges from 300 to 1300 inhabitants km^{-2} (Kenya Ministry of Agriculture and Rural Development, 2004). Rainfall ranges from 1000 to 2000 mm annually and is distributed in two cropping seasons in most of the region: the long rains from March to July and the short rains from August to November. The landscape is gently undulating in the East to fairly flat in the West, with the exception of scattered groups of hills. Nitisols, Ferralsols and Acrisols are the predominant soil types (Jaetzold and Schmidt, 1982). The land use systems are diversified and range from subsistence smallholdings to more cash-crop oriented farms, and different types of crop-livestock systems can be found across localities and between farmers of different social status. Maize (*Zea mays* L.), beans (*Phaseolus vulgaris* L.), sorghum (*Sorghum bicolor* (L.) Moench), cassava (*Manihot esculenta* Crantz) and finger millet (*Eleusine coracana* L.) are the main staple food crops grown in the region. Further details are given by Tittonell et al. (2005bc).

2.2 Field sampling

In 2002, on-farm research was conducted in the three locations described above to document the magnitude and origin of farmer-induced soil fertility gradients within smallholder farms, and their impact on crop productivity in relation to crop management factors. Results of studies on system characterisation and nutrient flows have been reported in Tittonell et al. (2005bc), on crop responses to mineral fertilisers within heterogeneous farms in Vanlauwe et al. (2006), and on the effect of management regulating resource flows and use efficiencies in Tittonell et al. (2007). The present paper uses farm and maize yield data reported by Tittonell et al. (2005bc) and uses CART analysis to elucidate the interacting effects of soil quality and management factors on crop productivity. Field data were collected to record different variables that affect maize productivity, grouping them into three categories: general, management and soil/landscape factors (Table 1). The latter included either the wet chemistry analytical results or the spectral prediction of soil properties. All the variables in Table 1 were included as candidate explanatory variables for yield variability in the CART analysis.

Table 1: Explanatory variables used in the CART analysis

Category	Variables	Detail
General	Site	Locations within western Kenya: Aludeka (Teso District), Emuhaya (Vihiga District) and Shinyalu (Kakamega District); average rainfall: c. 1400, 1700 and 2000 mm respectively.
	Wealth	Wealth ranking of farms: low, medium and high resource endowment (LRE, MRE and HRE)
	FSQC	Farmers' soil quality class: classification of the different fields of a farm as poor, average and fertile (each farmer classified their own farm)
Management	RDH	Relative distance from the homestead; relating the distance from the sampling point to the homestead to the maximum distance possible within the farm (furthest field)
	SDP	Standardised* delay in the planting date with respect to the optimum for each location
	PLD	Plant population density (pl m^{-2}) of maize
	Weed	Weed infestation level; score 0 to 3 (absent, low – high). Hand weeding twice in the season is regarded as good practice in the area; maize crops that were absent of weeds at sampling (physiological maturity) but were only weeded once in the season scored Weed = 1.
	Striga	*Striga* sp. infestation level; score 0 to 3 (absent, low – high)
	RUI	Resource use intensity; scores 0 to 3 indicating no, few, medium or high use intensity of nutrient resources (e.g. RUI = 1 means use of organic or mineral fertilisers at insufficient rates).
Soil and landscape	Soil wet chemistry	Silt+Clay, soil organic C (SOC, g kg^{-1}), total soil N (Nt, g kg^{-1}), extractable P (Ext_P, mg kg^{-1}), exchangeable K^+, Ca^{++} and Mg^{++} (Exc_K, Exc_Ca and Exc_Mg, $cmol_{(c)}$ kg^{-1}) and soil pH in water (1:2.5)
	Slope	Slope of the fields (%)
	Soil spectral	Principal component scores of the soil spectral data (PCA); principal component of the partial least square regression analysis (PLSR) relating maize yields to the spectra; predicted soil properties using the spectral models (PLSR)

*Standardisation was done with respect to the planting date considered optimum for each site (as recommended by local agricultural extension services) to make comparisons across sites possible
PCA: principal component analysis; PLSR: partial least square regression

Farms identified by key informants were visited and rapid appraisals were conducted for socio-economic characterisation, from which data we selected 20 case-study farms per site for more detailed characterisation. Farms were selected to capture the socio-economic diversity of households, and were classified following a wealth ranking approach into farms of low, medium and high resource endowment (LRE, MRE and

HRE, respectively – 'Wealth' in Table 1). At each farm visited, farmers classified their production units (fields) in classes of fertile, average, or poor (*rotuba sana*, *rotuba kadiri* and *rotuba kidogo*, respectively – 'FSQC' in Table 1) based on their own indicators. We walked through each farm along a transect together with the farmer and discussed each field in turn, aided by a map of the farm drawn by the farmer. Maize was the main crop grown in c. 80% of the fields surveyed. All the fields in the sample of 60 farms (n = 522) were classified by farmers into fertile (22% of all sampled fields), average (40%) or poor (38%), and the area of each field was measured using a Global Positioning System (GPS) device. Topsoil (0 -15 cm) samples were taken with an auger at five points per field from all the production units identified in each case-study farm; the five (sub-)samples from each field were mixed and one composite sample per field was sent for analysis (n = 522). The samples were air-dried, passed through a 2 mm sieve, and stored at room temperature prior to analysis.

Maize yields were estimated on-farm from non-destructive plant morphological measurements, using allometric models described by Tittonell et al. (2005a), in a representative subset of 159 out of the 522 fields that included high- and low-yielding fields (as indicated by farmers). Grain yield was estimated from measurements of plant height, stem diameter, and ear length taken at around the 'milky stage' of maize during the long rains season of 2002. Information on agronomic management practices was recorded, including: the cultivar(s) used, the type and amount of inputs used, timing of crop and soil management activities and their sequential order within the farm, average yields obtained, weed infestation levels (estimated through visual scoring during the cropping season), and general crop husbandry practices adopted (e.g. plant density) – including the variables under the category 'Management' in Table 1.

2.3 Soil analysis

2.3.1 Near infrared spectroscopy

All 522 samples taken from the farms were analysed by diffuse reflectance spectroscopy, using a FieldSpec FR spectroradiometer (Analytical Spectral Devices Inc., Boulder, Colorado) at wavelengths from 0.35 to 2.5 µm with a spectral sampling interval of 1 nm using the optical setup described in Shepherd et al. (2003). Using the spectral library approach described by Shepherd and Walsh (2002), a sub-sample of 190 soils was selected for wet chemistry analysis based on their spectral diversity. This was done by conducting a principal component analysis of the first derivative spectra and computing the Euclidean distance based on the scores of the significant principal components. Random samples were then selected from each quartile of the ranked Euclidean distances to make up the 190 samples for analysis by wet chemistry.

2.3.2 Wet chemistry analysis

The 190 selected soil samples were analysed following standard methods for tropical soils (Anderson and Ingram, 1993). Soil pH was determined in water using a 1:2.5 soil/solution ratio. Samples were extracted with 1 M KCl using a 1:10 soil/solution ratio, analysed by NaOH titration for exchangeable acidity and by atomic absorption spectrometry for exchangeable Ca and Mg. Samples with pH >5.5 were assumed to have zero exchangeable acidity and samples with pH <7.5, zero exchangeable Na (all samples in this case). Samples were extracted with 0.5 M $NaHCO_3$ + 0.01 M EDTA (pH 8.5, modified Olsen) using a 1:10 soil/solution ratio and analysed by flame photometer for exchangeable K and colorimetrically (molybdenum blue) for extractable P. Organic C (SOC) was determined colorimetrically after H_2SO_4 – dichromate oxidation at 150º C for 30 minutes. Total N was determined by Kjeldahl digestion with sulphuric acid and selenium as a catalyst. Particle-size distribution was determined using the hydrometer method after pre-treatment with H_2O_2 to remove organic matter (Gee and Bauder, 1986). Effective cation-exchange capacity (ECEC) was calculated as the sum of exchangeable acidity and exchangeable bases.

2.4 Exploratory analysis of the soil chemistry and spectral data

The analysis of the variation in the soil data was performed using Genstat Version 8. The soil variables were transformed (ln or square root) where necessary to obtain a normal distribution, and standardized before analysis. A principal component analysis (PCA) was first done on soil wet chemistry indicators (Silt+Clay, SOC, total N, extractable P and K, exchangeable Ca and Mg, and pH; n = 190) to explore their interrelationships. The PCA yielded a model in which three PC's explained 90% of the variation. PC1, which explained 56% of the variation, had positive loadings on soil organic C and exchangeable Ca and Mg. Total N was not included in the analysis, as it added little information to the model due to its correlation with soil C (r^2 = 0.8). Extractable P and K, and pH had positive loadings with PC2, and explained a further 24% of the variation in the data. PC 3 explained a further 10% of the remaining variation, with large positive loadings on extractable P. The clay + silt content of the soil had intermediate loadings on PC1 and PC2, and was positively and highly correlated with the organic C content (r = 0.92). Secondly, a PCA was done on the first derivative of the soil spectral data to summarise the spectral soil information in a few components. Seven PC's were necessary to explain 95% of the variance in the soil spectral data, which were then included in the maize-subset database for later use as explanatory variables for maize yield, as an alternative to using predicted soil analytical data (cf. Table 1).

2.5 Prediction of soil properties from the near infrared spectra

The wet chemistry variables were transformed when necessary to obtain a normal probability distribution. Partial least squares regression (PLSR), implemented in The Unscrambler (Camo Inc) was used to calibrate the transformed wet chemistry variables to the first derivative of the soil spectral data. Full hold-out-one cross-validation was done to prevent over-fitting and provide error estimates. Jack-knifing was done to exclude 'non-significant' wavebands. Samples with residual *y* variance >3 residual standard deviations were omitted as outliers. Models with reasonable validation results were used to predict the soil properties for the entire sample population (n = 522).

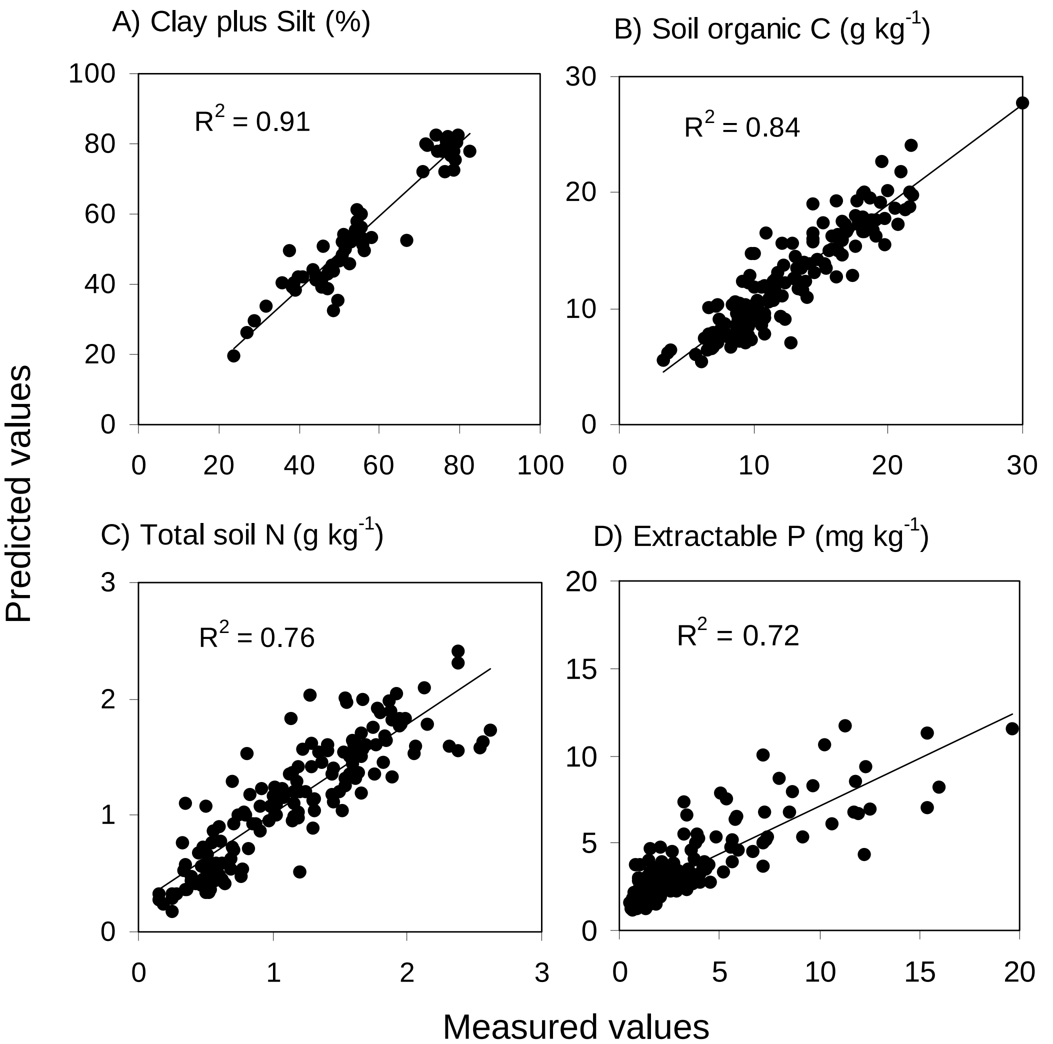

Figure 1: Predicted soil fertility indicators using spectral soil analysis plotted against their measured value using standard wet chemistry methods (n = 159, except A: n = 64).

A fairly good model was obtained for prediction of the clay + silt content, whereas the spectral predictions of soil organic C and total N were moderately accurate (Figure 1).

For extractable P the PLSR model predicted reasonable well in the low range (measured values < 4.5 mg kg^{-1}) but tended to under-predict in the high range of P values. The root mean square errors of these predictions calculated on the back-transformed data, and based on full hold-out-one cross-validation, were: clay + silt, 22.5%; C, 1.7 g kg^{-1}; N, 0.44 g kg^{-1}; and available P, 5.4 mg kg^{-1}. The validation of the spectral models for exchangeable K, for the effective cation exchange capacity (ECEC), and for pH (not shown) had r^2 values of 0.41, 0.82 and 0.67, respectively, with root mean square errors of prediction: K, 0.5 $cmol_c$ kg^{-1}; ECEC, 1.6 $cmol_c$ kg^{-1} and pH, 0.6.

Additionally, a PLSR was done using the maize-subset (n = 159) soil spectral data to predict maize yields using the first derivative of the spectra – a way of 'orientating' the spectra to the yield variation. The analysis was done for the square root transformed maize yields as response variable, using the first derivative of the spectra as independent variables. The cross-validated model gave r^2 = 0.37, indicating that soil reflectance had some explanatory power in prediction of maize yields. With strong influence of current agronomic management and climatic variation, we would not expect high amounts of variability in yield to be explained by soil quality. These findings, together with those of previous studies (Tittonell et al., 2007), guided us in designing the sequencing of explanatory variables included in the stepwise analysis using CART (cf. 2.6.1).

2.6 Classification and regression tree (CART) analysis

The aim of CART (Salford Systems Inc., San Diego, CA, USA) is to predict or explain the response of a categorical variable (classification trees) or a continuous variable (regression trees) from a set of predictor variables using binary recursive partitioning rules, which are based on thresholds in categorical or continuous predictor variables (Brieman et al., 1984; Steinberg and Cola, 1997). CART has some advantages over more conventional statistical methods: (i) there are no statistical distribution assumptions for dependent and independent variables; (ii) a mixture of categorical and continuous explanatory variables is allowed; (iii) it is not sensitive to outliers, multi-colinearity, heteroskedasticity, or distributional error structures that affect parametric methods; and (iv) it has ability to reveal variable interactions. The flexibility CART provides is well-suited to the problem in this study of uncovering the predictive structure of yield variability from diverse continuous and categorical variables, often having highly skewed distributions.

CART works by automatically searching through alternative values of a predictor variable that maximizes the quality of the split (separation) of the target variable into two 'child' nodes. The optimal splitting rules (e.g. if soil C concentration <1 g kg^{-1} then assign to left child node) are found using brute force search for all levels of all potential predictor variables. Once a best split is found, CART repeats the search process recursively for each child node, thereby creating a tree structure. CART grows very large trees and then prunes them back to an optimal sized tree based on relative error rates (misclassification error). Error rates are derived using cross-validation or hold-out validation. The trees consist of a number of intermediate, splitting nodes and a series of terminal nodes (TN) that represent homogeneous groups of observations in terms of the response variable (e.g. maize yield). The explanatory variables appear in the consecutive splitting nodes in a hierarchy of decreasing explanatory power. Literature and examples on the use of CART analysis in different branches of science can be found at: http\\www.salford-systems.com.

The CART analyses were performed using the subset of samples for which maize yields were available (n = 159). Maize yield variables (grain, biomass, grain yield per plant, biomass per plant) were used as the target variable in turn. In previous studies in this area environmental variables had less explanatory power than management variables (Tittonell et al., 2007). Therefore first management or agronomic practices were tested as explanatory variables together with general site and wealth characteristics, and in a second step soil data (spectral and wet chemistry) were added. Thus CART analyses were done using the following sets of candidate explanatory variables:

CART model 1: Maize yield = f (General, Management)
CART model 2: Maize yield = f (General, Management, Soil and landscape)

Where, 'General', 'Management', 'Soil and landscape' correspond to the groups of variables presented in Table 1. In setting up the analysis, all variables within these three categories are included as candidates and the program automatically chooses the ones with larger explanatory power. The categorical variables Site, Wealth and FSQC were included in all the analyses to account for differences in climate and/or other management-related differences that could have affected crop growth. CART default settings were used. The optimum tree, within one standard deviation of the minimum relative error, was selected using 10-fold cross validation. Further exploratory analysis was conducted by either further pruning (reducing the number of terminal nodes) or growing trees (increasing the number of terminal nodes). Of particular interest is the situation where a more parsimonious tree can be obtained with only small increase in relative error.

The data were first screened for outliers, and 8 out of 159 cases were omitted to avoid having terminal nodes with few observations. For example there were four samples with total soil N >2 g kg^{-1} that were often distinguished as a separate group by CART and associated with very high yields (>4 t ha^{-1}). Variables initially having marked asymmetrical distributions were also transformed into discrete classes to give relatively even distribution of numbers of observations within each class. Most fields sampled had slopes <5%, some between 5 and 20%, and fewer cases were observed between 20 and 50%. Due to this distribution pattern the continuous variable field slope was transformed into classes of flat (<2%), gently undulating (2 - 5%), sloping (5 – 20 or 25%) and steeply sloping (>25%). A similar regrouping was done for the scorings of resource use intensity (RUI) and *Striga* infestation level; for RUI, samples were reclassified into low (scores 0, 1) and high (scores 2, 3) intensity, whereas *Striga* infestation was expressed as "absence" (score 0) and "presence" (score 1-3).

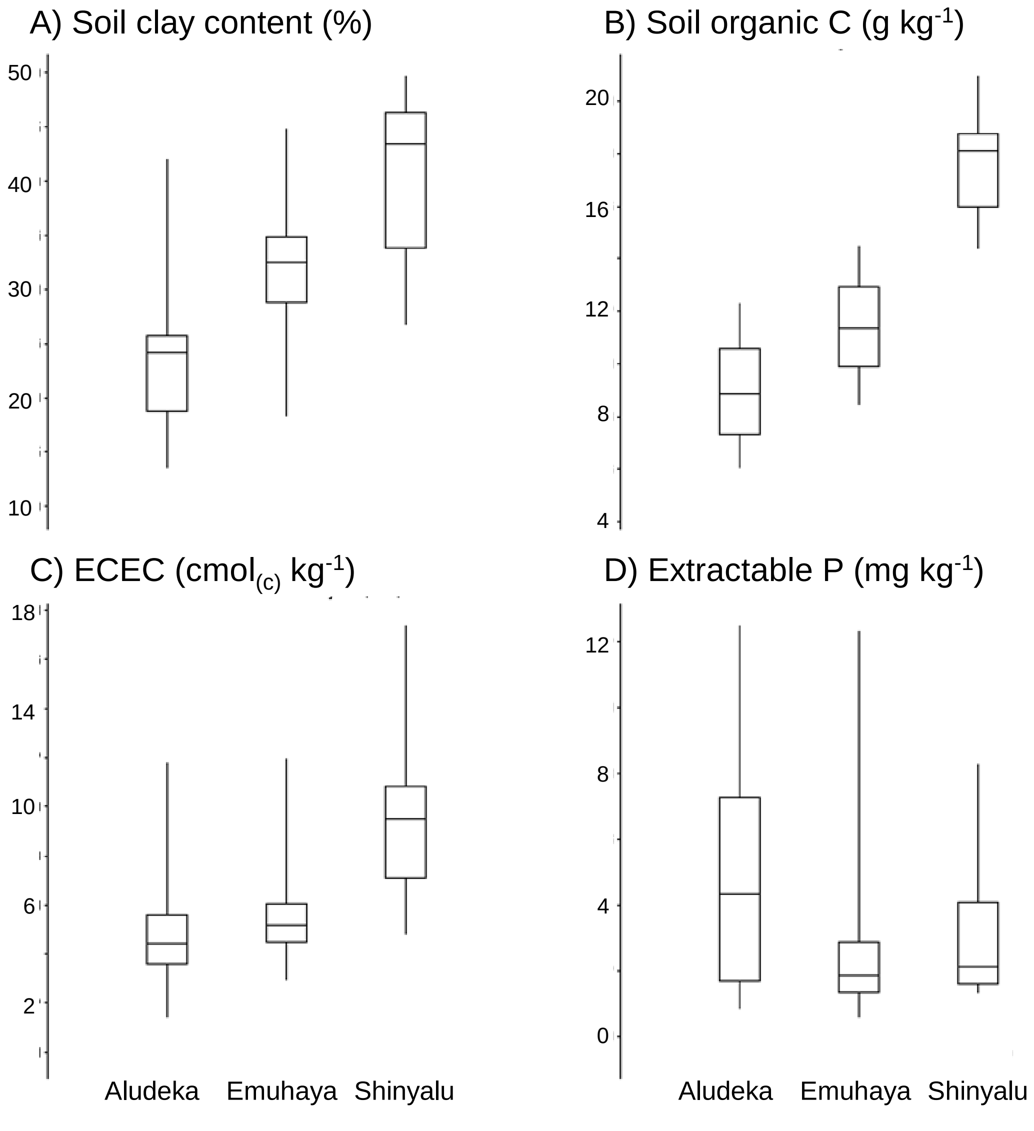

Figure 2: Range of variation of selected soil properties measured using standard wet chemistry methods across the three sites of western Kenya where the field samplings for maize yield and soil fertility were performed, Aludeka (Teso district), Emuhaya (Vihiga district) and Shinyalu (Kakamega district). The box-and-whisker diagrams include the range of 50% of the samples (rectangle), the median (cross bar) and the maximum and minimum values (extreme of the lines).

3. Results

3.1 Characterising soil quality and maize yield variability

Soil properties differed among sites, with Shinyalu having finer textured soils with greater soil C content and cation exchange capacity, and Aludeka having lowest fertility (Figure 2). Median extractable P concentrations were strongly deficient in Emuhaya and Shinyalu, at about 2 mg kg^{-1}. Aludeka had a higher median value (4 mg kg^{-1}) and a larger inter-quartile range than the other sites. In general, samples with high extractable P values (>12 mg kg^{-1}) were from fields close to the homesteads, where ash is commonly added to the soil (see also Tittonell et al., 2005 b,c). The spectral analysis was sufficiently sensitive to capture the variation in soil fertility between the different fields of individual farms, but because there are generally fewer samples with high nutrient levels available for calibration, spectral predictions tend to be poorest in the high range. As expected, different soil quality indicators showed covariation. For example, the samples with high predicted values for available P were also those with high predicted soil C content (Figure 3). All samples with available P above 4.5 mg kg^{-1} had soil C contents greater than 8.5 g kg^{-1} (equivalent to 1.5% of soil organic matter), and they correspond to the points in the zone I in the scatter plot of Figure 3. Points in the zones II and III of the graph constitute the most common cases, corresponding to samples with low available P values and either low or high soil C contents, respectively.

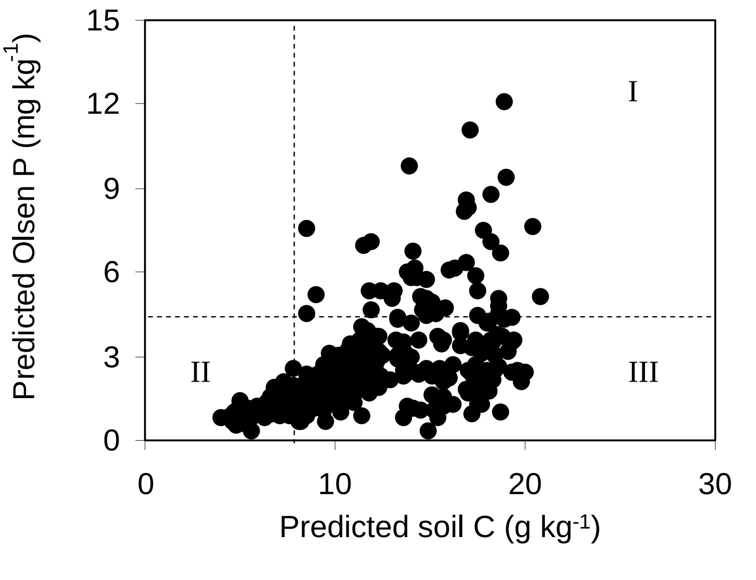

Figure 3: Spectral predictions of extractable (Olsen) phosphorus vs. predictions of organic carbon in the soils of all the fields sampled (*n* = 522). The dotted lines divide the scatter in three zones such that the observations in Zone I correspond to high extractable P (> 4.5 mg kg^{-1}) and high C (> c. 8.5 mg kg^{-1}); Zone II corresponds to low extractable P and low C; Zone III corresponds to low extractable P and high C. The P threshold corresponds to the values above which the spectral model showed a weaker predictive capacity; the C threshold is arbitrary, and was delineated to leave all samples above the P threshold to the right.

Although wide variation in grain yield was observed within each site, average maize grain yields were poorest in Aludeka ($P < 0.05$) (Figure 4). Only in Emuhaya, was there a consistent positive relationship between yield and resource endowment, but yields were least in the low resource endowment category at all three sites. Maize is both a food and a cash crop for MRE farmers in Emuhaia, who often grow it in the best soils of the farm (Tittonell et al., 2005b). Although each individual farmer classified their own soils as fertile to poor, using their own indicators, maize yields varied quite consistently between soil quality classes across sites (and farm types). The largest variability in maize yields was observed for the fields classified as poor, for which the coefficient of variation of the measured yields ranged between 70 to more than 100%. In general, the maize yields measured on the sampled farms were much lower than those achieved in on-station trials under controlled conditions (e.g. 6 – 7 t ha^{-1}; FURP, 1994), which are close to the potential yields for this agro-ecological zone in western Kenya.

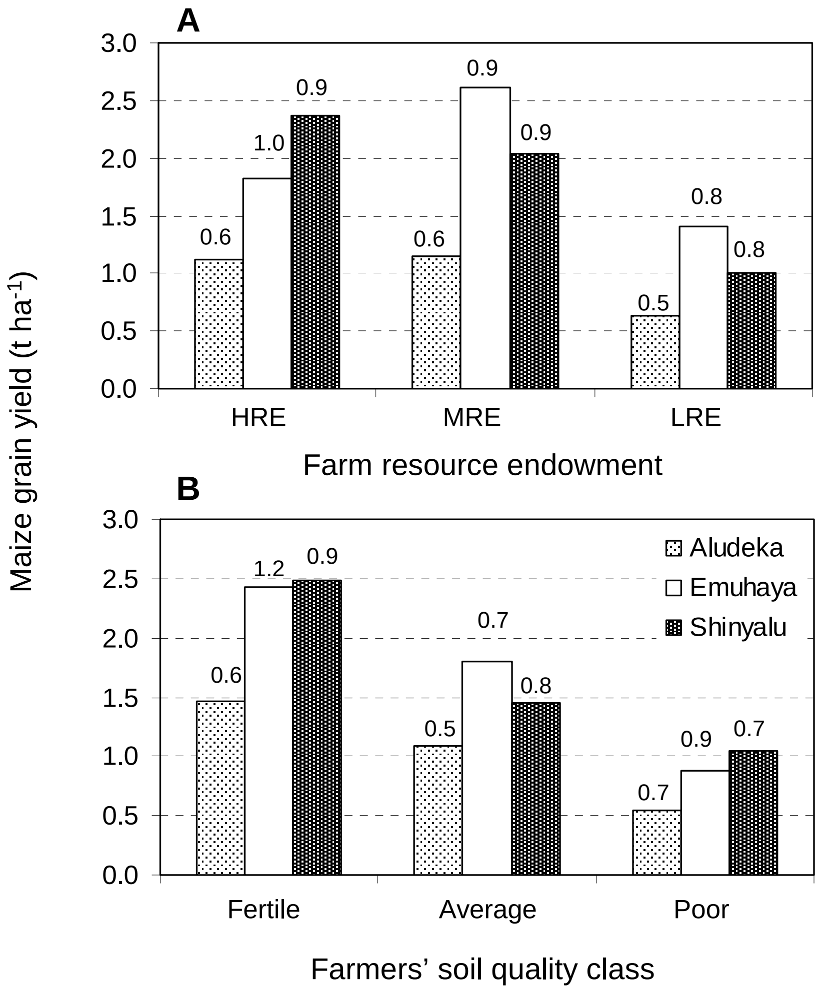

Figure 4: Variation of maize grain yields between farms of different resource endowment (A) and across different land qualities (fertile, average, poor) within the farm as perceived by the farmer (B), across the three sites in western Kenya selected for the study. HRE, MRE, LRE: high, medium and low resource endowment. Values on top of the bars indicate their standard deviation.

3.2 Explaining maize yield variability

3.2.1 CART model 1: agronomic practices

The optimum regression tree for maize grain yield as a function of management had eight terminal nodes (RE: 0.78) (Figure 5). Resource use intensity (RUI) was the primary splitting node: average yields were 1.3 t ha^{-1} at low RUI (values <1, i.e. no, few or insufficient input use) and 2.3 t ha^{-1} at high RUI. At the second level in the hierarchy, the splitting criteria were delay in planting and planting density. At Splitting Node 2, early planted crops (relative delay <= 0.053; *n* = 14) had an average maize grain yield of 2.1 t ha^{-1} (TN 1), which is a good yield for the on-farm conditions prevailing in western Kenya (Tittonell et al., 2005b), but late planted crops were the majority (*n* = 93) and gave smaller yields of average 1.2 t ha^{-1}. High weed infestation in this group further reduced yields to 0.5 t ha^{-1} (TN2).

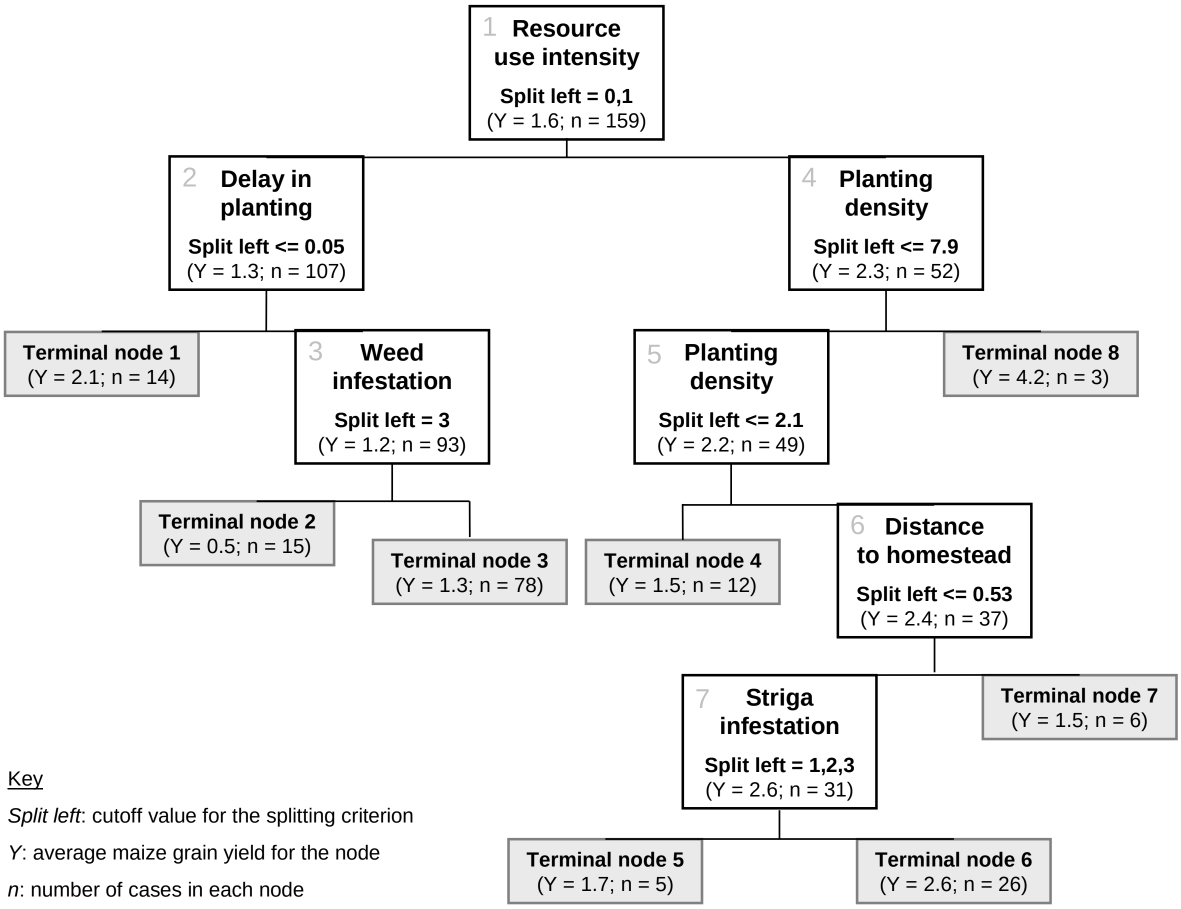

Figure 5: Classification and regression tree model to describe maize grain yield variability as a function of variables representing agronomic management decisions (cf. Table 1). White boxes are splitting nodes (SN) and grey boxes are terminal nodes (TN). Within each SN the following information is given: the variable that splits the group of observations in two 'child' nodes, its threshold value and classification criterion (e.g. for SN 4, split left <= 7.9 means that all values with plant density < or = 7.9 are grouped in SN 5, to the left), the average maize yield of each group (Y), and the number of observations in each group (n). For the TN, only the two latter are given.

With high RUI, low planting density (Splitting Node 4) halved yields compared with high planting density. However, the three high yielding fields with maize planted at high density (>7.9 plants m^{-2}; TN8) constitute exceptional cases. Small yields in crops with high RUI planted at low to moderate densities were additionally associated with fields distant from homesteads. For fields close to homesteads, heavy *Striga* infestation reduced yields by 40%. The low number of cases in TN7 and TN5 is due to the small number of cases in the data set where high resource intensities were observed in distant fields and where close fields, with medium or high resource use, were affected by *Striga*.

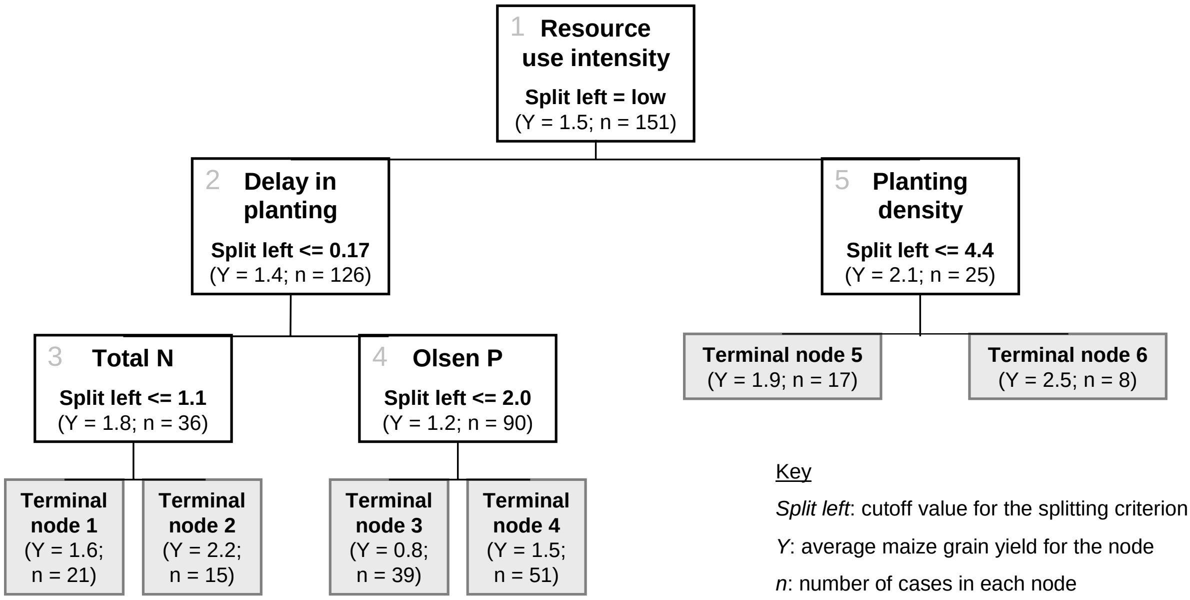

Figure 6: Classification and regression tree model to describe maize grain yield variability as a function of variables representing agronomic management decisions plus environmental variables (cf. Table 1). See Figure 5 for further explanation.

3.2.2 CART model 2: integrating agronomic and environmental factors

The full model including soil variables had similar higher level structure (top two levels) to the initial model that considered only agronomic practices (Figure 6), indicating that these were the dominant variables influencing yields. The relative error of the model (RE: 0.79) was not reduced with respect to CART model 1. At low RUI, early-planted crops had smaller average yields at low soil N (< 1.1 g kg^{-1}) than at high soil N; whereas late-planted crops had smaller yields at very low Olsen P (< 2 mg kg^{-1}) than at higher Olsen P concentrations. As in Model 1, at high RUI (right branch) denser crops (> 4.4 pl m^{-2}) performed better than sparser ones. The total soil N threshold of 1.1 g kg^{-1} is similar to the value used by Shepherd and Walsh (2002) to classify samples of an extensive library of African soils into soil quality classes. The splitting node 4 contained a large number of observations (*n* = 90). Such asymmetrical distribution of the observations, with the largest number of cases in TN 3 and TN 4 appeared to be realistic: late planted crops with low input use were the general case in the mid-distance to remote fields of the farms visited, and in those fields P availability tended to be low to extremely low. The larger number of observations with low P availability also stands out in Figure 3 (zones II and III of the scatter plot).

3.2.3 Site differences

The variable 'Site', which aggregated climatic variability, agro-ecological and socio-cultural diversity, was not selected by CART as an explanatory variable in the models, suggesting that site effects were accounted for by the management variables. However, there were some interesting trends in management x site interactions (Table 2a). For example, TN 1 (*n* = 21) had 14 cases from Aludeka, 5 from Emuhaya and 2 from Shinyalu. The splitting node 3 (*n* = 36) represents fields that were planted early, such as the home gardens, but cropped without nutrient inputs (particularly without manure). This is consistent with previous observations, as manure use is restricted in Aludeka as compared with the other sites for several reasons (i.e. a free grazing system that makes manure collection difficult, lack of knowledge on composting, small cattle population due to high incidence of tripanosomiasis). TN 1 is comprised of home gardens that are poor in total soil N; this is more common in Aludeka, as most of the home gardens (the fields around the homestead) from Emuhaya and Shinyalu fell in the strata of the right-hand branch, high resource use intensity and soils that are consequently more fertile.

Table 2: Distribution of observations falling: *a)* within the classes identified by CART across sites, and b) correspondence between classes distinguished exclusively by management with the perception of soil fertility by farmers

***a*)**

Site (*n*)	Maize yield ($t\ ha^{-1}$)	Number of observations per node					
		TN1	TN2	TN3	TN4	TN5	TN6
Aludeka (48)	1.1 ±0.6	14	1	20	11	2	0
Emuhaya (52)	1.7 ±0.9	5	5	13	18	8	3
Shinyalu (51)	1.6 ±0.9	2	9	6	22	7	5

***b*)**

Management class	CART Node	Fertile fields (%)	Average fields (%)	Poor fields (%)
Low resource use				
Planting early	SN3	28	28	9
Planting late	SN4	51	54	85
High resource use				
Sparser crops	TN5	18	10	3
Denser crops	TN6	4	8	3

SN: splitting node; TN: terminal node

Table 3: Average soil properties of the fields within each terminal node of CART model 2 (Figure 6)

Criteria	Terminal node	Clay + silt (%)	SOC (g kg^{-1})	TSN (g kg^{-1})	Olsen-P (mg kg^{-1})	Exch. K+ (cmol kg^{-1})	ECEC (cmol kg^{-1})	pH water (1:2.5)	Field slope (%)
Low resource use									
Early planting									
TSN > 1.1 g kg^{-1}	1	49 +/- 5	10.3 +/-1.8	0.7 +/-0.2	2.2 +/-0.6	0.35 +/-0.3	4.9 +/-0.9	5.6 +/-0.4	4 +/- 5
TSN > 1.1 g kg^{-1}	2	67 +/-11	15.2 +/-3.3	1.4 +/-0.2	3.9 +/-2.5	0.38 +/-0.2	8.4 +/-2.5	5.6 +/-0.5	7 +/- 4
Late planting									
Olsen-P < 2.0 mg kg^{-1}	3	47 +/-13	9.1 +/-3.1	0.6 +/-0.4	1.4 +/-0.4	0.18 +/-0.1	4.0 +/-2.5	5.2 +/-0.4	10 +/-14
Olsen-P > 2.0 mg kg^{-1}	4	60 +/-14	13.1 +/-3.7	1.0 +/-0.6	3.1 +/-1.3	0.30 +/-0.3	7.3 +/-3.0	5.5 +/-0.4	8 +/-10
High resource use									
Sparser crops	5	56 +/-14	13.3 +/-3.8	1.1 +/-0.4	3.3 +/-1.5	0.24 +/-0.2	6.9 +/-3.2	5.6 +/-0.5	5 +/-5
Denser crops	6	63 +/-11	14.6 +/-3.0	1.2 +/-0.3	3.5 +/-1.2	0.16 +/-0.1	7.3 +/-2.3	5.3 +/-0.5	8 +/-8
Standard error of the difference		4.6	1.23	0.17	0.39	0.09	1.00	0.15	3.6
P <		0.001	0.001	0.001	0.001	0.014	0.001	0.001	Ns

SOC: Soil organic carbon; TSN: total soil nitrogen; Olsen-P: extractable phosphorus; Exch. K+: exchangeable potassium; ECEC: effective cation exchange capacity

Table 4: Average values of several crop management variables for each of the terminal nodes in CART model 2 (Figure 6).

Criteria	Terminal node	Distance to homestead[1]	Resource use intensity[2]	Delay in planting (d)	Plant density (pl. m^{-2})	Weed infestation level[3]	*Striga* infestation level[3]
Low resource use							
Early planting							
TSN < 1.1 g kg^{-1}	1	0.34	0.5	3	3.0	1.1	0.3
TSN > 1.1 g kg^{-1}	2	0.46	0.6	5	2.9	1.1	0.0
Late planting							
Olsen-P < 2.0 mg kg^{-1}	3	0.51	0.3	32	2.5	1.8	0.6
Olsen-P > 2.0 mg kg^{-1}	4	0.54	0.4	27	3.2	1.3	0.2
High resource use							
Sparser crops	5	0.33	2.4	10	3.4	1.1	0.4
Denser crops	6	0.41	2.4	19	5.6	0.8	0.1
Standard error of the difference		0.09	0.19	4.1	0.54	0.33	0.26
P <		0.005	0.001	0.001	0.001	0.005	0.008

[1] Expressed in relative terms (distance to the homestead / maximum distance within the farm – cf. Table1).
[2] Average values for the score: 0, no use to 3, high use intensity.
[3] Average values for the score: 0, no infestation to 3, high infestation.

3.2.4. Farmers' perception of soil fertility

The observations stratified using CART analysis were cross-checked with the perception of soil quality of the farmers (Table 2b). More than 50% of the fields that were cropped with high resource use intensity were perceived by farmers to be fertile at the three sites, and most of the fields perceived to be poor were planted late with few or no nutrient inputs. Average maize yields (Figure 7), soil fertility (Table 3) and agronomic management (Table 4) indicators were calculated for each stratum. The yields corresponding to different strata were consistent across sites except for the fields within TN 2 (corresponding to fields planted early, cropped with no or few inputs and having total soil N > 1.1 g kg^{-1}) (Figure 7 B). Fields cultivated with high resource use intensity and planted with denser crop stands (TN 6) were present only in Emuhaya and Shinyalu (cf. Table 2a). They had less weed infestation and were located at intermediate distances from the homestead (Table 4). The poorest fields corresponded to TN 3, with the lowest yields across sites, the smallest values for most soil fertility indicators, a less intense management, and a higher frequency of cases from Aludeka.

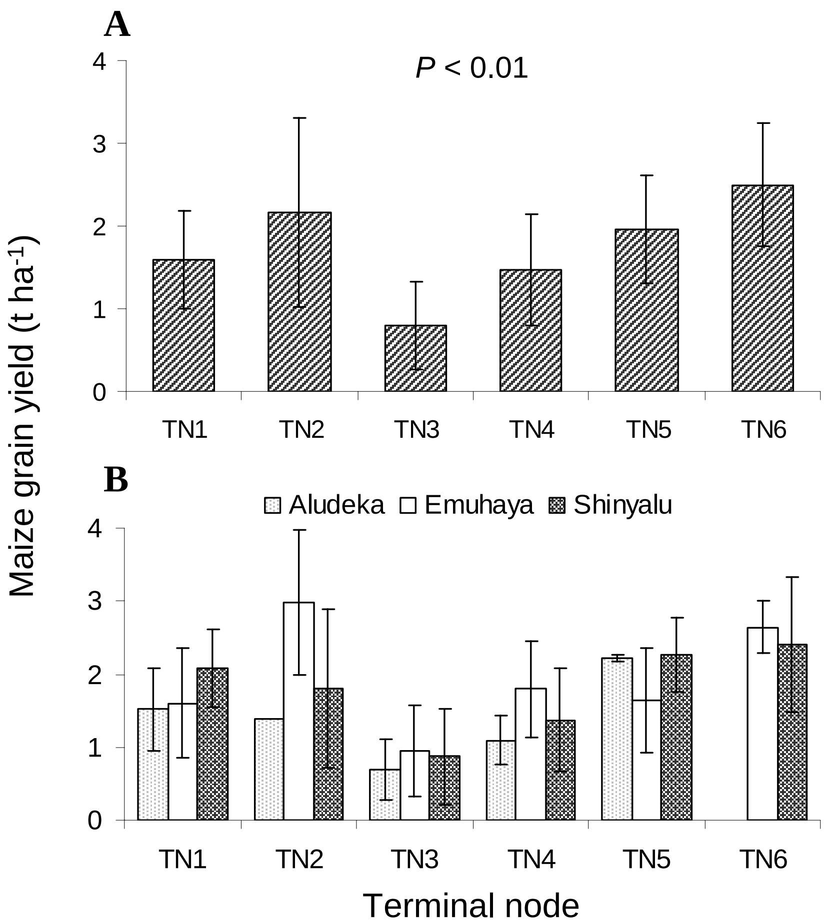

Figure 7: Average and standard deviation of maize grain yields for each of the terminal nodes (TN1 to TN6) from the classification and regression tree model of Figure 6 (A), and the average and standard deviation for each TN discriminating by site (B). Lettering on top of the bars in (A) indicates the statistical significance of the differences between means (P < 0.01).

3.3 Targeting fields with different soil qualities

To target technology recommendations to soil fertility problem domains that farmers recognise and manage differently, it is necessary to identify recognisable thresholds of soil indicators. Soil C and available P are comprehensive indicators that varied quite independently from one field to another for the lower range of extractable P values (cf. PCA results – Section 2.3; cf. also Figure 3), to which the majority of the soils sampled belong (cf. Splitting Node 4 in Figure 6). Plotting maize grain yield against C and P, and discriminating the observations that belong to the different CART strata, showed that the use of only these soil properties is insufficient to characterise yield variability within farms (Figure 8). The variation in yields as affected by these soil properties is best characterised by boundary line relationships. To illustrate this, the dotted lines in Figure 8 are simply 'hand-drawn' boundary lines considering only the observations in TN 3 and TN 4, which constitute the majority of the observations and are also those that are of most interest for targeting agronomic research. For low values of both soil C and available P, maize yields were invariably low, while for higher values of these soil indicators yields may be high or low, depending on other factors (chiefly management factors). In particular, yield limitation by very low P availability when extractable P < 2 mg kg^{-1} appeared very clearly. The upper yield level achieved in fields belonging to TN 3 and TN 4 (ca. 3 t ha^{-1}) may also be the result of factors that were unaccounted for in this study, such as the maize genotype.

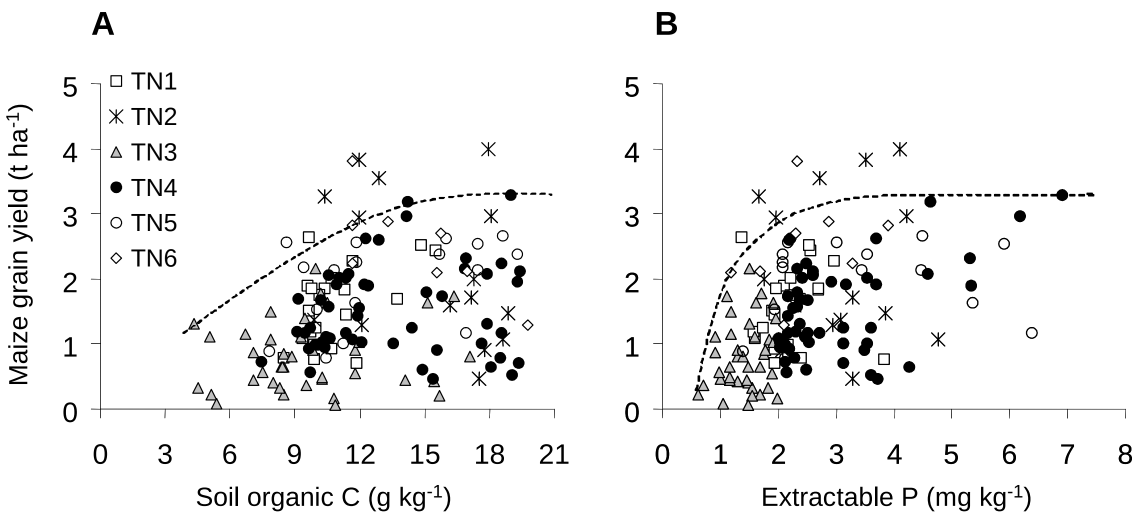

Figure 8: Maize grain yield as a function of soil C (A) and extractable P (B). Different symbols indicate observations that were classified within different terminal nodes (TN1 to TN6) in the CART analysis. The dotted lines were 'hand drawn' to represent the upper boundary of the observations corresponding to TN3 and TN4. Soil data correspond to spectral predictions.

4. Discussion

4.1 Explaining variability in crop growth

Crop growth performance is often assumed to be the first visual indication of the existence of spatial variability in soil fertility status within smallholder farms. However, soil fertility variables were subservient to crop management variables in the optimal CART model (cf. Figure 6) and were only important at low levels of resource use intensity. Farmers appear to give priority to crop and soil management in the fields within their farms that they perceived to be fertile. Although farmers' management strategies can be proactive in some situations (Tabu et al., 2005), in this study farmers appeared to follow a reactive strategy (i.e. based on predetermined soil fertility). Thus soil heterogeneity determines crop yield variability not only through water or nutrient limitations, but also by influencing farmers' management decisions, which in turn feedback to reinforce the soil fertility patterns within farms.

The results of CART model 1 (Figure 5) were in agreement with common field observations. First, when no or few resources are used, reasonably good yields can be produced if the crops are planted early on relatively good soils; in western Kenya, the first fields to be planted with maize are the home gardens, where maize cobs for roasting can be harvested early. The home gardens are often zones of nutrient concentration within the farm. Second, when nutrient inputs are used, the density of the crop stand becomes critical in determining maize yield (crop architecture). Farmers often adjust crop density to the perceived fertility of their soils, as seen in other areas of Africa (e.g. Mutsaers et al., 1995). Third, crops planted in distant fields normally produce poor yields even when nutrients are used, due to the poor soil quality of those fields, leading to weak crop responses to input use (cf. Wopereis et al., 2006). Fourth, *Striga* infestation is a more important factor that reduces yields of crops that receive nutrient inputs and are planted in close fields, compared with poor crops grown in remote fields, despite the greater prevalence of *Striga* in remote fields.

The observations grouped in TN 3 and TN4 of CART model 2 (Figure 6) were the most numerous and corresponded to fields cropped with few or no inputs, planted late (up to one month later than the recommended planting dates – Table 4) and at large relative distances from the homestead (RDH) > 0.5. Yields in the TN 3 and TN 4 ranged around 1 t ha^{-1} – an average reference yield for the highlands of East Africa (e.g. Mugendi et al., 1999) but well below the maximum yields attained in controlled experiments in western Kenya (FURP, 1994). TN 3 grouped maize yield observations corresponding to values of extractable P in the soil < 2 mg kg^{-1}; such soils tended to be also poor in organic C (Figure 8). An extractable (Olsen) P value of 2 mg kg^{-1} may be considered a threshold between 'extremely poor' and 'poor' soils in terms of P availability (Young, 1997) – note in Figure 8 that some grain yields corresponding to TN 3 were almost nil. Vanlauwe et al. (2006) derived a threshold of 7 mg kg^{-1}

extractable P for maize responses to applied P in western Kenya. However, the relative response to P in fields with less than 7 mg g^{-1} P in that study varied from 0.2 to 1.2. Such variability cannot be ascribed only to P availability but to the existence of multiple-limiting factors operating simultaneously.

The terminal nodes from the CART analysis define problem domains to which specific intervention strategies can be targeted. For example, the yield gap between TN 5 and TN 6 could be simply bridged by improved agronomy (i.e., establishing proper plant stands in this case), whereas TN 3 and TN 4 would require major soil rehabilitation including addition of P and organic matter. These results, however, may be affected by climatic variability. Although the amount of rainfall registered during the long rains of 2002 was close to the average value for each site (i.e. neither drought nor excess rainfall were registered), inter-annual rainfall variability may affect not only the average maize yields but also the relative influences of the various factors determining maize productivity. The regional variation in average rainfall is also closely related to the variation in soil types across sites (cf. Figure 2). Finer soil textures in a cooler and wetter climate lead to greater contents of organic C in the soils in Shinyalu, where all fields had values > 14 g kg^{-1}, notably larger than all fields from the other two sites. Although this does not necessarily translate into larger average yields (cf. Figure 4), most of the observations in the highest yielding groups TN 2 and TN 6 were from Shinyalu (Figure 7, Table 2a). These observations correspond to home fields managed with (TN 6) or without (TN 2) inputs, but with (relatively) fertile soils (cf. Table 3).

4.2 Reconciling soil quality categories with local knowledge

Farmers' perception of soil quality 'niches' cannot be reconciled directly with the usual indicators of soil fertility such as soil C and nutrient contents (cf. Table 3, Figure 7), despite methodologies designed to support this approach (e.g. Barrios et al., 2001). In the first place, because of the co-existence of multiple nutrient limitations, farmers perceive soils as having low or high productivity regardless of their main limitation; the concept of limiting nutrients for plant growth appears too abstract to farmers (Tittonell et al., 2005 d). During our field assessments, farmers had a more holistic definition of 'suitability niches' to which they allocated their production activities and resources within their farms. Suitability not only considers soil fertility but also other field characteristics such as soil depth, proximity to woodlots (shading), type of fencing to protect the crop from roaming livestock, the slope and the relative position of the field within the farm; i.e. crops grown in remote fields are more prone to theft. In this sense, the definition of the variable 'relative distance to homestead' (RDH) as a 'management' factor in the CART analysis may be questionable. In the heavily-dissected landscape of western Kenya, the slope of the fields tends to increase with increasing distance from the homestead and soil types naturally vary for fields located at different positions in the catena (Tittonell et al., 2005c). At the same time, the effort to carry bulky materials such as manure or compost to fertilise crops planted far from the homestead is even larger due to the steep slope of these fields. Thus, the interrelationship ‘distance from the homestead – soil management – current soil fertility’ is complex in the farms of western Kenya. Although the categorisation of field types according to their location within the farm (e.g. close vs. remote fields) may be practical for certain studies, its arbitrariness makes it less useful to communicate with farmers when attempting to target recommendations.

4.3 CART analysis

CART analysis allowed us to: (i) unravel interactions and combined effects in a complex dataset; (ii) identify thresholds in the relationship between maize yield and different soil and management variables; and (iii) define problem domains for targeting different intervention strategies. The approach provided insight into the structure of interrelationships within the dataset more easily than if multiple regression modelling had been used, and obviated the need for data transformations and use of dummy variables to satisfy assumptions required by parametric approaches. The in-built cross-validation routine helped to ensure only robust predictive models were selected. Although some subjective decisions were required, such as defining cut-off values for dividing variables into discrete classes, and defining the acceptable error in the final model, these decisions are also required with more conventional statistical modelling approaches: they should be made explicit. Alternative models that provide a similar degree of predictive power (i.e. relative error) could also be explored to increase insights into yield limiting factors.

5. Summary and conclusions

Soil fertility variability within smallholder farms determines farmers’ management strategies and resource allocation among farm fields, with more nutrients, labour and other inputs being apportioned to the most fertile fields. Over time these resource allocation patterns feed back to positively reinforce the spatial variation in soil fertility. In our study, fields that were considered by farmers as poor in fertility (which were invariably low in soil extractable P) were managed with few or no inputs and planted late. These fields represent the majority of the farming area in western Kenya and need to be targeted with major rehabilitation strategies to improve land productivity and rural livelihoods. Such rehabilitation strategies will not, however, translate into improved crop productivity unless accompanied by improvements in agronomic practices, such as planting density and timeliness of planting and weeding. Farmers already apply more inputs to their most fertile fields for which only soil fertility maintenance strategies are required. Use of CART in relation with systematic surveys of agronomic practice provided a useful approach for analysing crop production constraints and targeting of intervention strategies. This approach could be adapted to provide a tool for monitoring the impact of intervention programmes designed to improve farm productivity.

Chapter 5

Effect of soil variability on resource use efficiency and crop responses to applied nutrients†

† Adapted from:

Tittonell, P. Vanlauwe, B., Corbeels, M., Giller, K.E., 2007. Farm heterogeneity, nutrient use efficiencies and crop responses to mineral fertilisers: narrowing the gap between attainable and current maize productivity on smallholder farms in western Kenya. Plant and Soil, submitted.

Abstract

The need to promote fertiliser use by African smallholder farmers to counteract the current decline in per capita food production is widely recognised. However, soil heterogeneity generates variable responses of crops to fertilisers due to variability in resource use efficiency within single farms. We used existing databases on maize production under farmer (F-M) and researcher management (R-M) to analyse the effect of soil heterogeneity on the different components of nutrient use efficiency by maize grown by smallholders in western Kenya: nutrient availability, capture and conversion efficiencies. Subsequently, we used the simple model QUEFTS to calculate attainable yields with and without fertilisers based on measured soil properties across heterogeneous farms. The yield gap of maize between F-M and R-M varied from 0.5 to 3 t grain ha^{-1} $season^{-1}$ across field types and localities, and was not only caused by soil fertility; poor fields under R-M yielded better than F-M, even without fertilisers. Such differences, of up to 1.1 t ha^{-1} greater yields under R-M conditions are attributable to improved agronomic management and germplasm. The relative response of maize to N-P-K fertilisers tended to decrease with increasing soil quality (soil C and extractable P), from a maximum of 4.4-fold to –0.5-fold relative to the control. Soil organic C and soil P availability exhibited co-variability in the most and least fertile fields of the farms due to long-term organic matter management by farmers; P availabilities > 10 mg kg^{-1} were only measured in soils with > 10 g kg^{-1} organic C. Calculated N, P and K availabilities from their current content in the soil indicate that P is the most limiting nutrient across sites and farms. Soil heterogeneity affected resource use efficiencies mainly through effects on the efficiency of resource capture (e.g., recovery efficiencies varied between 0 and 70% for N, 0 and 15% for P, and 0 to 52% for K), with less variation in the resource conversion efficiency (with average values of 97 kg DM kg^{-1} N, 558 kg DM kg^{-1} P and 111 kg DM kg^{-1} K taken up). Using measured soil chemical properties QUEFTS over-estimated observed yields under F-M indicating that variable crop performance within and across farms cannot be solely ascribed to soil nutrient availability. For the R-M plots QUEFTS predicted positive crop responses for a wide range of soil qualities, indicating that there is room to improve current crop productivity through fertiliser use. However, the promotion of mineral fertiliser use in sub-Saharan Africa should go hand-in-hand with the implementation of measures to improve fertiliser use efficiency.
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Keywords: Sub-Saharan Africa; QUEFTS model; N use efficiency; P use efficiency; Resource use efficiency; Soil fertility gradients

1. Introduction

Afrique – "Le développement ne se fera pas sans engrais" (Africa – "Development will not be achieved without fertilisers" – Le Courrier International on April 14 2006, quoting an African political leader prior to the Africa Fertiliser Summit held in June 2006 in Abuja, Nigeria). There is increasing agreement among the research, development and donor communities on the need to facilitate farmers' access to mineral fertilisers to improve agricultural productivity in sub-Saharan Africa. Fertilizers are regarded to be essential to tackle land degradation and food insecurity in densely-populated regions such as western Kenya, where small landholdings prevent the practice of fallow to replenish soil fertility, and lack of communal rangeland limits the inflow of nutrients through livestock into the farm system. Currently, crop production in the region is strongly limited by soil N and P availability and the gap between the actual and the attainable yield of maize, the major crop in the area, may be as wide as 5 t grain ha^{-1} $year^{-1}$ (Tittonell et al., 2007a). However, mineral fertilisers represent an important investment for farmers, particularly in remote areas with limited access to input markets - in Kenya transport costs often double the price of fertilisers in rural areas (IFDC, 2003). From both economic and environmental viewpoints, mineral fertilisers should be targeted strategically within the cropping systems to ensure efficient nutrient recovery and conversion into crop biomass and yield.

The use of mineral fertilisers in much of sub-Saharan Africa has been promoted through 'blanket recommendations', i.e., recommendations based on regional soil surveying or on agroecological zoning that are specific for a given crop and area or soil type. (e.g. FURP, 1994; Benson, 1997). A major constraint to this approach is the fact that in many areas smallholder farms are spatially heterogeneous in terms of soil quality, and thus the potential effect of applied nutrients may vary dramatically from field to field (as well as from season to season). Evidence for this variability between fields has been presented for cereal and legume crops in East (Vanlauwe et al., 2006), West (Wopereis et al., 2006) and Southern Africa (Zingore et al., 2007b). These studies highlighted important differences in nutrient recoveries from applied fertilisers between the various fields of individual farms, stressing the need to consider this heterogeneity when deriving fertiliser recommendation domains. But how does farm heterogeneity specifically affect fertiliser use efficiency?

Farm heterogeneity results from the inherent variation in soil types on the landscape plus the effect of historical land use and management practices in different fields within the farm. Reinforcing this variability, farmers often prioritise resource and labour allocation to their best yielding fields; hence fields with better soils are planted earlier, weeded more frequently, and cultivated with improved seeds and nutrient inputs (Tittonell et al., 2007a). Biophysical and managerial factors and their interaction at farm scale affect both components of resource use efficiency – capture efficiency and conversion efficiency – thus determining the yield gap between current maize yields obtained by smallholder farmers and attainable yields as attained under well-controlled conditions (e.g. in research plots). The factors that determine this yield gap affect also the response to fertilisers. Comparing farmer- and researcher-managed crops may give ,(Vanlauwe et al., 2006) therefore, a first indication of how management within smallholder farms influences yield gaps and what may be the room of manoeuvre to improve utilisation of nutrients at various levels of their availability. The hypothesis of this study is that the small amounts of mineral fertilisers that farmers can access should be targeted to niches of high crop responsiveness within heterogeneous farms.

Our objective was to analyse: (i) the impact of soil heterogeneity on the components of crop productivity and nutrient use efficiency that determine crop responses to N-P-K mineral fertiliser applications; and (ii) the expected response of maize to mineral fertilisers on the basis of soil fertility indicators. We focused on the major nutrient resources for crop production, N, P and K (water and other nutrients were not explicitly considered). The components of nutrient use efficiency analysed were thus: N, P and K availability, capture and conversion efficiency. We examined the range of variability in the values of these components within individual farms and across localities by re-analysing existing datasets from on-farm surveys and experiments in western Kenya. We used the model 'Quantitative Evaluation of the Fertility of Tropical Soils' (QUEFTS – Janssen et al., 1990) to predict crop yields from information on actual soil fertility and recovery fractions of applied nutrients. QUEFTS is a simple and robust tool, relatively undemanding of data, that has been applied to the evaluation of fertiliser requirements in the tropics (e.g. Witt et al., 1999; Pathak et al., 2003). Predicted yields using QUEFTS are an indication of attainable yields given the nutrient availability from soil and fertilisers. We analysed variability in nutrient use efficiency and crop responses to fertilisers by calculating the extent to which maize yields predicted from soil nutrient availability using QUEFTS deviated from those measured on-farm (from either farmer- or researcher-managed plots).

2. Materials and methods

2.1 System characterisation and analytical approach

The western Kenya region is one of the most densely populated areas of sub-Saharan Africa, due to large initial human settlements that were attracted by its high agroecological potential for crop production: a bimodal rainfall regime and relatively deep soils dominated by clay and loam textures, which were inherently fertile. Yet, there is ample sub-regional variability in rainfall/evapotranspiration regimes and soil-landscape types across western Kenya. The datasets that we used in this study included three sites in western Kenya: Aludeka division in Teso district (0° 35' N; 34° 19' E), Emuhaia division in Vihiga district (0° 4’ N; 34° 38’ E) and Shinyalu division in Kakamega district (0° 12’ N; 34° 48’ E). Gradients in altitude, rainfall, topography and soil types as well as differences in population density, ethnic groups, and access to markets and land use were observed between these sites, which encompass much of the variability found in the region (Table 1).

Table 1 Key characteristics for the three sites selected to represent the socio-economic and biophysical variability of western Kenya

	Locality		
	Aludeka	Emuhaia	Shinyalu
Agroecological zone*	*LM2*: lower midland sugar cane zone; altitude: 1180 m; mean annual temperature: 22.2 C; annual rainfall: 1460 mm (bimodal)	*UM1*: upper midland tea-coffee zone; altitude: 1640 m; mean annual temperature: 20.4 C; annual rainfall: 1850 mm (bimodal)	*UM1*: upper midland tea-coffee zone; altitude: 1820 m; mean annual temperature: 20.8 C; annual rainfall: 2150 mm (bimodal)
Topography and soil types	Slopes 2 – 5%; Acrisols (petroferric phase), Luvixols, Lixisols, Vertisols.	Slopes 2 – 15%; Nito-humic Ferralsol and dystro-mollic Nitisol (acidic phase)	Slopes up to 45%; Humic Nitosols and dystro-mollic Nitosols (acidic phase)
Socioeconomic and land use aspects	Relatively sparsely populated (310 inh. km^{-2}); limited access to urban markets, marginal rural markets; Main crops: maize, cassava, sorghum and finger millet	Highly densely populated (930 inh. km^{-2}); moderate access to urban markets, important rural markets; Main crops: Maize/beans, banana, sweet potato, local vegetables	Densely populated (650 inh. km^{-2}); limited access to urban markets, important rural markets; Main crops: Maize/beans, fruit trees, sweet potato, local vegetables

*According to the agroecological zoning of Kenya by Jaetzold and Schmidt (1982)

In conducting our analysis, we conceptualised crop productivity as resulting from the availability of biophysical resources such as light, water and nutrients, the ability of the crop to capture these resources and its capacity to convert them into biomass and grain yield, i.e.:

Crop productivity = Resource availability × Resource capture × Resource conversion efficiency

where, resource capture efficiency represents the fraction of the total resource available that is intercepted/taken up by the crop, while the conversion efficiency represents biomass production per unit of resource taken up. For a given resource R the units are: $[kg\ dry\ matter\ ha^{-1}] = [kg\ R\ ha^{-1}] \times [kg\ R_{available}\ kg^{-1}\ R_{taken\text{-}up}] \times [kg\ dry\ matter\ kg^{-1}\ R_{taken\text{-}up}]$. The partitioning of the total crop biomass towards harvestable crop parts may be considered as an intrinsic component of the conversion efficiency (e.g. Trenbath, 1986). Here, we considered the *Harvest index* as a separate component of crop productivity (expressed in grain yield units). Both soil properties and agronomic management or decisions on resource allocation may affect, individually or simultaneously, each of the above crop productivity components. Focusing on nutrient resources, we analysed the impact of biophysical and management factors on crop productivity and its different components by re-analysing two existing datasets: (i) one dataset comprised maize yields, management variables and soil properties from farmer-managed (F-M) fields on 60 farms across the three sites mentioned above (Tittonell et al., 2005c), and (ii) the other contained data from on-farm researcher-managed (R-M) experiments which were conducted to evaluate maize responses to N-P-K fertiliser applications in the same localities (and farms) (Vanlauwe et al., 2006). We used the model QUEFTS to calculate expected yields under different N, P and K fertiliser regimes and examine the variability in crop responses to fertilisers that is caused exclusively by the availability of nutrients in the soil and their interactions.

2.2 Datasets

2.2.1 Soil fertility and maize yields under farmer management (F-M)

We selected 20 case-study farms per locality (Table 1), encompassing the socio-economic diversity of households, from a farm survey conducted during the long rains season of 2002. We walked through each farm along a transect together with the farmer and discussed each field in turn, aided by a map of the farm drawn by him/her. Focusing on maize, we recorded the cultivar(s), the type and amount of inputs used, the timing and sequential order of crop and soil management activities within the farm, the average yields obtained, weed infestation, and general crop husbandry practices (e.g. plant density). Maize yields were estimated on-farm by non-destructive plant morphological measurements, using allometric models described by Tittonell et al. (2005a). Topsoil (0 – 15 and 0 – 30 cm) samples were taken from all geo-referenced fields where maize yields were estimated; samples were air-dried, sieved through 2 mm, stored at room temperature, and analysed for particle size distribution, organic C, total N, extractable P (Olsen), exchangeable K^+, Ca^{2+}, Mg^{2+} and H^+ using standard methods for tropical soils (Anderson and Ingram, 1993). In total 159 observation points were generated containing maize yield, management factors and soil fertility data (Tittonell et al., 2007c). They are referred to as the farmer-managed (F-M) plots.

2.2.2 On-farm maize response to fertilisers under researcher management (R-M)

At each locality, six farms were chosen out of the surveyed sample of farms (cf. Section 2.2.1) to include farmers from different social status or resource endowment (two with respectively high, medium, and low access to resources) and gender. In each farm, 3 fields were chosen at different distances to the homestead (homefields, midfields, outfields), based on the results of resource flow analysis that revealed different patterns of resource allocation in those fields. Farmers’ opinions on the soil fertility status of the different fields were also solicited during the selection of the fields. In each of the fields, 5 treatments were laid out on plots of 4.5 × 2.25 m, following a one-farm, one-replicate design: a no-input control, a fully fertilized treatment (100 kg N ha^{-1}, 100 kg P ha^{-1}, and 100 kg K ha^{-1}), and three treatments with one of the major nutrients (N, P, or K) missing. These are referred to as the researcher-managed (R-M) plots. The experiment was conducted during the short rains of 2002; a hybrid maize cultivar HB513 (mid-maturing type) was grown, receiving fertiliser as urea, triple super phosphate, and muriate of potash. Topsoil (0 - 15 cm) samples were taken with an auger at eight sampling points (4 on each diagonal) per field from the three fields chosen within each farm, and analysed following standard methods (Anderson and Ingram, 1993). A summary of the soil characteristics across locations and field types is presented in Table 2. Maize was harvested about 15 weeks after planting; fresh and dry weights of and N, P and K contents in different plant parts were determined. Further details on this dataset were reported by Vanlauwe et al. (2006).

Table 2 Average soil properties and their range of variation measured on the experimental plots laid out on farmers' fields (R-M plots - Section 2.2.2)

Locality/ position within the farms	Soil Organic C ($g\ kg^{-1}$)		Total Soil N ($g\ kg^{-1}$)		Extractable P ($mg\ kg^{-1}$)		Exchangeable K ($cmol_{(+)}\ kg^{-1}$)	
Aludeka								
Homefields	10.9	(9.6-12.2)	0.9	(0.6-1.4)	12.0	(1.9-26.3)	0.79	(0.16-1.76)
Midfields	6.6	(5.8-7.6)	0.6	(0.5-0.7)	3.2	(1.2-6.0)	0.32	(0.12-0.47)
Outfields	6.7	(4.5-7.6)	0.6	(0.4-0.8)	2.8	(1.3-6.8)	0.30	(0.13-0.75)
Emuhaya								
Homefields	17.4	(12.2-25.5)	1.3	(0.9-1.6)	11.1	(2.8-29.4)	0.60	(0.15-1.96)
Midfields	12.8	(8.9-16.4)	1.2	(0.8-1.5)	4.8	(2.1-8.9)	0.62	(0.07-2.16)
Outfields	11.7	(7.5-15.1)	1.1	(0.9-1.4)	1.7	(0.6-2.2)	0.22	(0.06-0.59)
Shinyalu								
Homefields	19.6	(16.9-24.0)	1.7	(1.5-1.9)	10.0	(2.6-26.4)	0.41	(0.18-0.63)
Midfields	17.2	(13.6-21.0)	1.6	(1.2-1.9)	3.8	(1.9-7.3)	0.47	(0.08-1.05)
Outfields	16.2	(13.5-18.4)	1.5	(1.2-1.7)	2.5	(1.6-4.3)	0.24	(0.10-0.46)

2.3 The model QUEFTS

2.4.1 Overview

The model for QUantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) was developed and calibrated to estimate fertiliser requirements and grain yield of tropical maize (Smaling and Janssen, 1993). The model assumes that crop yield is a function of N, P and K availabilities (native soil supply + mineral fertiliser added) and their interaction. The model estimates grain yield through four calculation steps:

Quantification of the potential native soil supply of N (SN), P (SP) and K (SK) using soil chemical data or from crop nutrient uptake measured in nutrient-omission trials;
Estimation of the actual crop nutrient uptake (UN, UP and UK, respectively) as a function of the native soil supply of a nutrient plus the supply from chemical fertiliser taking a fertiliser recovery fraction into account;
Estimation of N-, P- and K-determined yield ranges as a function of calculated nutrient uptake and a cultivar-specific potential yield (Y_{max}), considering minimum and maximum internal N, P and K use efficiencies (i.e. the inverse of the crop-specific maximum and minimum N, P and K concentrations, respectively), leading. to, respectively, minimum and maximum N, P and K-determined yields (YNA: yield at maximum N accumulation, YND: yield at maximum N dilution, etc.);
Estimation of the final yield by accounting for the interactions between N, P and K, i.e. as the average of yield estimates that are calculated for each possible pair of nutrients.
These four steps are described in detail in Janssen et al. (1990). Here, we only present the equations for calculation of the potential soil supply of N, P and K, as they are explicitly referred to in some of our analyses:

$$SN = fN \times 6.8 \times \text{Soil organic C} \quad \text{Eq. I}$$
$$SP = fP \times 0.35 \times \text{Soil organic C} + 0.5 \times \text{Extractable (Olsen) P} \quad \text{Eq. II}$$
$$SK = (fK \times 400 \times \text{Exchangeable K}) / (2 + 0.9 \times \text{Soil organic C}) \quad \text{Eq. III}$$

Where, soil organic C is expressed in g C kg^{-1} soil, extractable P in mg P kg^{-1} soil, exchangeable K in $cmol_{(+)}$ kg^{-1} soil, and *f*N, *f*P and *f*K are correction factors due to soil pH, calculated as:

$$fN = 0.25 \times (pH - 3) \quad \text{Eq. IV}$$
$$fP = 1 - 0.5 \times (pH - 6)^2 \quad \text{Eq. V}$$
$$fK = 0.625 \times (3.4 - 0.4 \times pH) \quad \text{Eq. VI}$$

2.4.2 Model parameterisation and simulations

First, we performed yield calculations with QUEFTS using the standard parameterisation from Smaling and Janssen (1993) for maize in Kenya, and soil characteristics from the survey of the F-M maize fields. The default values for the recovery fraction of applied N, P and K were 0.5, 0.1 and 0.5, respectively. Maize yields predicted by QUEFTS were compared with yields measured in F-M fields without nutrient inputs (no chemical fertilizer, no manure application). F-M fields receiving nutrient inputs were not used for model testing due to the poor reliability in the estimates of such inputs. Farmers do not always recall accurately the amounts of fertiliser they applied to their crops in the previous season. We assessed the model's

sensitivity to nutrient inputs (on F-M fields) by running it for a series of scenarios of combined N, P and/or K applications, each element at a rate of 100 kg ha^{-1}.
Secondly, we calibrated QUEFTS using data from the R-M experimental plots by tuning capture efficiencies of applied nutrients within the range of recovery efficiencies calculated from the experimental data (Section 2.2.2) to minimise differences between model predictions and measured yields. With this new parameterisation QUEFTS was used to assess maize yield responses to application of P fertiliser (as P was observed to be the main limiting nutrient – see later) at a rate of 30 kg P ha^{-1} (30P) alone or in the presence of N fertiliser, applied at a rate of 90 kg N ha^{-1} (30P/90N) – the maximum rate for an economic response estimated in previous studies (FURP, 1994), and above the general minimum recommendation of 60 kg N ha^{-1}.

2.5 Data analysis and calculations

The yields from both the farm surveys (F-M) and the on-farm experiments (R-M) were analysed through simple calculations of relative yield responses to fertilisers, nutrient capture and conversion efficiencies.

Relative yield responses to fertiliser applications were calculated as follows:

$$\textit{Relative response to treatment X} = \frac{[\textit{Grain yield}_{(treatment\ X)} - \textit{Grain yield}_{(control)}]}{\textit{Grain yield}_{(control)}} \qquad \text{Eq. VII}$$

where, treatment X represents N-P, N-K, P-K or N-P-K fertiliser application. The apparent nutrient recovery (a proxy for nutrient capture efficiency) from fertilisers was calculated by comparing nutrient uptake between treatment and control. For instance, the apparent recovery of N in N-P-K treatments is calculated as:

$$\textit{Apparent N recovery} = \frac{[\textit{N uptake}_{(NPK)} - \textit{N uptake}_{(control)}]}{\textit{Applied N}} \qquad \text{Eq. VIII}$$

where the rate of applied N, as well as P and K was 100 kg ha^{-1} for all treatments receiving nutrients. The efficiency of conversion of nutrients taken up by the plant into crop biomass was calculated as follows:

$$\textit{Conversion efficiency of nutrient X} = \frac{\textit{Total aboveground biomass}}{\textit{Total uptake of nutrient X}} \qquad \text{Eq. IX}$$

where, the total aboveground biomass is the sum of grain plus stover biomass, expressed on a dry weight basis. The conversion efficiencies for N, P and K have the units: kg DM kg N^{-1}, kg DM kg P^{-1}, kg DM kg K^{-1} taken up by the crop, respectively. The uptake of nutrients was calculated from measurements of N, P and K contents in grain and stover biomass (roots were not considered). The harvest index (HI) of maize was calculated as: *HI = grain dry weight / total aboveground dry weight*, where the total aboveground biomass is the sum of grain plus stover biomass. Regression analysis and analysis of variance (ANOVA) were performed using Genstat 8. To evaluate the accuracy of the QUEFTS model predictions, regression analysis was performed between the predicted and the measured yields and the total difference was calculated as the root mean square error, RMSE.

3. Results and discussion

3.1 Magnitude of yield gaps

Maize yields under farmer management (F-M) differed significantly across localities (P = 0.002; with averages of 1.1, 2.0 and 1.9 t ha^{-1} for Aludeka, Emuhaya and Shinyalu, respectively) and decreased significantly from the home- to the outfields (P < 0.001) in all localities (the interaction locality x position within farm was not significant) (Table 3). Yields on the same field plots but under researcher management (R-M) did not vary significantly across localities (P = 0.058) on the control subplots (without fertilizer); however, they differed significantly (P < 0.001) when full rates of mineral N-P-K fertilisers were applied, with averages of 4.3, 4.0 and 2.8 t ha^{-1} for Aludeka, Emuhaya and Shinyalu, respectively. Conversely, while yields on R-M control plots within each locality decreased with the distance from the homestead (P < 0.01), they did not differ significantly when N-P-K fertilisers were applied at full rate. At this scale of analysis, these results suggest that: (i) improved crop management under R-M contributed to reduce the gap between potential and actual yields even when fertilisers were not applied (control plots), reducing differences across localities; and that (ii) N-P-K fertiliser applications at full rate (100:100:100 kg element ha^{-1}) contributed to erase or minimise yield differences between different fields of the farm.

Maize yields under F-M were larger in Emuhaya and Shinyalu than in Aludeka, while yields in Aludeka were larger than for the other localities under R-M, especially when fertilisers were applied. The gap between F-M and R-M yields was as wide as 3 t ha^{-1} across all field types in Aludeka (Figure 1 A), while it was narrower and tended to increase with distance from the homestead in Emuhaya and Shinyalu. Shinyalu is a higher and somewhat cooler location (cf. Table 1), where the short rains season is considered marginal for maize production and many farmers leave the fields as short fallow, use them for grazing or plant short cycle crops such as beans (Tittonell et al., 2005b). In Aludeka, maize is a relatively new crop that increasingly is replacing other staple food crops such as sorghum or cassava; yields were virtually doubled simply by the effect of improved agronomic management in this locality, as shown by the yield gap between F-M and control R-M plots without fertilisers (Table 3).

Table 3 Average and range of variation of maize grain yields (t ha^{-1}) under farmers' management (F-M, Section 2.2.1), average yields and yield ranges for selected treatments from the researcher-managed on-farm experiments (R-M, Section 2.2.2) and reference yield levels under controlled, on-station trials (FURP, 1994).

Locality/ position within the farms	Farmers' fields (farmer management)		Control plots (on-farm experiment)		Full N-P-K plots (on-farm experiment)		FURP-reference* (on-station experiment)	
Aludeka							Control	Fertilised**
Homefields	1.7	(1.2-2.3)	3.6	(2.1-7.3)	4.7	(2.5-7.4)		
Midfields	1.0	(0.8-1.3)	2.0	(1.0-2.8)	4.1	(3.2-5.0)	1.6	5.2
Outfields	0.7	(0.3-1.1)	1.8	(1.1-2.4)	3.9	(2.1-5.0)		
Emuhaya								
Homefields	2.4	(1.1-3.8)	2.9	(0.9-5.5)	4.2	(3.3-6.2)		
Midfields	2.2	(0.9-3.6)	2.6	(1.2-3.7)	4.0	(2.9-4.8)	2.3	6.0
Outfields	1.4	(0.7-2.9)	1.8	(0.3-3.0)	3.8	(2.7-5.5)		
Shinyalu								
Homefields	2.6	(1.7-4.0)	2.3	(1.3-3.3)	2.9	(1.4-5.4)		
Midfields	1.7	(0.7-2.1)	1.6	(1.1-1.9)	2.8	(2.0-3.5)	2.3	7.1
Outfields	1.4	(0.8-2.3)	1.0	(0.2-2.3)	2.5	(1.2-3.7)		
SED	0.26		0.39		0.38			
CV	0.46		0.54		0.31			

*The position within the farm does not hold in this case; FURP: Fertiliser Use and Recommendation Programme, Kenya National Agricultural Research Laboratory

**The figures correspond to fertilizer combinations and rates leading to the highest yields (excluding those that also received animal manure) at each site. Maize grown during the long rains season.

SED: Standard error of the differences; *CV*: coefficient of variation (= standard deviation/ grand mean across sites and fields)

The yield gaps under between F-M and reference maize yields of fully fertilised crops from on-station trials (FURP, 1994 – Table 3) were large (on average 4.1, 4.0 and 5.2 t ha^{-1} in Aludeka, Emuhaya and Shinyalu, respectively), indicating the potential for improving actual crop productivity. However, these yields from on-station trials were reported about a decade earlier, for a growing season with presumably different rainfall and using different maize cultivars. These factors may contribute to widening or narrowing the actual yield gaps. Intervention and fertiliser adoption studies in western Kenya indicate maximum yields attained on farmers' fields to be around 3 t ha^{-1} when farmers were given a 50 kg-bag of N and a 50 kg-bag of P fertilisers (e.g., Achieng et al., 2001), or up to 6.1 t ha^{-1} with addition of 60:60:0 N-P-K fertiliser, with an absolute maximum of 14.2 t ha^{-1} with 178 kg N ha^{-1} and 104 kg P ha^{-1} in on-farm trials conducted by the Kenya Ministry of Agriculture in Vihiga district (Kipsat et al., 2004).

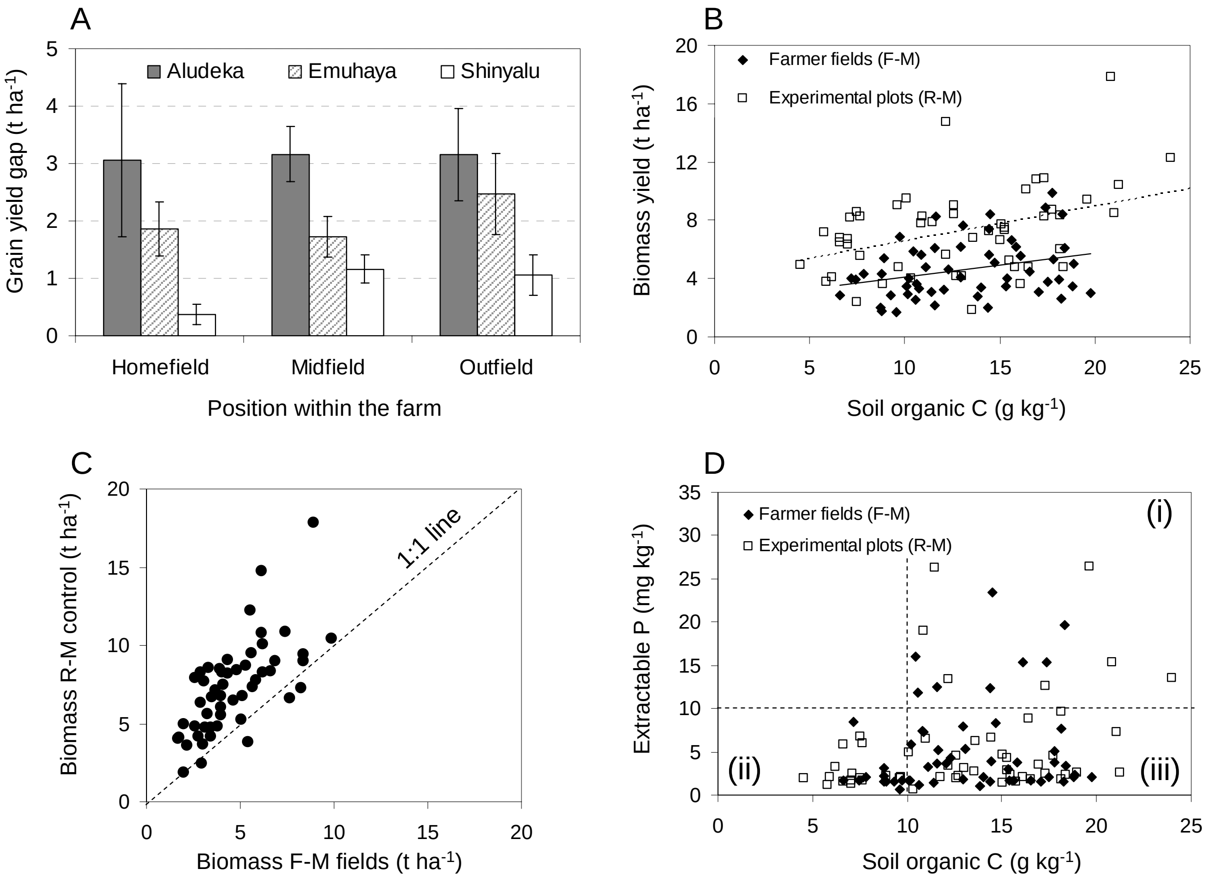

Figure 1: Maize yield variability and yield gaps in farmers' fields. (A) The gap between maize yields on farmer-managed (F-M) fields and yields obtained with application of N-P-K fertilisers on the same fields under researcher management (R-M); (B) Maize grain yields under F-M and under R-M without fertilisers plotted against soil organic C; (C) Total aboveground biomass produced under F-M in the long rains vs. biomass produced in the same fields without fertilisers (control) under R-M during the short rains; (D) Measured soil extractable P plotted against measured soil organic C in all F-M and R-M fields prior to the experiment.

3.2 Management-induced heterogeneity and its effect on crop responses

Experimental R-M plots were planted early in the season, with proper plant population densities, early weeding and pest/disease control, and using hybrid seeds. Under such well-controlled conditions, there was a relationship between crop biomass production and soil organic C (as a proxy for soil fertility) (Figure 1 B). This relationship was weak (r^2 = 0.21, P < 0.01),, but tighter than that for biomass yields under farmer management (r^2 = 0.10, P < 0.01) (Figure 1 B). While native soil N availability for crop growth is normally positively correlated with the amount of soil organic C, P availability (i.e. Olsen-extractable P) may also be related to soil C through the management history of the fields. This is because larger yields achieved under R-M also result in greater C input to the soil through crop residues and roots, even in control plots without fertilisers (Figure 1 C). Under farmer management, small areas close to their homesteads receive P inputs (through e.g. ash, animal manure or sporadic fertiliser use) together with C inputs (e.g., manure, household waste). This also leads to larger biomass yields and, thus, C inputs to the soil.

Due to such management-induced co-variation, soils with less than 10 g kg^{-1} of organic C had extractable P values below the indicated threshold of 10 mg kg^{-1} – [quadrant (ii) in Figure 1 D], whereas soils with larger organic C content might have high [quadrant (i)] or low [quadrant (iii)] availability of P. Such a pattern of a positive relationship between soil C and P availability was also observed for a set of c. 600 samples from western Kenya (Tittonell et al., 2007c). When mineral P fertilisers are applied alone, fields in quadrant (i) are expected to respond weakly due to relatively good availability of P, fields in quadrant (ii) may show little response to P if mineral N fertilisers or manure are not simultaneously applied, while fields in quadrant (iii) are expected to show the strongest response to sole P applications.

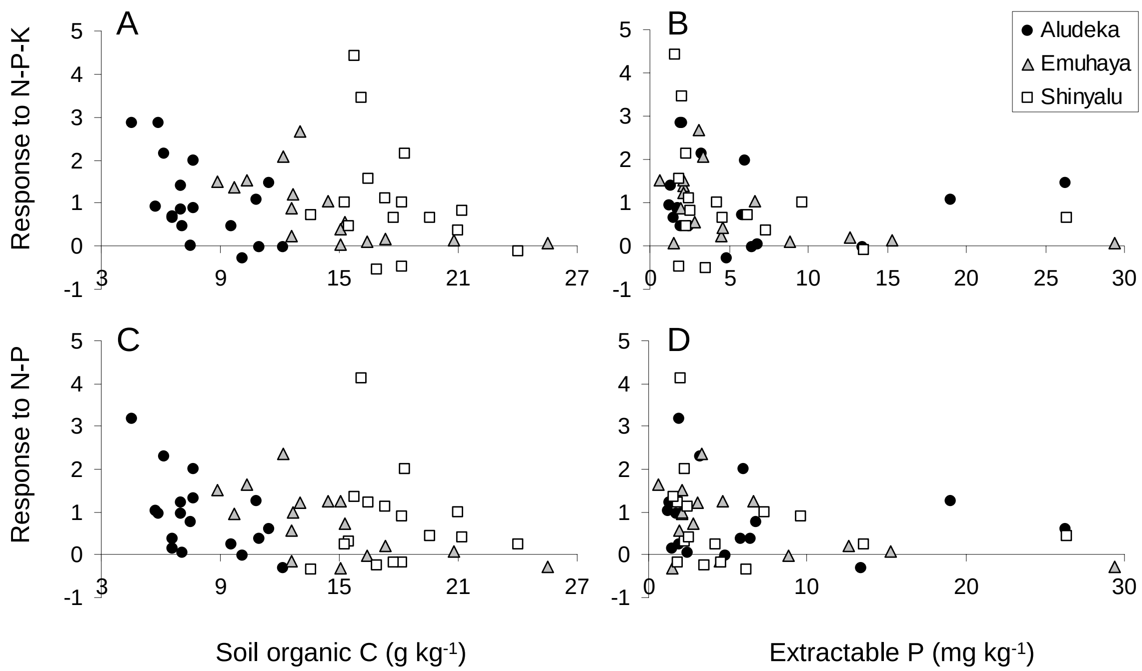

Figure 2: Relative yield responses (yield increase relative to control plots) to combined N-P-K and N-P mineral fertiliser applications at rates of (100 kg N ha^{-1}, 100 kg P ha^{-1} and 100 kg K ha^{-1}) in a nutrient-omission trial conducted on 18 farms from Aludeka, Emuhaya and Shinyalu divisions in western Kenya (i.e., the on-farm R-M experiment). Relative responses plotted against soil organic carbon (A, C, E, G) and soil extractable P (B, D, F, H).

In R-M plots, the relative grain yield response to full N-P-K fertiliser applications (Eq. VII) tended to decrease for soils with higher organic C and extractable P contents in all localities (Figures 2 A and B). Such a pattern was mostly explained by the application of N and P, as the relative yield increase induced by combined N-P applications showed similar trends as for N-P-K (Figures 2 C and D). When either P (combined N-K application) or N (combined P-K application) was removed, somewhat larger responses were observed for soils of intermediate fertility in terms of C and P within each site (not shown). Yield increases with N-P-K were slightly larger than with N-P only in Emuhaya, indicating some degree of yield limitation by K availability in those soils. Substantial yield responses to any of the nutrient combinations in the applied fertiliser were only observed across localities in soils with extractable (Olsen) P less than c. 10 mg kg^{-1} – a trend that has been previously observed across 18 sites in Kenya (Schnier et al., 1997). However, yield responses to N-P-K and N-P in these fields were also often negligible (Figures 2 B and D). Such variability in the response to fertilisers is related to the efficiency with which the crop captures the available nutrients and converts them into biomass. In the following section, we examine the range of variability of the components of resource use efficiency underlying variability in crop yields and their response to fertilisers.

3.3 Nutrient availability and utilisation across heterogeneous farms

Following the logic outlined in Section 2.1, nutrient-limited crop yields are the result of nutrient availability, nutrient capture efficiency and nutrient conversion efficiency. In the following paragraphs we examine the variability in soil N-P-K availabilities (i.e., prior to fertiliser addition), apparent N-P-K recovery efficiencies (proxies to N-P-K capture efficiencies from applied fertilisers) and N-P-K conversion efficiencies (the inverse of their concentration in crop biomass) within the farms sampled across the three localities.

3.3.1 Soil nutrient availability

The potential soil supply of N, P and K was calculated for all F-M fields using Equations I, II and III and plotted against measured soil properties (Figure 3). Considering the average maize grain yield in western Kenya of 1.1 t ha^{-1} (e.g. Hassan, 1998) and an average harvest index of 0.36 (as measured in the F-M fields), the total aboveground biomass production is about 3 t ha^{-1} (1.1/0.36 = 3), The dotted lines in Figures 3A, C and E indicate the crop uptake of N, P and K, respectively, that would be necessary to produce 3 t ha^{-1} of aboveground maize biomass (the conversion efficiencies assumed were: 88, 319 and 97 kg of dry matter per kg of N, P or K taken up by the crop, respectively – Nijhof, 1987). According to these calculations maize production is most often limited by P availability, with only a few points above the required uptake of 9.7 kg P ha^{-1} (mostly those in which soil extractable P > 10 mg kg^{-1}). The potential supply of N and P tended to increase with increasing soil organic C (Figure 3 B, D, F). For N, the calculated required uptake of 35.2 kg N ha^{-1} was met in soils with organic C > 10.1 g kg^{-1} (Figure 3 B) – notably the same soil C threshold above which soils with extractable P > 10 mg kg^{-1} were observed (Figure 3 D).

3.3.2 Nutrient capture efficiency

The average total N, P and K uptake by the maize crop and the apparent recovery efficiencies of applied N, P and K were calculated using data on nutrient concentrations in grain and stover from the R-M on-farm experiments (Table 4). Nutrient uptake decreased significantly from the home- to the outfields, following the trends in maize yields on the control plots (cf. Table 3), and the soil nutrient concentrations of the different fields (cf. Table 2). No significant effect of locality, and no significant interaction locality × position within the farm were observed for any of the variables (Table 4).

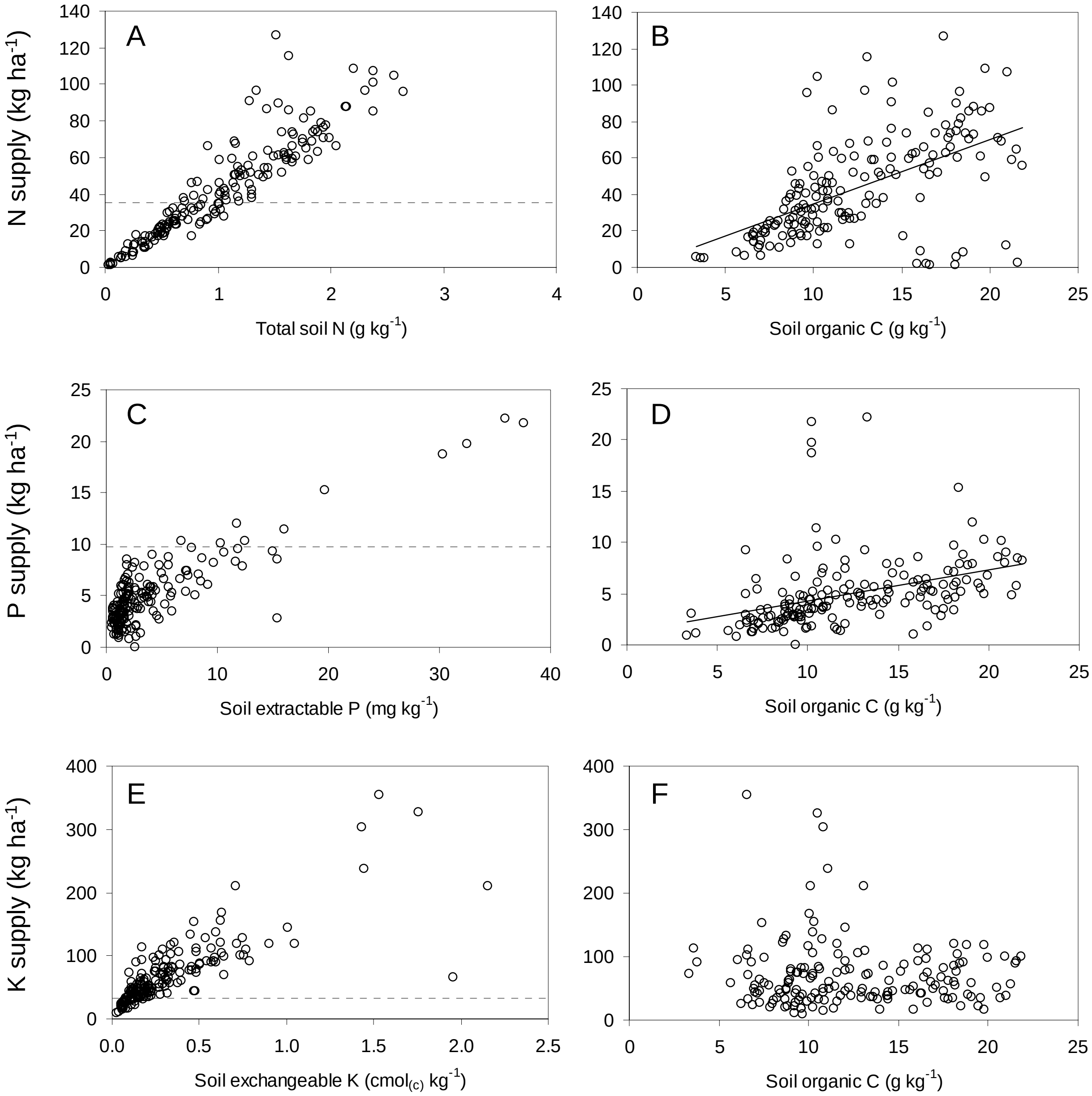

Figure 3: Calculation of potential N, P and K supply from 170 soils in western Kenya using the formulas of QUEFTS (Equations I, II and III in the text - Janssen et al., 1990), plotted against measured total soil N, extractable P, exchangeable K and organic C content of these soils.

Table 4 Average N, P and K uptake by maize on the control plots (without fertilizers) and apparent N, P and K recovery fractions for different combinations of mineral fertilizer applications

Locality and position within the farm	Nutrient uptake (kg ha^{-1})			Apparent N recovery			Apparent P recovery			Apparent K recovery		
	N	P	K	NPK	NP	NK	NPK	NP	PK	NPK	NK	PK
Aludeka												
Homefields	99	25	93	0.21	0.32	0.10	0.06	0.03	0.05	0.40	0.18	0.35
Midfields	57	11	66	0.69	0.40	0.59	0.15	0.15	0.04	0.52	0.41	0.02
Outfields	60	14	76	0.55	0.68	0.38	0.12	0.14	0.00	0.41	0.02	-0.10
Mean	72	17	79	0.48	0.46	0.36	0.11	0.11	0.03	0.44	0.20	0.09
Emuhaya												
Homefields	87	17	83	0.70	0.39	0.26	0.07	0.02	0.02	0.50	0.18	0.02
Midfields	74	11	46	0.60	0.58	0.35	0.10	0.08	0.05	0.45	0.53	0.18
Outfields	56	10	40	0.64	0.33	0.25	0.07	0.07	0.06	0.35	0.11	0.42
Mean	72	13	56	0.65	0.43	0.29	0.08	0.06	0.04	0.43	0.27	0.21
Shinyalu												
Homefields	102	15	99	0.38	0.35	0.17	0.06	0.03	0.00	0.40	0.57	-0.06
Midfields	73	13	75	0.48	0.58	0.23	0.05	0.09	-0.02	0.40	0.06	-0.03
Outfields	50	8	51	0.28	0.45	0.00	0.04	0.07	0.01	0.28	-0.04	0.02
Mean	75	12	75	0.38	0.46	0.14	0.05	0.07	0.00	0.36	0.20	-0.02
SED	10.5	2.3	12.0	0.14	0.13	0.13	0.03	0.03	0.02	0.16	0.17	0.13

SED: Standard Error of the Difference

The recovery efficiencies of the applied nutrients varied widely and were affected by the type and combination of nutrients applied and by the position of the field within the farm. The overall average recovery efficiencies across localities, positions within the farm and fertiliser applications (i.e. the grand means) were 0.40, 0.06 and 0.26 for N, P and K, respectively. For N and P, these values are close to those used as default in QUEFTS (0.5 and 0.1, respectively - Smaling and Janssen, 1993). The maximum values for N recovery efficiencies (c. 0.6 to 0.7) were measured on R-M fields that received the full rate of N-P-K fertilisation (Table 4). In Emuhaya and Shinyalu, the N recovery efficiency was lower when no P was applied (i.e. for N-K combinations). Across sites, P recovery was generally poorer when no N was applied (i.e. for P-K combinations), while K recovery was affected by both N and P, as both N-K and P-K combinations led on average to lower efficiencies than N-P-K.

3.3.3 Nutrient conversion efficiency

N, P and K conversion efficiencies (Eq. IV) were calculated from nutrient concentrations and biomass measurements on R-M fields (Figure 4, Table 5). The theoretical minimum and maximum efficiencies with which N, P and K are converted into maize biomass (i.e. their maximum concentration and dilution within the plant) as calculated from reference nutrient concentrations given by Nijhof (1987), are indicated by the lines in Figures 4 A-C. These theoretical values encompass reasonably well the variability in observed nutrient uptake and aboveground biomass yield on the R-M plots. While measured N and K conversion efficiencies were closer to their maximum theoretical concentrations in the plant (Figure 4 A and C), P was often more diluted, with values closer to its minimum theoretical concentration (Figure 4 B). In general, the conversion efficiencies of N, P and K were less variable across localities, fields and fertilisation treatments than the corresponding recovery efficiencies (cf. Tables 4 and 5).

The overall average conversion efficiencies across localities, positions within the farm and fertilisation treatments were 97 kg DM kg^{-1} N, 558 kg DM kg^{-1} P and 111 kg DM kg^{-1} K taken up. The average N, P and K conversion efficiencies were significantly ($P < 0.05$, 0.01 and 0.01, respectively) larger in Emuhaya than in the other localities, and nutrients tended to be on average more diluted in the crop biomass on control plots than on fertilised plots. N and P uptake and their conversion efficiencies (Figure 4 A and B) are within similar ranges as those measured for maize in on-farm experiments conducted on clayey and sandy soils in Zimbabwe (Zingore et al., 2007b), including different positions within the farm and different rates of mineral N and P and manure applications. Although in the Zimbabwean study N and P concentrations were somewhat closer to their maximum than in our case, nutrient conversion efficiencies can be considered more conservative: i.e. less variable across environments and management practices than nutrient capture efficiencies. In the next section we further analyse the observed variability in nutrient capture efficiency and responses to fertilizers with the help of the QUEFTS model.

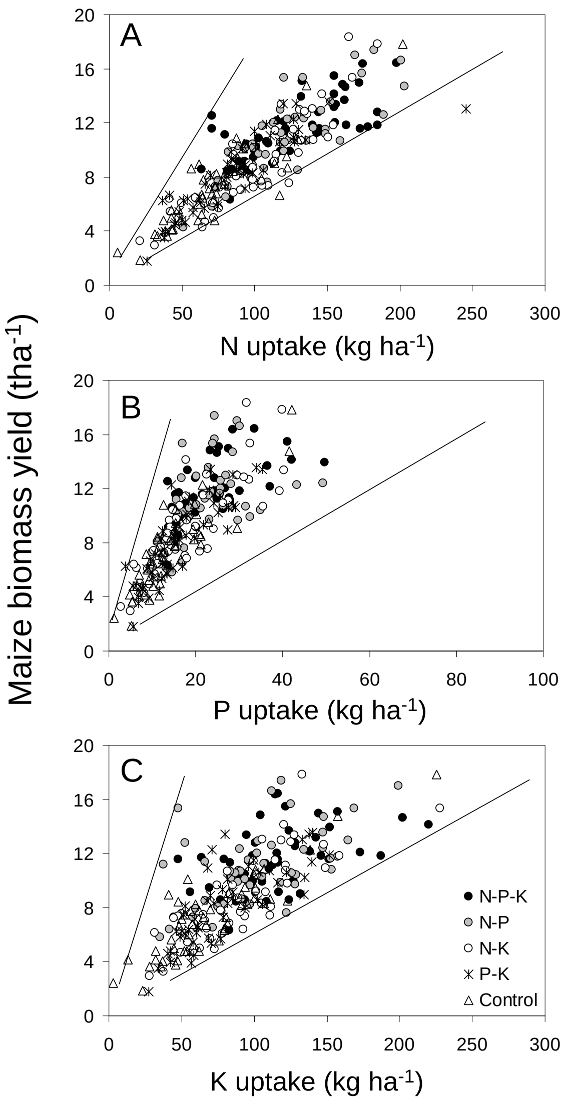

Figure 4: The relationship between crop N, P and K uptake and aboveground biomass yield measured in all plots of the on-farm R-M experiment. Upper and lower boundary lines indicate the physiological maximum dilution and concentration of each nutrient in plant biomass (Nijhof, 1987).

3.4 Predicting maize yields from soil nutrient availability

QUEFTS calculates the maize yields that may be expected on farmers' fields based on current soil fertility. In this way, we firstly used the model to provide an indication of the extent to which current maize productivity on the F-M plots deviates from attainable productivity levels given the soil and fertiliser nutrient availability. Results are illustrated only for Aludeka (Figure 5), where the coexistence of two highly contrasting soil types known locally as *Apokkor* (clay loam) and *Assinge* (sand loam to sand) generates wide variability in crop response.

Table 5 N, P and K conversion efficiencies calculated from plant nutrient concentrations and biomass measured on the R-M plots (Section 2.2.2).

Locality and position within the farm	N conversion efficiency (kg DM kg^{-1} N)					P conversion efficiency (kg DM kg^{-1} P)					K conversion efficiency (kg DM kg^{-1} K)				
	Control	NPK	NP	NK	PK	Control	NPK	NP	NK	PK	Control	NPK	NP	NK	PK
Aludeka															
Homefields	99	100	92	101	97	397	418	434	456	377	105	93	110	107	88
Midfields	112	98	100	83	105	577	463	399	395	502	98	103	86	95	105
Outfields	110	95	95	94	102	458	434	487	550	465	89	95	117	106	98
Mean	107	98	95	93	101	478	438	440	467	448	97	97	104	102	97
Emuhaya															
Homefields	112	92	92	95	94	593	572	576	572	505	134	102	144	102	115
Midfields	98	92	90	105	93	674	589	634	706	613	148	143	196	109	140
Outfields	165	104	103	82	106	885	677	552	665	585	284	154	106	137	104
Mean	125	96	95	94	98	717	613	587	647	568	189	133	149	116	120
Shinyalu															
Homefields	97	86	85	87	94	650	567	641	587	585	99	87	118	71	96
Midfields	92	88	88	78	119	548	598	528	604	815	94	92	95	93	113
Outfields	93	103	84	85	91	566	647	532	571	462	88	99	89	89	81
Mean	94	92	86	83	101	588	604	567	587	621	93	93	101	84	97
Standard error of the differences between averages of:															
Site			4.3					24.4					7.1		
Position within the farm			4.3					24.4					7.1		
Fertilisation treatment			5.6					31.5					9.2		
ANOVA-Significance for the effects of:															
Site			*					**					**		
Position within the farm			ns					ns					ns		
Fertilisation treatment			**					ns					*		

All interactions non-significant except Site x Fertilisation treatment ($P < 0.05$) for P conversion efficiency. ns = not significant

Maize yields in F-M plots calculated from soil N, P and K availability without fertilisers were poorly predicted by QUEFTS (r^2 = 0.22, RMSE = 0.53 t ha^{-1}) for Aludeka (Figure 5 A), as well as for the other localities (Emuhaya, r^2 = 0.29, RMSE = 1.8 t ha^{-1}; Shinyalu, r^2 = 0.05, RMSE = 1.7 t ha^{-1}). The model was however sensitive to differences in fertility between soil types and the results of simulated N-P-K applications (100:100:100 kg element ha^{-1}) indicated strong response to N and secondarily to P (Figure 5 B), in agreement with previous observations in the vicinity of Aludeka (Alupe Experimental Station – FURP, 1994). The maximum yields predicted by the model for both soil types, corresponding to crops receiving N-P-K fertilisers, were within the range of the maximum yields measured in F-M fields in Aludeka (cf. Table 3); the estimated average gap between simulated yield of fully fertilised crops and measured yields was 2.9 and 2.5 t ha^{-1} for *Apokkor* and *Assinge* soils, respectively (Figure 5 B). The lack of agreement between predicted and observed yields is not surprising, given the various sources of variability that affect maize production under F-M. Observed maize yields without fertilisers tended to increase with increasing soil organic C and available P (Figure 5 C and D), whereas late planting and sparse plant population densities led to poorer yields (Figure 5 E and F).

Maize yields predicted by QUEFTS tended to follow similar trends with respect to these soil fertility and management factors (the lines fitted to the QUEFTS-predicted maize yields had r^2 values of 0.40 for soil C, 0.12 for available P, 0.45 for delay in planting and 0.16 for plant density) (Figure 5 C, D, E and F). While it is expected that QUEFTS predicts larger yields for soils with higher C and P contents, the trends in predicted yields with agronomic management variables are not directly related to the basis of the model (i.e. planting dates and plant density are not considered as parameters in QUEFTS). The reason for the simulated patterns is the fact that soil fertility and management decisions are correlated; e.g. farmers plant earlier and with a higher plant density on the more fertile fields.

Secondly, we used QUEFTS to calculate the attainable yields with N-P-K fertiliser applications on the R-M plots. The agreement between simulated and measured grain yields on these plots was also rather poor ($RMSE_{control}$ = 1.53 t ha^{-1}; $RMSE_{NPK}$ = 2.83 t ha^{-1}) when the default values for fertiliser recovery efficiencies were used. Since soil heterogeneity affects nutrient use efficiency mainly through its effect on nutrient capture efficiency, the calculations were re-done using the fertiliser recovery efficiencies that we observed as model input (Section 3.3.2) (cf. Table 4). With this new parameterisation, we used QUEFTS to calculate grain yields with application of 30 kg P ha^{-1} and 30 kg P ha^{-1} plus 90 kg N ha^{-1} (Figure 6). The response to 30 kg P ha^{-1} increased with increasing soil C, as evidenced by steeper slope of the trend lines describing simulated grain yield with 30 kg P ha^{-1} compared with the control in Figure 6. This is in agreement with the observed relationship between soil C and available P (cf. Figure 1 D), which points to the existence of non-P-responsive and P-responsive fields. When P was added in combination with N, yields increased also on plots with < 10 g kg^{-1} of soil organic C, and the distribution of yields against soil C was more dispersed (r^2 = 0.31). According to these model predictions, there is room to increase maize yields of poor fields by combined application of N and P fertilisers.

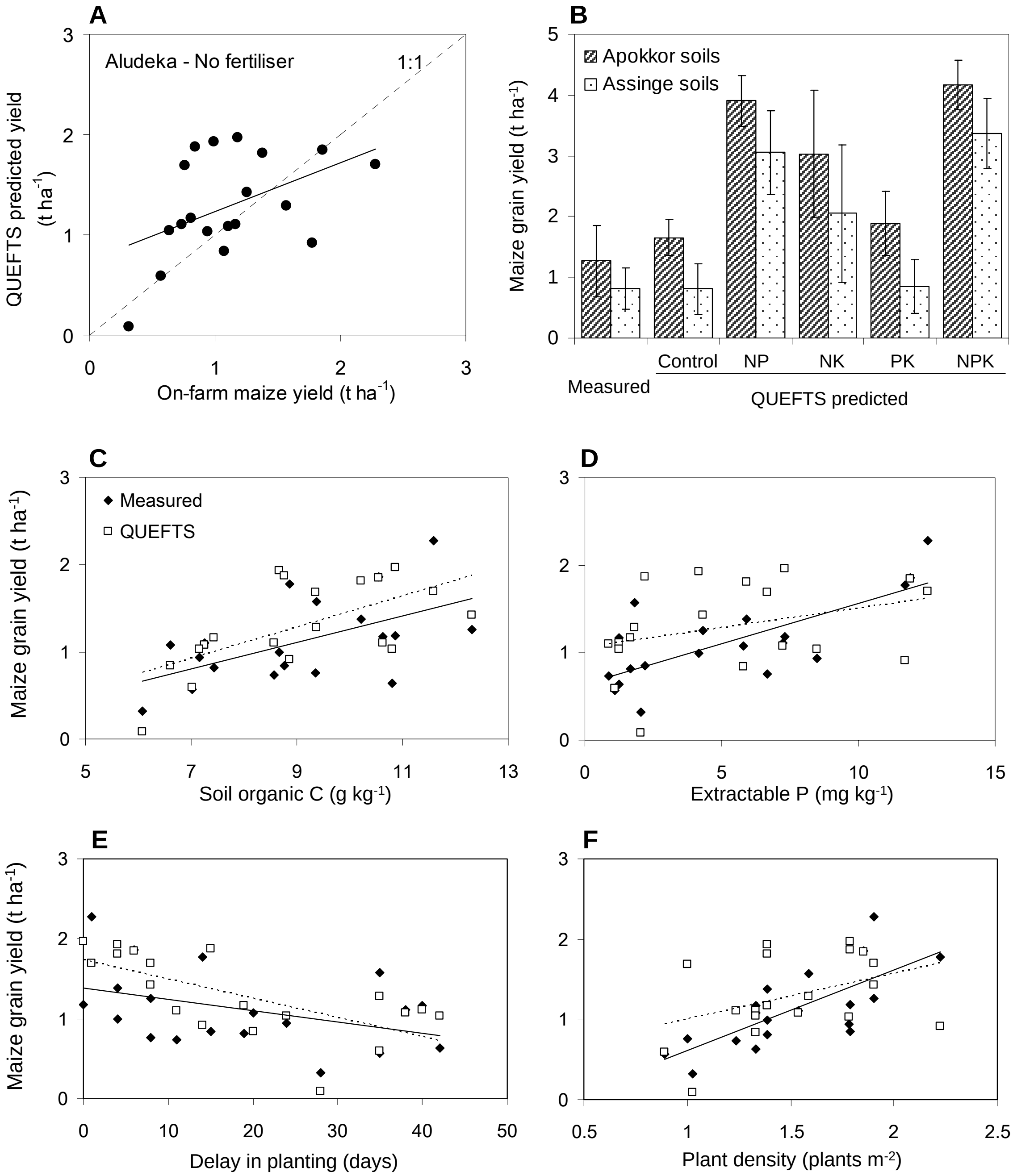

Figure 5: (A) Comparisons between maize yields measured on-farm vs. yields predicted by QUEFTS for Aludeka, considering only fields that did not receive fertilisers (solid trend line and dashed 1:1 line); (B) on-farm measured and QUEFTS-predicted yields for the two main soil types found in Aludeka (Apokkor: Acrisols, Assinge: Lixisols) – vertical lines indicate standard deviation; (C, D, E and F) on-farm measured and QUEFTS-predicted yields as a function of soil organic C and available P (Olsen), days of delay in planting and plant population densities, respectively. In C-F the solid lines describe the trend in measured values, the dashed ones the QUEFTS predicted values.

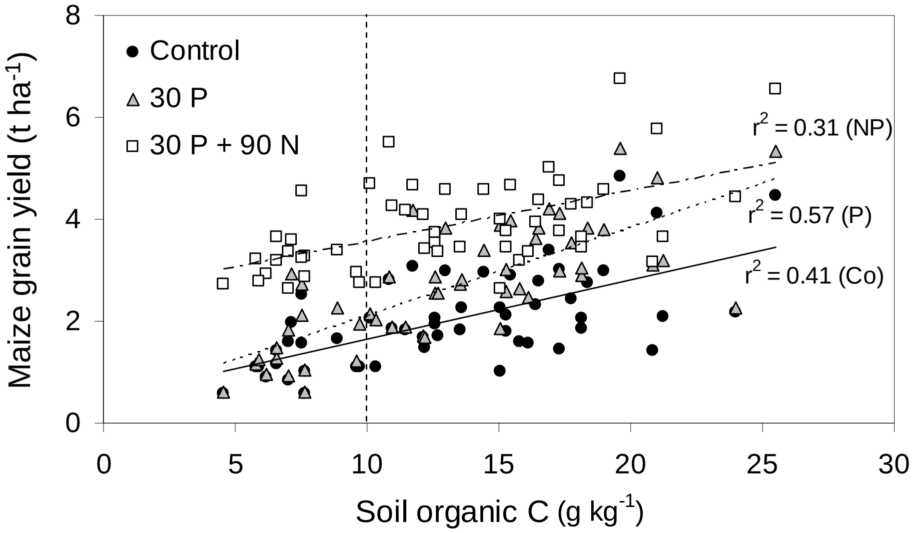

Figure 6: Predicted maize responses to applied P and N fertilisers (30 P = 30 kg P ha^{-1}; 30 P + 90 N = 30 kg P ha^{-1} plus 90 kg N ha^{-1}) using QUEFTS with N, P and K recovery efficiencies as measured in the experiment; predicted yields plotted against soil organic C. The trend lines correspond to control (solid line), 30 P (dashed line) and 30 P + 90 N (dot-dashed line). The vertical dotted line indicates the threshold of 10 g kg^{-1} of soil C.

3.5 Targeting mineral fertilisers to narrow the current yield gaps

We observed a wide variability in nutrient recovery efficiencies (Table 4) across heterogeneous farms that may lead to very poor crop responses to applied fertilisers (Figure 2). Despite having singled out P as the most limiting nutrient for maize production (Figure 3), its apparent recovery was as low as 1-3% (Table 4). From this, it is clear that the promotion of mineral fertiliser use in sub-Saharan Africa should go hand-in-hand with the implementation of measures to improve fertiliser use efficiency. These may include, amongst others, improved water capture through more infiltration and less run-off and erosion, improving water and nutrient holding capacity through increasing organic matter in sandy soils, improving availability of applied and native soil nutrients through pH correction, and improved cultivars and agronomic management (e.g., early planting, weeding, etc.). Our results show that the latter may have an important impact on crop productivity (Table 3). Resource imbalances may also affect recovery efficiencies (Kho, 2000), as when, for example, lack of P limits plant growth and prevents uptake of applied N or K (Table 4). On the other hand, fertile fields such as the home gardens may also be poorly responsive to applied fertilisers – a case of ‘saturated soil fertility’ (Janssen and de Willingen, 2006) (cf. Figure 2).

Fertilizer recommendations should be fine-tuned to target soil fertility ‘niches’ within heterogeneous farms, differentiating responsive fields where fertilisers can be applied from non-responsive fields that need long-term rehabilitation through organic matter management. This requires a framework for communication between researchers, extension agents and farmers. Soil heterogeneity must be categorised and each category of soil fertility status must be easily recognisable. Approaches based on local soil quality indicators (e.g. Barrios et al., 2006) are sometimes useful but difficult to generalise across agro-ecological zones. The use of local soil classification faces the same type of scale-related limitations as the use of soil maps or agroecological zones (e.g., Smaling et al., 1992), since different local soil names normally identify inherently different soil types (e.g. *Ingusi* and *Oluyekhe* are names used for red clayey and brown sandy soils in Emuhaya – Tittonell et al., 2005b) without considering the current fertility status of the soil units.

Farmers often classify their fields into fertile and infertile based on their own experience about past and present crop productivity, history of management and land degradation events (e.g. Mairura et al., 2007). Their criteria were also used in the selection of fields in which the R-M experimental plots were established (Table 2). Farmers' soil classes often reflect differences in the current content of organic matter in the soil, which is the result of inherent soil properties (e.g. texture) and management history (e.g. use of animal manure, years under cultivation/fallow, etc.). They may, however, not discriminate between P (and/or K) responsive and non-responsive soils. Our study indicates that most fields sampled were deficient in P (Figure 3) and that soil P and C co-vary within farms as induced by farmers' management practices. A simple framework, based on the contents of organic carbon and available P in the soil, categorises fields that may be (cf. Figure 1 D): poorly-responsive fertile fields [quadrant (i)], poorly-responsive infertile fields [quadrant (ii)], and responsive medium-fertile to infertile fields [quadrant (iii)]. Major reasons for the co-variation of soil organic C and available P in the most fertile and least fertile fields of the farms are respectively the use of animal manure (containing both C and P) as a major nutrient input and the removal of crop residues from the poorest fields of the farm (that are not receiving P inputs).

Animal manure is a key nutrient resource used by farmers with cattle in western Kenya (Waithaka et al., 2006). However, since farmers often own just one or two cows, the amount of available manure for application to crops after collection and storage is normally insufficient to fertilise a substantially large area of their farms. Due to inefficiencies in nutrient cycling via manure (e.g. feed scarcity leading to unbalanced animal diets, delayed collection and/or deficient composting/ storage of manure), the content of nutrients in the applied manure is also often poor (Rufino et al., 2007a). The limited amounts of manure available to fertilise crops would be more efficiently used in combination with mineral fertilisers, as several examples in literature report complementarities and/or synergies between both resources translating in larger crop responses (e.g. Bationo et al., 2006). Further research should examine the potential contribution of long-term manure application strategies (and crop residue management) to improve fertiliser use efficiencies.

Simple modelling tools such as QUEFTS may be useful for exploring responses to fertilisers allocated to fertility niches within heterogeneous farms (Figure 6). However, considering only soil nutrient availability and soil chemical properties has a number of limitations to capture the dynamics of complex farming systems: (1) since farm heterogeneity affects crop responses to fertilisers operating mostly through the nutrient capture efficiency (cf. Tables 4 and 5), recovery fractions of applied nutrients should be a model output rather than an input parameter in this type of analysis; (2) QUEFTS is a 'static' model, so that key soil-plant feedbacks within the system such as temporal changes in soil organic matter and nutrients supply due to e.g. increased crop productivity with increased C inputs to soil are not considered; (3) in the rolling landscape of western Kenya, differences in soil water holding capacity and water capture efficiencies by crops (through different infiltration/runoff ratios) across fields may be large, affecting crop responses to applied nutrients; (4) on F-M plots management factors such as competition by weeds (and the impact of pest and diseases), the source of nutrients applied (organic vs. mineral), planting dates or the presence of intercrops are also affecting crop responses to fertilisers and are thus an extra source of yield variability.

Across the various agro-ecological zones of western Kenya smallholder farms are highly heterogeneous and socially diverse. Fertiliser recommendations should then be tailor-made to target such variability. Ojiem et al. (2006) developed the concept of 'socio-ecological niches' for the integration of legume-based technologies in smallholder farming systems of western Kenya. Opportunities for different technology options including fertilizer use can be represented as a multi-dimensional space (niche) delimited by several criteria, which include farmers' production objectives, characteristics of the biophysical and socio-economic environments, and various locality-specific and organisational support factors, e.g. market development, technology support services. The latter two are major factors constraining the adoption of fertiliser-based technologies in western Kenya (Barrett et al., 2002). In view of the limited support provided by agricultural extension services and the large variability in crop responses to fertilisers that can be expected in heterogeneous farms (cf. Figures 2 A-H), the limited use of mineral fertilisers currently observed in smallholder farms of western Kenya (e.g. an average of 20 kg N ha^{-1} for fields that receive fertilisers – Tittonell et al., 2005c) is therefore not surprising.

4. Conclusions

The gap between attainable and actual maize yields in western Kenya, which is partly demonstrated by the yield gap between farmer- and researcher-managed plots, is associated with generalised poor resource use efficiency on farmers' fields. Resource use efficiencies are highly variable within and across heterogeneous farms, as a result of soil variability and farmers' management decisions, affecting crop responses to applied nutrients. Of the two components of nutrient use efficiency: capture and conversion efficiency, the former varies more broadly across fields, farms and agro-ecological zones. The major limitation to maize production in western Kenya, however, is not resource use efficiency but resource availability, and improving the availability of one resource may improve the utilisation of others.

Maize yields calculated on the basis of soil nutrient availability deviated substantially from yields observed on farmers' fields, either under farmer management or researcher management. Deviations from yields under farmer management are not surprising, since the effects of agronomic management decisions or the various yield-reducing factors were not taken into account. Deviations from yields measured under controlled conditions (i.e. proper agronomic management) suggest that other factors such as water availability (its capture and conversion efficiencies), which were not considered in the yield predictions, may vary considerably within heterogeneous farms.

Targeting mineral fertilisers to narrow the current yield gaps demands going beyond 'blanket recommendations', and considering the current heterogeneity in soil fertility status, resource use efficiency and crop response to fertilisers within smallholder farms. Poor crop responses to fertiliser applications discourage their adoption among farmers. Thus, paraphrasing the conclusions from the Abuja Fertiliser Summit, if farm heterogeneity is not recognised and embraced within fertiliser recommendations in sub-Saharan Africa, 'development' will be *hard* to achieve even with fertilisers'.

Acknowledgements
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Chapter 6

Trade-offs in resource and labour allocation within heterogeneous smallholder farms[†]

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

Abstract

Smallholder farms in Sub-Saharan Africa face multiple trade-offs when deciding on the allocation of their financial, labour and nutrient resources. Day-to-day decisions have implications for the sustainability of their farming system, implying multiple trade-offs between short- and long-term objectives that have biophysical and socio-economic dimensions. We show that inverse modelling techniques can be used effectively for optimisation and trade-offs analysis of farming systems. By combining the MOSCEM (Multi-Objective Shuffled Complex Evolution Metropolis) algorithm and a crop/soil dynamic simulation model we were able to select farming strategies that resulted in the best possible trade-offs between different farming objectives. This integrated analytical tool allows optimisation of farmers' goals similar to linear programming, but an advantage over linear programming is that the proposed method takes into account the whole spectrum of biophysical processes including their interactions and feedbacks. Tradeoffs between resource productivity, use efficiency and conservation in relation to different patterns of resource allocation were analysed for a maize-based, simplified case study farm from western Kenya (2.2 ha – comprising fields of poor, medium and high soil fertility), under three scenarios of financial liquidity to invest in labour and inputs (2000, 5000 and 10000 KSh ha^{-1}; 75 KSh = 1 US$). The maximum farm-scale maize production achieved was larger when financial resources increased. However, increasing maize yields above a certain threshold by applying mineral fertilisers was associated with larger N losses by leaching, runoff and soil erosion; such threshold was 2.7 t grain ha^{-1} for the scenario of no financial limitations (10000 KSh ha^{-1}). N losses at farm scale fluctuated between 36 to 54 kg N ha^{-1} $season^{-1}$, while the maximum maize yields achieved were around 3.4 t grain ha^{-1}. Soil losses by erosion increased abruptly beyond a certain maize yield (e.g. 1.8 t grain ha^{-1} for the 2000 KSh ha^{-1} scenario), while the minimum rate of soil loss differed between financial scenarios. Investments in hiring labour were prioritised over fertiliser use to obtain the greatest yields and the allocation of available resources favoured the more fertile fields. This inverse modelling exercise allowed us to analyse trade-offs between different farmers' objectives and to compare potential resource allocation strategies to achieve them. The set of strategies to achieve a certain goal was more numerous and variable when the conditions were less conducive for farming. This questions the validity of the prevailing model of extension/communication, based on generalised recommendations for resource-poor farmers in Africa.

Keywords: DYNBAL model, MOSCEM, soil erosion, N balance, maize yield

1. Introduction

Smallholder farms in Sub-Saharan Africa face multiple trade-offs when deciding on the allocation of their available financial, labour and nutrient resources to competing production activities within their farms. Such trade-offs are reinforced by their limited access to production resources (Giller et al., 2006), poor development of factor markets (Ruben and Pender, 2004), and the fact that smallholder farms are spatially heterogeneous, due to the existence of gradients of decreasing soil fertility with increasing distance from the homestead (Tittonell et al., 2005c). The operational, day-to-day decisions made by farmers in allocating resources have implications for the future fertility of their fields, and thence for the sustainability of the entire farm system. Studies across Africa indicate that smallholder farmers invest proportionally more (cash, nutrient and labour) resources in the relatively fertile fields near the homestead, particularly on mixed crop-livestock farms (e.g. Samaké et al., 2006; Zingore et al., 2007a; Tittonell et al., 2007a). This resource allocation pattern leads to the creation of zones of soil fertility within farms that do not necessarily result in efficient allocation of farm resources.

To increase productivity and ensure sustainability of smallholder farms in Sub-Saharan Africa (SSA) it is necessary to understand the trade-offs between immediate concerns such as generating food and cash, and reducing soil and nutrient losses or maintaining favourable soil physical properties, which have a cumulative impact on soil quality in the long-term. Nutrient losses through run-off and soil degradation by erosion are often indicated by farmers in the highlands of western Kenya as being underlying causes of poor productivity of their land (e.g. Tittonell et al., 2005c), and formal assessments of soil losses in the area confirm this perception (e.g. de Bie, 2005). Nutrients are also lost through other processes that are normally less evident to farmers; e.g. leaching, which may take place at high rates for nutrients that are soluble in the soil. Such is the case for nitrogen (N), which is highly mobile in the soil solution, and one of the major limiting nutrients for crop production in SSA (Sanchez et al., 1997). Thus, a strategy of building up N capital in the soil would need to be coupled with the building up of soil organic matter (i.e. organic N), as mineral N is rapidly lost by leaching if not captured by crops (Giller et al., 1997). However, N inputs sufficient to increase biomass production and thereby soil organic matter are unlikely to be justified by immediate physical and/or financial returns, unless the efficiency of N ‘capture’ within the farm system is increased.

Analysing trade-offs of this nature implies also that multiple indicators need to be monitored simultaneously for the assessment of management strategies. Next to food production and changes in soil properties for a certain field within the farm, emphasis should be placed on labour productivity, since labour is often assumed to be the most limiting resource for the household (Barrett et al., 2002). Thus, the complexity of the interaction between multiple processes underlying agricultural production and farmers’ decision making has to be embraced while designing research questions. For example, how best can farmers invest their labour and resources in the different fields (i.e. soil quality classes) within their farms in terms of achieving high overall physical (food) and economic returns to such resources at farm scale? Trade-offs in resource and labour allocation can be identified and analysed by means of integrated bio-economic models, which are able to simulate the biophysical processes that affect crop production and resource use (capture and conversion), the effect of management decisions, and their resulting impact on household income.

In search of methodologies to build up a truly integrated bio-economic model, Brown (2000) reviewed different modelling approaches and classified them along a continuum: at one extreme, the biophysical models to which an economic balance has been added, and at the other, the economic optimisation models that include biophysical components as ‘activities’ among the various choices for optimisation. The latter is the case of the multiple-goal linear programming models (MGLP), which have a strong economic focus and in which the biophysical processes are introduced as input/output combinations, represented by linear functions. MGLP models have been extensively applied to land use studies at different scales (e.g. van Ittersum et al., 1998), and since linearity is not common among the functional relationships that describe biological processes relevant to agricultural production piecewise linear functions have been used to approximate non linear functions (e.g. Herrero et al., 1999). Despite some interesting applications to the multi-scale analysis of trade-offs related to land use in sub-Saharan African systems (e.g. Lopez-Ridaura, 2005), their performance in assessing alternatives and innovations for natural resource management in smallholder farms has been critically revised (van Paassen, 2004). Biophysically-biased, dynamic simulation models are suited to capturing farm heterogeneity in resource use efficiency, non linear relationships (e.g. crop responses to applied nutrients) and feedbacks among different processes. However, optimisation of multiple objectives using dynamic models *per se* is virtually impossible, and often inverse modelling techniques are used to select combinations of values for a number of model parameters to optimise an objective function related to model performance (e.g. to minimise the difference between model output and measured variables). Dynamic models are also often used as technical coefficient generators for MGLP models, involving several operational instances and not achieving a true functional integration of the biophysical and economic aspects of the system (e.g. Castelán-Ortega et al., 2003).

Understanding the trade-offs faced by farmers when making operational (i.e. day to day) management decisions is a basic premise for addressing farm-scale questions related to: (i) the efficient use of their available resources; and (ii) the possibilities for technological interventions aimed at the sustainable intensification of the smallholder systems. We propose a new method for optimising farm-scale objectives and analysing trade-offs relevant to the sustainable intensification of farming systems, using inverse modelling techniques. MOSCEM (Multi-Objective Shuffled Complex Evolution Metropolis) (Vrugt et al., 2003) is an algorithm that can be used to optimise several objective functions and map out Pareto-optimal sets of value combinations for a number of model input parameters. DYNBAL (DYNamic simulation of Nutrient BALances), a dynamic, process-based model that was tested and used in western Kenya (Tittonell et al., 2006), was linked to MOSCEM and used to simulate the underlying biophysical relationships that operate at field scale (crop growth, water balance, soil erosion, C and N dynamics, etc.), coupled with labour requirement relationships based on household data collection. This integrated analytical tool allows analysis of trade-offs while maintaining an appropriate degree of detail on the biophysical processes simulated and on their interactions and feedbacks.

We used this combined analytical tool to explore alternative management strategies for maize production in a case study farm from a densely-populated region in the highlands of western Kenya. This region has high agricultural potential, with soils that were originally fertile, mild temperatures and ample rainfall (Jaetzold and Schmidt, 1982). However, continuous cultivation without sufficient nutrient input has led to current maize yields ranging from 1 t ha^{-1} up to 2 t ha^{-1} in the more fertile fields (while on-station yields may be as high as 8 t ha^{-1} – Schnier et al., 1997), due mainly to poor soil availability of N and P (Shepherd et al., 1996). Nutrient resources such as mineral fertilisers and cattle manure represent important cash and labour investments for smallholder farmers, and the physical returns to such investments are highly affected by the spatial heterogeneity in soil quality characteristics of these systems (Vanlauwe et al., 2006). To reduce nutrient losses and thereby increase the efficiency of nutrient use (capture) within the system, parallel measures such as soil erosion control need to be employed. Our objective was to analyse trade-offs between N, cash and labour allocation strategies for ensuring food security, improving the efficiencies of nutrient capture and reducing soil losses in a simplified, case-study smallholder farm system from Kakamega district, western Kenya.

2. Materials and methods

2.1 A simplified case-study farm system in western Kenya

2.1.1 The farm system

The village selected (Mutsulio, Kakamega district, western Kenya) was located in an area characterised by major constraints related to access to and development of markets, high pressure on land due to high population density, and poor soil fertility status after continuous cultivation for decades with few or no nutrient inputs (Table 1 A). Rainfall in the area has a bimodal pattern (i.e. the long and the short rains) and maize is the main grain crop cultivated for home consumption and the market. The analysis focused on a simplified farm system derived from data collected through qualitative and quantitative on-farm system analysis, using participatory rural appraisal techniques to assess resource flow and labour allocation patterns (Tittonell, 2003). The case study farm system selected for scenario analysis represented a relatively wealthy farm within its context, better-endowed than the village average for the total area of cropped land, area under cash crops, number of livestock, farm assets and general wealth indicators (e.g. type of house) (Table 1 B). It was purposely selected to allow an ample range of assumptions to be made in relation to investments, resource availability and resource allocation decisions made by the farmer. This particular case farm household generated most of its income from farming, by growing tea and keeping dairy livestock, having surpluses of food crops that were also sold on the market. The farm had an area of 2.2 ha under maize, which was the dominant crop grown for home consumption with the surplus sold into the local market (Figure 1).

Table 1: (A) Biophysical and socioeconomic characteristics and main production activities of the study area in Kakamega district, western Kenya; (B) Comparison of key indicators between the average for 20 farms sampled in the village and the case-study farm household (values between brackets indicate standard deviation)

(**A**)

Biophysical and socioeconomic characteristics	Altitude 1800 m.a.s.l.; Total annual rainfall 2200 mm; Mean temperature 20.8 °C; Landscape: Very undulating topography (slopes up to 45%), heavily dissected fluvial landscape characterise by a continuum of ridges (uplands), breaking slopes, foot slopes and valley bottomlands; Soil types: Dominated by *humic Nitosols* and *dystro-mollic Nitosols* (FAO) in the uplands and slopes, locally known as *Ingusi* soils; Population density: 650 inhabitants km^{-2}, Ethnic group: Luhya
Main production activities	Food crops: maize/beans, secondarily sorghum, cassava and sweet potato; Cash crops: tea, coffee, sugarcane, fruits and vegetables; maize and beans also regarded as income-generating crops; Livestock: Local Zebu breeds and some graded dairy cows. Zero grazing, or grazing in communal land.

(**B**)

	Cropped area (ha)	Family size	Number of livestock*	% area under tea	% off-farm income	Months food self sufficiency
Village average	1.3 (1.5)	6.8 (1.7)	3.2 (2.4)	10.5 (22)	25 (16)	8.9 (1.7)
Case study farm	2.4	8.0	1.3	17.5	23	11.0

*No distinction made with regard to breeds; the value for the case study farm indicates 1 dairy cow + 1 calf (1.0 + 0.3).

Soil samples were taken from each individual field and analysed for particle size distribution, soil organic C, total N, available P, exchangeable bases and pH following standard methods for tropical soils (Anderson and Ingram, 1993). Soil bulk density was measured using standard sampling rings at intervals of 0.1 m up to 0.3 m depth. The slope of the field was measured using a clinometer. During one of the visits to the farm, the farmer was requested to classify his land according to his perception of soil quality into fertile (+), average (+/-) and poor (-) fields, and the area of all the fields belonging to each of these classes was summed up (Figure 1). The slope of the fields (soil erosion) and the colour of the topsoil (organic matter content) were the main criteria used by the farmer to classify his fields, and there was in general good agreement between farmers' classification and the variation in the value of most soil fertility indicators that were measured (Tittonell et al., 2005c).

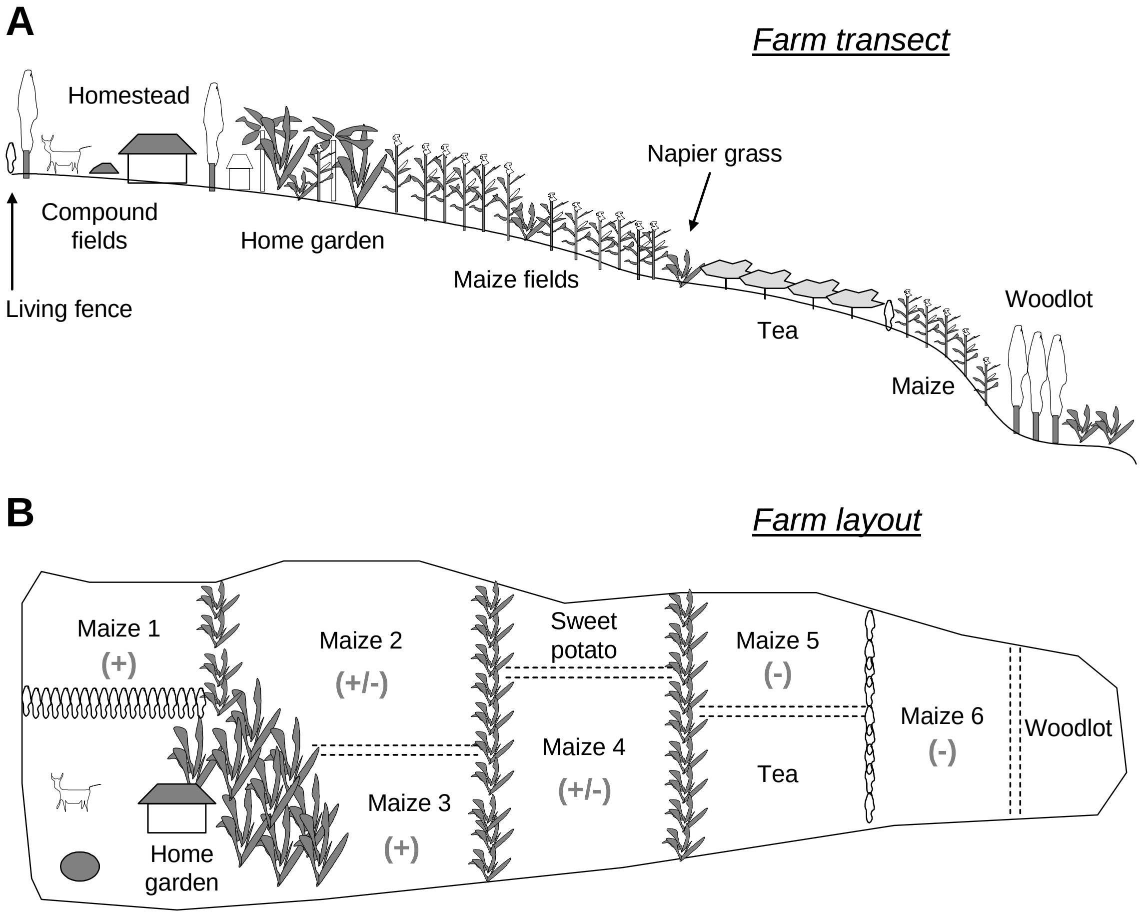


Figure 1: A schematic representation of the case study farm. (A) Farm transect; (B) Farm layout. The 'quality' of each individual field or portion of the farm as classified by the farmer is indicated with signs: (-) poor, (+/-) average and (+) fertile land. In our simplification of the system, only maize was considered (ca. 80% of the cropped area), the farm was divided in three land quality units, the area of all fields planted to maize within each land quality unit was summed up, and weighed average soil indicators calculated for each unit and used to parameterise 3 instances of the model DYNBAL.

The simplified farm was divided into these three land quality units that were assumed to be homogeneous in terms of soil properties, and all the fields of the farm planted to maize were grouped in each of them (e.g. in Figure 1, Maize 1 and Maize 3 were treated as one unit: (+) fertile). Thus, our simplified farm system consisted of three maize fields: one poor (0.4 ha), one average (1.3 ha) and one fertile (0.5 ha) (Table 2). To parameterise the model for these three different land qualities, the various indicators of soil properties were averaged for each land quality unit, using:

$$WASP_{(X)j} = \sum_{i=1}^{n} SP_{(X)ij} * (FAi / TALQj)$$

Where,

$WASP_{(X)j}$ = Weighed average soil property *X* for land quality *j* (with *j* = 1 to 3: poor, average and fertile)

$SP_{(X)ij}$ = Soil property *X* measured in field *i* (= 1 to *n* fields) within land quality *j*

FA_{ij} = Area of each particular field *i* within land quality *j* [ha]

TALQj = Total area of the farm classified as land quality *j* [ha]

The main biophysical parameters used to characterise the land quality units for the simulation runs (weighed averages) are presented in Table 2, and current prices at farm gate collected during January/February 2005 in several villages across western Kenya in Table 3.

2.1.2 Assumptions

Several assumptions were necessary to simplify the system for the analysis at this early stage in the development of our methodology. It was assumed that maize was the only (sole) crop grown in all fields of the farm. Apart from the main operations considered in the model (cultivation, weeding and soil erosion control), timely management was assumed for all other operations and fields (e.g. date of fertilisation), which in reality does not occur, as farmers prioritise their best fields when allocating their labour (Tittonell et al., 2007a). Labour was priced using local wages paid for hired labour, without discriminating between labour owned and hired, and in both cases man-days of 8 h per day were assumed. This assumption could be made on the basis that wealthier farmers normally use hired labour (permanent or temporary) for most farm activities. Other costs associated with hiring labour (e.g. offering meals to the casual workers) were not considered. Differences in soil fertility between land quality classes were assumed to be due to soil C and total N, while other nutrients were not limiting. This assumption, however, is quite unrealistic for P (Vanlauwe et al., 2006). Based on the latter study, it was simplistically assumed that fertiliser P was added to the soil when the rate of N fertilisation exceeded 60 kg N ha^{-1} at a rate of 0.1 kg ha^{-1} of P per kg ha^{-1} of applied N (a 10:1 N/P ratio), thereby increasing the costs of the nutrient inputs. Availability of fertilisers in local markets was assumed (i.e. low transaction costs for fertiliser acquisition assumed), which is not always the case in rural areas of western Kenya. Many of these simplifying assumptions may result in departures of optimal outcomes generated by the model from the actual situation. Thus results at farm scale should be interpreted with caution, particularly because other farm and non-farm activities that generate income (e.g. tea growing, dairy production, off-farm employment, cash remittances, etc.) were not considered when aggregating results at farm scale.

Table 2: Key biophysical parameters used to characterise the different land quality units for the simulation runs and range of measured maize yields

Land quality class	Area per land class (ha)	Clay content (%)	Silt content (%)	Soil organic C (g kg^{-1})	Total soil N (g kg^{-1})	Bulk density (Mg m^{-3})	Slope length (m)	Slope steepness (%)	Water content at field capacity (% v/v)*	Maize yields (t ha^{-1})
Fertile	0.5	39 +/-5.4	41 +/-3.0	21.6 +/-3.9	2.3 +/-0.4	1.26 +/-0.4	25 +/-8	2.1 +/-1.9	42	1.8 – 2.9
Average	1.3	33 +/-8.5	44 +/-5.6	17.9 +/-3.0	1.6 +/-0.5	1.24 +/-0.4	38 +/-18	9.6 +/-2.1	38	0.9 – 1.4
Poor	0.4	21 +/-7.2	50 +/-9.0	14.4 +/-3.2	1.7 +/-0.2	1.29 +/-0.3	39 +/-22	22.7 +/-11.0	35	0.5 – 1.2

*Calculated on the basis of particle size distribution, soil C content and bulk density (van Keulen, 1995).

Table 3: Reference prices and calculated costs used for the simulation scenarios; data collected during January-February 2005 through interviews with key informants: farmers, extension agents, input suppliers and technicians of research institutes (*n* = 9 – 16). Exchange rate 75 KSh = 1 US$.

Item [unit]	Price (KSh)	*CV (%)*	Use* (units ha^{-1})	Cost** (KSh ha^{-1})
Maize grain [Bag of 90 kg]				
January to June**	1620	*7.3*	-	-
July to December	860	*10.4*	-	-
Maize seed (hybrids 513, 614) [kg]	135	*4.0*	30	4050
Fertiliser prices [Bag of 50 kg] ***				
Di-ammonium phosphate (18:46:0)	2100	*6.7*	-	-
Calcium ammonium nitrate (46:0:0)	1870	*16.4*	-	-
Triple super phosphate (0:46:0)	2000	-	-	-
Manure [wheelbarrow ca. 30 kg FW]				
Good quality manure (e.g. 3% N)	50	*26.7*	-	-
Poor quality manure (e.g. 0.7% N)	32	*49.6*	-	-
Hired labour [person-day]				
First ploughing (hoe)	160	*14.0*	20.0	3200
Second ploughing, manure application and planting	87	*26.6*	24.4	2120
Weeding	380	*50.6*	11.1	4222
Harvesting (including chopping of crop residues)	97	*13.5*	26.6	2590
General farm husbandry (e.g. animal feeding, milking)	55	*15.7*	-	-
Soil movement (digging, trenching)	150	-	-	-
Ox ploughing [acre]	1350	*15.7*	2.2	3000

*Calculated for a typical maize crop, using input rates derived from participatory resource flow mapping. Labour needs for certain practices (e.g. manure application) depends on field characteristics such as distance from the homestead, accessibility, application rates, soil texture, crop yield, etc.
**In reality, casual labour costs are higher, as farmers are obliged to provide two meals per full working day to each employed person.
**Scarcity period: from the end of the short rains until harvest of the long rain season. Retail prices for that period are about 40 KSh per *goro-goro* (c. 2 kg).
***Prices are highly variable and more expensive when fertilisers are sold in bags of 1 – 2 kg by local input suppliers.

2.2 The analytical tool

2.2.1 The dynamic model: DYNBAL

Different crop and soil management situations within the farm were simulated using DYNBAL, a dynamic model that calculates N balances considering daily rates of inputs to and outputs from a certain field within a farm. The model includes four different sub-models or modules: crop growth, soil organic matter dynamics, water balance and soil erosion that provide the information for calculating the N balance, and simulate the interactions taking place during crop growth (e.g. effect of leaf area expansion on soil cover and erosion losses), using daily weather data inputs. The net rate of change of N in the system (field), or nitrogen balance, is the result of the N inputs and outputs to that particular soil/crop unit within the farm. N inputs include applications as mineral and organic fertiliser and as household wastes, N inputs from wet and dry deposition and from non-symbiotic N_2-fixation. N outputs include gaseous losses, leaching, soil erosion and N removal by harvest. The model considers a soil/crop system defined by the area of a certain field within a farm, so each field is simulated separately. The time span is the growing season, starting with soil preparation for planting and finishing after harvest (of grain and stover). The crop chosen for simulation is maize, as it is the main grain crop grown in the region and is highly responsive to soil fertility and management. The model parameterised for maize has been tested against on-farm data from western Kenya and yielded reasonably accurate predictions of on-farm yields and the response of the crop to applied fertilisers on different soil qualities (Figure 2). A more detailed description of the model and its calibration and testing for the region is given in Tittonell et al. (2006).

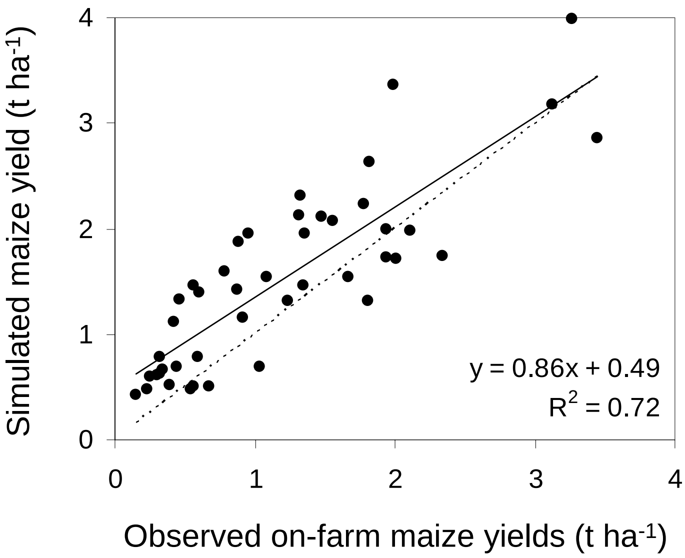
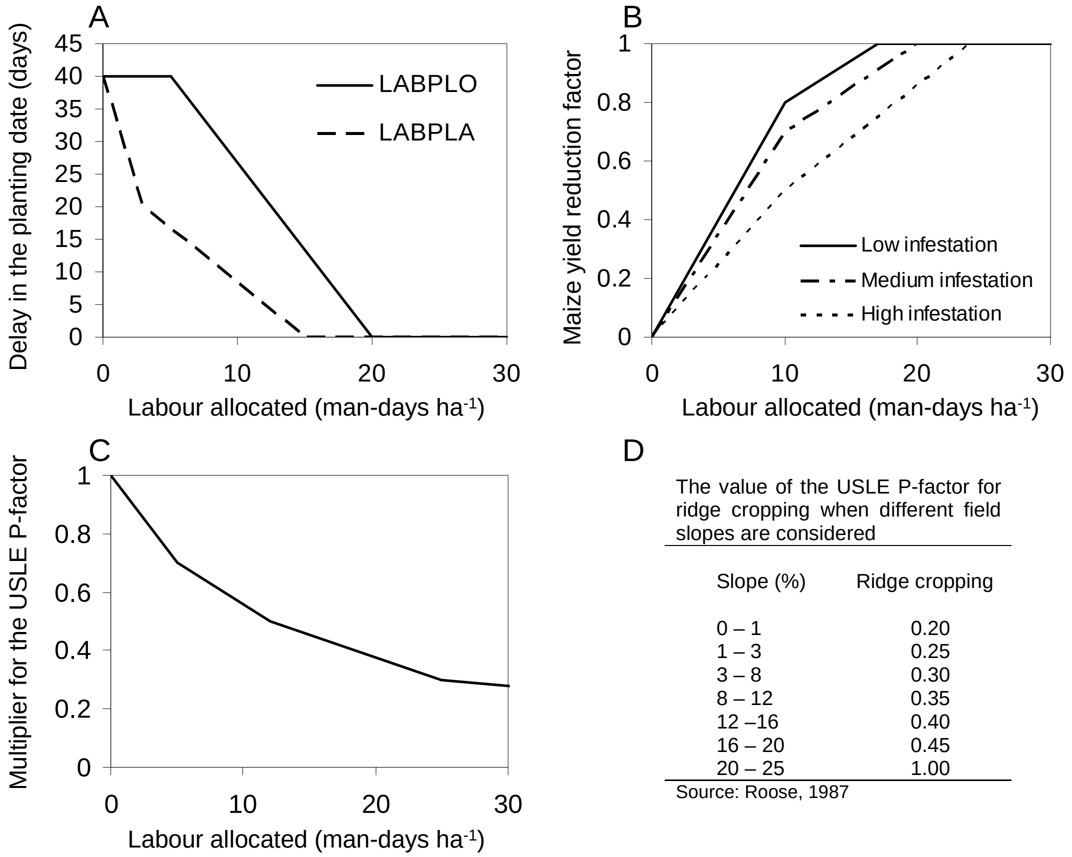


Figure 2: Testing of the model DYNBAL against on-farm maize grain yields in western Kenya, including fertilised and non-fertilised fields, using mineral and organic fertilisers. Details on the process modelled and model performance for western Kenya given by Tittonell et al. (2006).

2.2.2 Labour demand functions

Labour demands of different management activities were derived from data on labour calendars and participatory resource flow mapping exercises conducted on 60 farms from western Kenya (Tittonell, 2003), and functions relating labour allocation to different model parameters were built into DYNBAL (Figure 3). Three types of labour directly affect processes simulated by the model: labour allocated to land preparation and planting (*LABPLO* and *LABPLA*), to weeding (*LABWD*) and to erosion control through ridge cropping and mulching (*LABEC*). Such a distinction was made because these activities may take place at different times during the growing season.



The value of the USLE P-factor for ridge cropping when different field slopes are considered

Slope (%)	Ridge cropping
0 – 1	0.20
1 – 3	0.25
3 – 8	0.30
8 – 12	0.35
12 –16	0.40
16 – 20	0.45
20 – 25	1.00

Source: Roose, 1987

Figure 3: Labour demand functions developed from participatory resource flow mapping and plenary discussion with farmers in western Kenya and build into the integrated analytical tool DYNBAL-MOSCEM. (A) Labour availability for land preparation and planting vs. delay in planting date; (B) Labour availability for weeding vs. maize yield reduction factor due to weed competition for fields with different weed infestation levels (scored by farmers); (C and D) the P-factor of the universal soil loss equation (USLE), indicative values for ridge cropping and a multiplier to account for labour availability for ridging.

The allocation of total available labour to cultivation and planting affects the planting date of the crop; cultivation is done manually by hand hoe (animal traction is not employed). When insufficient labour is allocated to these activities there is a delay in the start of crop growth which, depending on the length of this delay, will affect crop yield (Figure 3 A). The mathematical expression used to calculate this effect in the model was:

$$DELAY = MIN\left\{40, 40 - \frac{40}{20} \times (LABPLO - 5)\right\}$$

Where, *LABPLO* is the amount of labour (man-days ha^{-1}) allocated to land preparation and *DELAY* is the delay in planting date (days) with respect to the optimum date for the area. The shape of these functions is explained by the fact that no delay in the planting date longer than 40 days was recorded; for labour allocated to second ploughing (including manure application) and planting (*LABPLA*), 3 man-days per ha was considered by farmers as a reasonable threshold.

Restricting labour allocation to weeding reduces the value of a yield reduction factor due to weed competition (Figure 3 B). This simplistic approach was chosen because weed competition is not simulated dynamically in the current version of DYNBAL. A database consisting of on-farm maize yield measurements, management practices applied, soil fertility and weed infestation levels was used to derive these functions (Tittonell et al., 2007a). It was assumed that when a certain amount of the available labour is allocated, weeding is done on time and there is no effect on crop yield. This threshold value varies for different intensities of weed infestation, regardless of the type of weed considered; three weed infestation intensities were recorded in the field and no *Striga* infestation was observed in any of the farms visited in Kakamega. The equation used in the model to calculate this effect was:

$$Yield_{reduction} = MAX\left\{0, MIN\left[1, \frac{0.8}{10} \times LAB_{weed}, 0.8 + \frac{0.2}{7.5} \times (LAB_{weed} - 10)\right]\right\}$$

Where, LAB_{weed} represents the amount of labour allocated to weeding (man-days ha^{-1}), and $Yield_{reduction}$ is the multiplier (taking values between 0 and 1) used to calculate the reduction in yield due to weed competition.

Soil losses by erosion are calculated in DYNBAL using a version of the universal soil loss equation (USLE) adapted for tropical conditions (Roose, 1983):

Soil Loss $(t\ ha^{-1}\ yr^{-1}) = R \times K \times S \times L \times C \times P$

Where, R represent the erosivity of rainfall, *K* the soil erodibility, *S* and *L* the steepness and length of the slope, *C* the type of crop covering the soil surface and *P* the effect of erosion control practices. In DYNBAL, *R* is calculated based on daily rainfall using the equation proposed by Roose (1983), *K* is estimated from soil texture and C content using the nomograph of Whitmore and Burnham (1969), and *C* is linked to leaf area development as simulated by the crop module and affected by a coefficient that represents the effect of mulching if present (Colvin, 1981). Values for the factor *P* for the practice of ridge cropping, as calculated by Roose (1987) when the slope of the field increases from 0 to 25%, are given in Figure 3D.

Labour allocated to soil erosion control through 'non-permanent' methods such as soil ridging was related to the factor *P* of USLE through a multiplier ranging between 0 and 1, which increases the value of the factor *P* as less labour is available for erosion control (Figure 3 C). This empirical curve was derived from estimated values of *P* for different cropping systems from soil erosion plots in western Kenya (Rao et al., 1999), and by assuming that labour demands for soil movement to control erosion are similar to those for land preparation (first ploughing). Semi-permanent erosion control measures such as terracing were not considered, as they are not currently practised by farmers in the region (existing terraces were built when enforced by law during colonial times).

These functional relationships represent working assumptions that consider the interaction of various factors that may operate simultaneously within the farming systems analysed. For example, when ploughing of a certain field is delayed too late into the cropping season due to labour shortage, farmers may decide not to plant a crop at all and to leave the field fallow. Or, when certain fields within the farm were planted on time, labour demands for weeding the emerged crops start competing with labour demands for working on the other fields that remained unploughed. We recognise that linearity does not always hold for the relationship between labour availability and timing of management practices that are often affected by stochastic events (illness, social demands such as funerals etc.), but we consider this a reasonable assumption for the aims of this analysis.

2.2.3 The farm-scale aggregation and optimisation algorithm: MOSCEM

As stated in the introduction, farmers in Africa operate under severely resource-constrained conditions, and are often confronted with multiple competing options for investment in hired labour and/or inputs. To help understand the trade-offs faced by such farmers, we propose the use of multi-objective evolutionary algorithms to examine the entire range of acceptable (Pareto optimal) management strategies. The multi-objective optimization problem can be stated as follows (here expressed as a minimisation problem):

$$\min_{\theta \in \Theta} F(\theta) = \begin{bmatrix} f_1(\theta) \\ \vdots \\ f_T(\theta) \end{bmatrix}$$

where $f_i(\theta)$ is the *i*th of *T* objective functions. The solution to this problem will in general, not be a single "best" parameter set but will consist of a Pareto set of solutions corresponding to various trade-offs among the objectives. This Pareto set defines the parameters (or decision variables) along the best possible trade-off curve between a certain number objectives (f_i to f_T), without stating a subjective relative preference for minimizing one specific component of $F(\theta)$ at the expense of another. To further illustrate this concept, consider Figure 4 which depicts the Pareto solution set for a simple problem where the aim is to simultaneously optimize two objectives (f_1, f_2) with respect to two parameters (θ_1, θ_2). In our case, the parameters will define the management strategy in the DYNBAL model, and will therefore from now on be termed decision variables. The points A and B indicate the solutions that optimize each of the individual criteria f_1 and f_2, whereas the solid black line joining A and B corresponds to the Pareto set of solutions. The black dots represent an initial set of parameter estimates, while the number in subscript denotes their corresponding Pareto rank. Moving along the line from A to B results in the improvement of f_2 while successively causing deterioration in f_1. The points falling on the line AB represent trade-offs between the objectives and are called non-dominated, non-inferior, or efficient solutions.

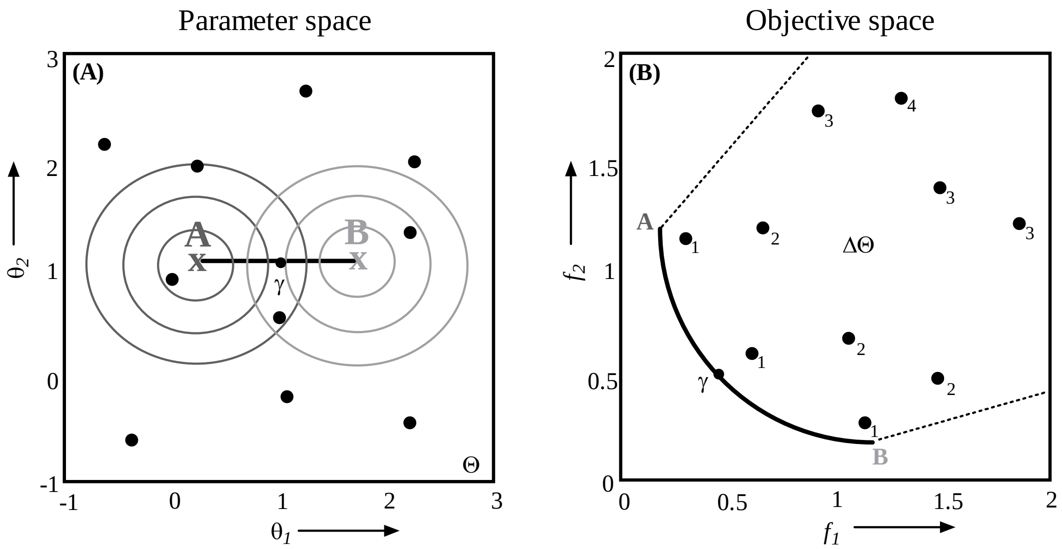


Figure 4: Illustration of the concept of Pareto optimality for a problem having two parameters (θ_1, θ_2) and two criteria (f_1, f_2), in the parameter (Fig. A) and objective (Fig. B) space. The points A and B indicate the solutions that minimize each of the individual criteria f_1 and f_2. The thick line joining A and B corresponds to the Pareto set of solutions; γ is an element of the solution set, which is superior in the multi-criteria sense to any other point in Θ (After Vrugt, 2004).

While it may be relatively simple to pose the optimization problem in a multi-objective framework, solving this problem to identify the Pareto set of solutions is not easy and has been the subject of much research. Ideally, the multi-objective optimization algorithm should find the set of all non-dominated solutions, which will constitute the global trade-off surface. However, because computational resources are finite, multi-objective solution algorithms typically approximate the Pareto set using a number of representative solutions. For linear models, multi-objective linear programming (MOP) methods can be used to analytically derive the set of efficient or non-dominated Pareto solutions (Cohon, 1978). However, for nonlinear settings with a dynamic state variable model such as DYNBAL (in which the time dimension is included and in which the values of state variables can change over time), an alternative class of solution algorithms is needed.

An effective and efficient non-classical method for solving the multi-objective optimization problem in its original form has recently been developed (Vrugt et al. 2003). The method, entitled the Multi-Objective Shuffled Complex Evolution Metropolis (MOSCEM-UA) algorithm, is a general purpose global optimisation method that provides an efficient and effective estimate of the Pareto solution space within a single optimisation run and does not require subjective weighting of the various objectives. The MOSCEM-UA algorithm combines the strengths of complex shuffling (Duan et al. 1992), Metropolis annealing search (Metropolis et al. 1953), and multi-objective fitness assignment (Zitzler and Thiele 1999). The specific strengths of this method are the global search in space and a relative fast convergence to the parameter ranges of optimal solutions. Experiments conducted using standard synthetic multi-objective test problems have shown that the final population provides a fairly uniform approximation to the Pareto solution space (Vrugt et al. 2003).

Operationally, MOSCEM takes an initial population of points (i.e. combinations of management parameters for the DYNBAL model in our case), randomly spread out in the feasible parameter space. For each individual of the population the multi-objective vector $F(\theta)$ is computed, and the population is ranked and sorted using an improved version of the fitness assignment concept developed by Zitzler and Thiele (1999). The population is partitioned into several groups and, in each group k (k= 1,2,3…. q), a parallel sub-group is launched starting from the point that exhibits the highest fitness. A new candidate point in each sub-group k_1 is generated using a multivariate normal distribution centred on the current draw of sub-group k_1 augmented with the covariance structure induced between the points in group k. A Metropolis-type of acceptance rule is used to test whether the offspring (candidate point) is accepted. If the offspring is accepted, it replaces the worst member of the current group k. After a number of iterations, the groups are replaced into the fixed population of points and new groups are formed through a process of shuffling (short sliding step or movement). Iterative application of the various algorithmic steps causes the population to converge toward the Pareto set of solutions.

2.2.4 The integrated tool

We used DYNBAL to construct a simplified representation of a smallholder farm in Western-Kenya with three zones of soil fertility. The criteria to simplify the system and the assumptions necessary were given in Section 2.1. Three instances of DYNBAL were parameterised, each representing a land quality unit, using the values given in Table 2 for parameterisation and initialisation of the model; no spatial interactions between land quality units were simulated. As each land quality unit comprises various fields and represent different areas within the farm, there might be a certain degree of variability within each unit that may lead to aggregation errors at farm scale.

A certain amount of cash was assumed to be available at the beginning of the season, which could be invested in fertilizer or in hiring extra labour. The assumption on investments in labour and fertilisers was based on calculations done from the results of the resource flow maps drawn by the farmer for the long rains season (i.e. amounts of fertiliser and labour allocated to each field times the price of these production factors – Table 3). An average investment in hired labour and fertilisers for maize production of c. 3400 KSh ha^{-1} was calculated for this particular (relatively wealthy) case study farm. These externally-sourced resources together with the resources available internally within the farm were then allocated over the three fields. Using these inputs together with the other, standard inputs for DYNBAL (e.g. rainfall, radiation, temperature) each instance of the DYNBAL model was run for one growing season. Outputs of each of the DYNBAL instances, each representing one field type, were then aggregated to obtain results at the scale of our simplified farm system. For example, total farm maize yield was calculated by summing the maize yields of each of the land quality units. The objectives maximising farm yield, minimising farm erosion and minimising farm scale N losses – see later: Section 2.3.2 and Table 4, were optimised using MOSCEM by searching the best combination of values for the various decision variables with regard to cash investments and allocation of resources (i.e., labour for specific activities and mineral fertiliser) over the three land quality units.

The optimisation using MOSCEM leads to identification of the combinations of decision variable values that result in optimal two-dimension trade-off curves between these objectives. These trade-off curves (Pareto sets) can be used in aiding decision-making provided that weights (preferences) and threshold values are given to each of the objectives, for example, by defining which level of soil erosion is acceptable and what would be the maximum yield that could be achieve under those circumstances. This type of model outcome can also be used in discussions among stakeholders about different objectives, such as productivity vs. land degradation. In contrast with the type of results obtained using techniques such as MOP, which provide only the best, optimal solutions, the results generated by MOSCEM indicate combinations of decision variables that yield results close to the optimal trade off curve, giving insight into a diversity of farming strategies that lead to similar values of the objective functions (i.e., management strategies that may lead to acceptable, although not optimal solutions).

2.3 Scenario analysis

2.3.1 The problem at stake

Nutrient use (fertilisers, manure) by farmers in the study area is limited due to their scarce availability (about 1 t manure cow^{-1} season^{-1} can be recovered with good management, representing an application rate as low as <0.5 t ha^{-1} for our case-study farm), to their cost (in terms of cash and/or labour) and to the poor results obtained with their use; i.e. large nutrient losses, particularly for N. Soil erosion is a major problem for the sustainability of the farming systems on this heavily dissected landscape receiving 2000 mm of rain per year (cf. Table 1). During the field assessments, farmers often ascribed yield variability to differences in the slope of the fields (i.e. this was true for some 60% of the farmers who participated in the study in Shinyalu division, Kakamega). Areas of steep terrain within their farms were perceived as ‘poor soils’, prone to excessive run-off and ‘washing out’ of soil and fertilizers. Quantifiable indicators pertaining to both short- (food production) and long-term processes (soil erosion) were selected for the different objectives (Table 4). In the scenarios analysed, a certain amount of cash was available to the farmer at the beginning of the season, and decisions had to be made for its allocation to purchasing nutrient inputs and labour; these resources had to be allocated to different activities for the various field types (soil qualities) within his/her spatially heterogeneous farm.

2.3.2 Optimisation

Three scenarios of financial liquidity were analysed, in which initial cash reserves of KSh 2000, 5000 and 10000 (1 US$ = 75 KSh) per hectare were available to the farmer at the beginning of the season to invest solely in cropping practices (i.e. other household expenditures or investments in other activities such as livestock feeding were not considered). Investments in cropping practices included: buying mineral N fertiliser (Calcium Ammonium Nitrate), and hiring labour for land preparation and planting, for weeding and for soil erosion control. Since most labour was hired in by this particular household, a conservatively small value of 20 man-day season^{-1} was assumed to be the total amount of family labour allocated to maize production (based on labour calendars – Tittonell, 2003, 2007a), for all of the activities considered in this analysis, and all labour needed above that threshold must be hired. Another set of decision variables described the allocation of available resources at farm level (total N fertiliser bought by the farmer and the total labour hired in for land preparation and erosion control, planting and weeding) to each land quality unit within the farm. Parameters of the type ‘*fraction of the resource $\times$ allocated to the land quality j*’ were defined for the land quality units fertile and average (Fields 1 and 2, respectively), while the fraction allocated to the poor land quality unit (Field 3) was computed as 1 minus the sum of the fractions allocated to fertile and average.

The combination of possible investments in cropping practices and spatial allocation of the available resources led to a set of 12 decision variables to be analysed:

1. Fraction of the total cash reserves invested in mineral fertiliser;
2. Fraction of the total cash reserves invested in hiring labour for ploughing and planting;
3. Fraction of the total cash reserves invested in hiring extra labour for erosion control;
4. Fraction of the total cash reserves invested in hiring labour for weeding;
5. Fraction of mineral fertiliser bought allocated to fertile fields;
6. Fraction of mineral fertiliser bought allocated to average fields;
7. Fraction of labour hired for ploughing and planting allocated to fertile fields;
8. Fraction of labour hired for ploughing and planting allocated to average fields;
9. Fraction of extra labour hired for erosion control allocated to fertile fields;
10. Fraction of extra labour hired for erosion control allocated to average fields;
11. Fraction of labour hired for weeding allocated to fertile fields;
12. Fraction of labour hired for weeding allocated to average fields.

Table 4: Objectives selected for the optimisation and trade-off analysis. The underlined indicators were those selected to define objective functions.

Objective	Time scale relevance	Decision frame	Indicators	Optimisation criteria
I Primary				
1. Food production	Short-term	Operational	<u>Maize grain production</u> (t farm^{-1})	Maximise farm yield
2. Resource capture and use efficiency	Short and mid-term	Operational, tactical	<u>N losses</u> (kg N farm^{-1}) N balance (kg N ha^{-1}) Nitrogen productivity (kg grain kg^{-1} N applied) Gross N use efficiency (kg grain kg^{-1} N available) Rainfall use efficiency (kg grain mm^{-1})	Maximise N balance and minimise losses; N productivity larger than fertiliser:grain price ratio
3. Resource degradation	Mid and long-term	Tactical and strategic	<u>Soil losses by erosion</u> (t farm^{-1}) Changes in the N stock (%)	Minimise soil losses; positive changes in N stock
II Complementary				
4. Labour productivity	Short-term	Operational	Economic return to labour (KSh man-day^{-1})	Economic return above local labour wages
5. Economic viability	Short and long-term	Operational, tactical and strategic	Value of production (KSh) Gross benefit (KSh season^{-1}) Benefit/cost ratio	Maximise margin; minimise cost for potential production

Different combinations of these 12 decision variables were used, together with the standard model parameterisation for the three land quality units of this particular farm (cf. Table 2), to run the dynamic model. Indicators corresponding to those defined as primary objectives were selected for optimisation (i.e. defined as objective functions), while others were calculated from the model outputs for each scenario analysed (Table 4). Primary objectives included maize yield, N losses by leaching and erosion, and soil losses by erosion, all of them on a seasonal basis and aggregated at the farm scale, which were used to construct trade-off curves. For simplicity, and because the model runs were set for a single season (the long rains), it was assumed that soil lost from one field does not end up in the other fields as a sediment; i.e., fields were not spatially connected. We consider this to be a realistic assumption given the steepness of the most of the fields. From the model outputs, complementary indicators such as returns to labour, N use efficiency or gross economic margin were derived.

3. Results

3.1 Trade-offs between productivity, efficiency and resource conservation

3.1.1 Maize production and nitrogen losses

Increasing maize yields by applying mineral fertilisers was necessarily associated with larger N losses by leaching, runoff and soil erosion, as shown for the scenario of highest financial liquidity (KSh 10000) in Figure 5. Each point in the graph represents the model output for a certain combination of parameters (i.e. parameter set), when the objective functions were farm scale N losses and maize grain yields. The optimisation routine in MOSCEM starts with a randomly drawn initial population of parameter combinations (i.e. 'farm strategies') represented by the dots within the circle. During the optimisation, the population of solutions evolves towards the best possible trade-off curve between the two objectives. Such evolution is represented by the arrows in Figure 5 and all points on the outer curve represent Pareto efficient solutions. This trade-off curve is an outcome of the optimisation as it indicates either the maximum yields that can be achieved accepting a certain rate of N losses, or the minimum N losses that may be achieved sacrificing maize yields. On the Pareto efficient frontier, N losses at farm scale fluctuated between ca. 80 and 120 kg farm^{-1}, corresponding to rates of 36 to 54 kg N ha^{-1} season^{-1}, while the maximum maize yields achieved were around 3.4 t grain ha^{-1} season^{-1} (a farm scale production level of c. 7.4 t).

When the results of the different scenarios of financial liquidity are contrasted (KSh 2000, 5000 or 10000 available to the farmer; Figure 6), it is clear that the lower boundary of N losses at farm scale was similar in all three cases. This represents a baseline N loss rate (36 kg N ha^{-1} season^{-1}) calculated by the model that may be expected on this farm system under any of the resource allocation strategies. The major difference between the analysed scenarios was the attainable maize yield; it increased when more cash was available, but this led also to larger N losses. A rapid, more than proportional increase in the rate of N losses was obtained when maize production at farm scale increased above 6 t farm^{-1} (i.e. an average yield of 2.7 t ha^{-1}) in the highest cash availability scenario. Several allocation strategies within the poorest financial scenario led to the production of 4 t farm^{-1} of maize (average yield 1.8 t ha^{-1}), with farm scale N losses ranging around the baseline of 80 kg farm^{-1}. Yield levels as high as 1.8 t ha^{-1} are normally achieved in the most fertile fields of smallholder farms in western Kenya (cf. Table 2). N losses by leaching reported by previous studies on African systems were highly variable: 8 to 15 kg N ha^{-1} year^{-1} (Grimme and Juo, 1985), 10 kg N ha^{-1} year^{-1} (Akonde et al., 1997), or 36 to 153 kg N ha^{-1} year^{-1} (Poss and Saragoni, 1992), while N losses by erosion measured in western Kenya for different cropping systems ranged between 41 and 159 kg N ha^{-1} year^{-1} (Rao et al., 1999).

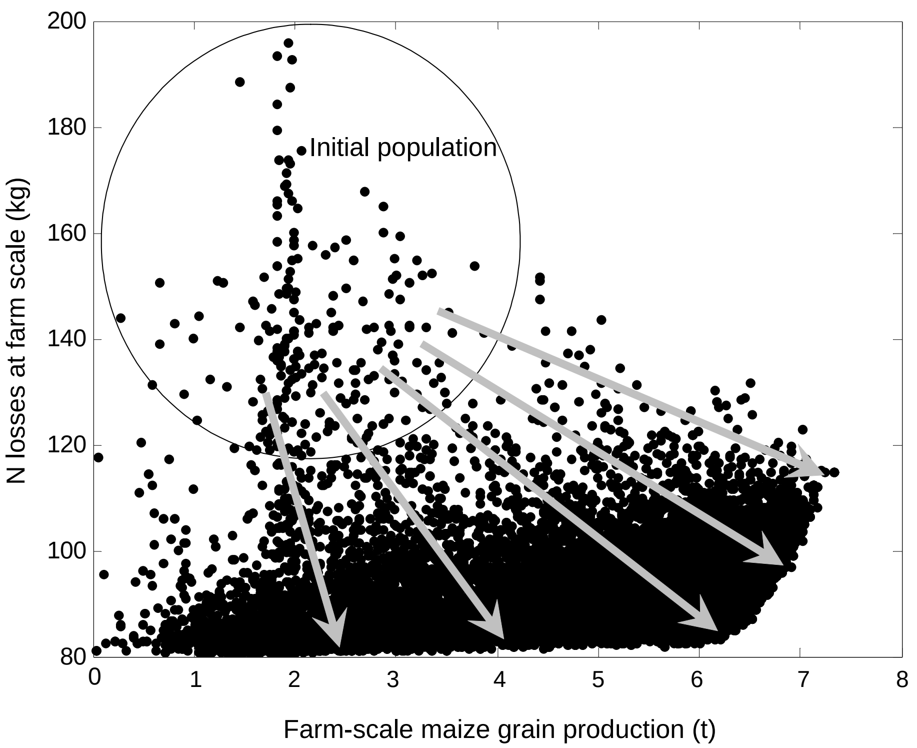


Figure 5: Results of the optimisation of the objectives ‘maximising maize production at farm scale’ and ‘minimising N losses at farm scale’ for the scenario of high investment capacity (10000 KSh ha^{-1}). The circle indicates the initial random population of feasible solutions (sets of DYNBAL parameter combinations) and the arrows indicate their evolution towards the Pareto efficient frontier (trade-off curve) after several iterations.

The model simulations indicate that more than c. 6.2 t farm^{-1} of maize can only be obtained by increasing the use of N fertiliser, directly resulting in larger N losses by leaching and poorer N capture efficiencies. To analyse what these trade-off curves imply in terms of investment and resource allocation strategies, the points (i.e.

'strategies', parameter sets) corresponding to farm-scale maize yields above 4.2, 5.5 and 6.8 t ha^{-1} (i.e. the points on the Pareto frontier to the right of each vertical line drawn in Figure 6) for the scenarios of KSh 2000, 5000 and 10000 initial cash reserves, respectively, were isolated. The combination of key model parameters leading to these points, which represent the fulfilment of the food production goal, are analysed in the following section.

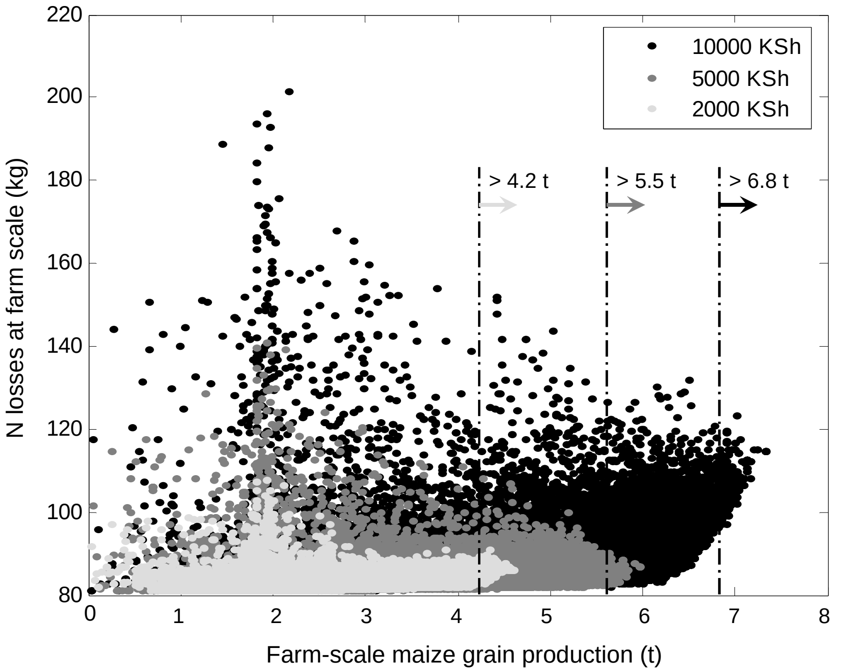


Figure 6: Results of the optimisation of the objectives 'maximising maize production at farm scale' and 'minimising N losses at farm scale' for the three scenarios of investment capacity (2000, 5000 and 10000 KSh ha^{-1}). The vertical lines indicate the yield thresholds for selection of the best sets of solutions in terms of maize production for each of the scenarios.

3.1.2 Investment and allocation strategies

Different investment strategies, in terms of hiring labour for the various management practices and buying mineral N fertilisers, which led to the highest maize production for each scenario are depicted in Figure 7. The investment strategies are expressed as fractions of the total cash available invested. Plotting the relative investment in buying N fertiliser against the relative investment in hiring labour for weeding (Figure 7 A), shows that hiring labour is a priority in all scenarios to obtain the greatest yields. Large yields were also obtained for the three scenarios when investments in hiring labour for land preparation were prioritised over labour for soil erosion control (Figure 7 B). These prioritisation patterns were stronger for the scenario with the least investment capacity, and the set of solutions leading to the greatest yields in this case was the most variable.

For the scenarios of poor and intermediate levels of investment capacity (KSh 2000 and 5000), prioritising weeding over mineral N fertiliser use was a more explicit decision pattern than when KSh 10000 were available to the farmer (Figure 7 A). Under the situation of low initial cash reserves, high maize production (> 4.2 t farm^{-1}) was achieved with a wider range of relative investments in weed control (0 to 50%) and N fertiliser (0 to 25%), compared with the other scenarios (i.e. the 'cloud' of solutions was more dispersed). When cash availability was KSh 5000, the strategies leading to the most production (> 5.5 t farm^{-1}) where those in which between 50 and 70% of the available cash was invested in weeding, while little was invested in N (0 to 10%). When KSh 10000 were available the relative investment in mineral N fertilisers increased up to 30-40% of the total cash available. The yield obtained using more N fertiliser in the high investment scenario (> 6.8 t farm^{-1}) allowed relatively less investment in labour for weeding (compensation), ranging roughly between 30 and 50%.

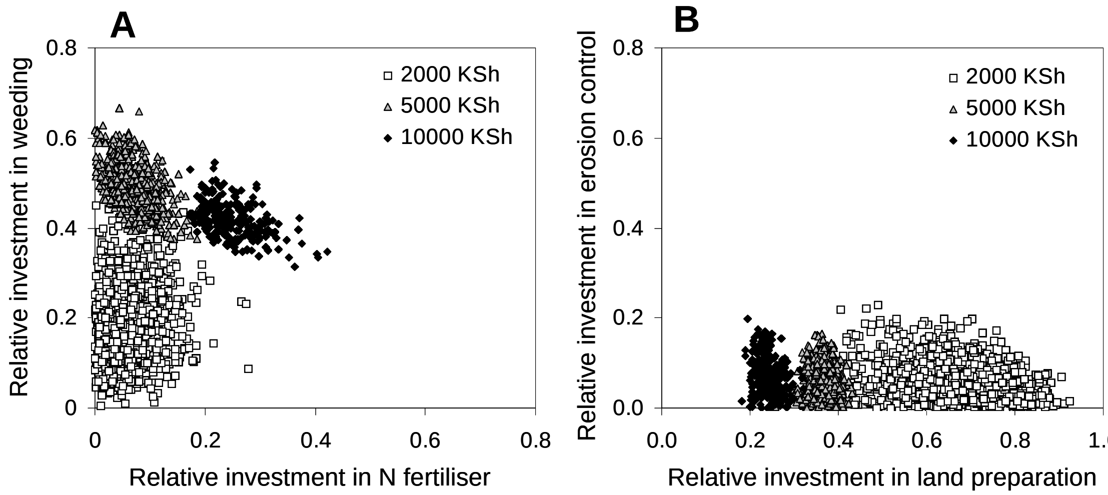


Figure 7: Relative investment of the available cash for the selected subsets of solutions (cf. Figure 5): maize production above 4.2, 5.5 and 6.8 t ha^{-1} for the scenarios of 2000, 5000 and 10000 KSh ha^{-1}, respectively. (A) Relative investment in labour for weeding vs. purchasing N fertiliser; (B) relative investment in labour for early land preparation vs. labour for erosion control (ridging of sloped fields).

Model results also indicated that in the case of low initial cash reserves, KSh 2000, most of that cash (45 to 85%) has to be invested in preparing the land for timely planting to fulfil the joint objectives of maximising yields and minimising N losses. In absolute terms, the investment in land preparation did not differ much between the scenarios of KSh 2000 and KSh 5000, while availability of KSh 10000 allowed earlier land preparation and therefore timelier planting of the crop. The strategy of prioritising labour for land preparation allowing early planting over using labour for ridge cropping is in line with previous model- and data-based studies that indicated planting date as one of the main factors affecting maize yield and nutrient use efficiency (Tittonell et al., 2007a). Again, the cloud of solutions leading to the highest yields for the scenario of low initial cash reserves was more dispersed (i.e. less sensitive) than those when more cash was available. It is important to note that early planting allows a faster canopy closure and proper soil cover that protects the soil surface from the effect of rainfall, also reducing soil erosion. The smaller investments in soil erosion control at the farm scale are also the result of differential resource allocation to the various fields of the farm. Ridging will substantially reduce soil erosion only in the fields of the farm where the slope is pronounced (cf. Table 2).

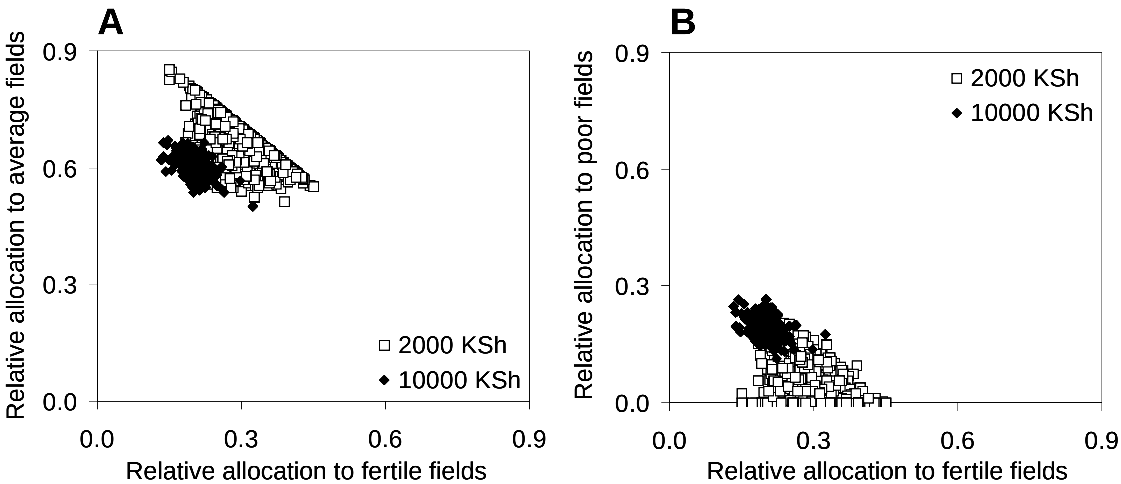


Figure 8: Relative allocation of labour available during weeding time to fields of different soil quality (fertile, average and poor) for the selected subsets of solutions (cf. Figure 5): maize production above 4.2 and 6.8 t ha^{-1} for the scenarios of 2000 and 10000 KSh ha^{-1}, respectively. (A) Relative labour allocation to fertile and average fields; (B) relative labour allocation to fertile and poor fields.

Thus, the relative spatial allocation of the acquired resources (fertiliser and labour) within the farm also had an impact on the strategies leading to the greatest yields for each scenario. This is illustrated for the allocation of labour to weeding within the farm for the lowest and highest investment capacity scenarios (Figure 8). When KSh 2000 were available to the farmer, the relative investment in (and the absolute amount of) labour available for weeding was small (cf. Figure 7 A). The best strategy to allocate this labour, according to the model results, is to focus it on the fields of better soil quality; 15 to 45% to the fertile fields and 50 to 80% to the average fields, which leaves little labour for the poor-fertility fields. The larger relative allocation to the fields of average soil quality is partly explained by its larger area, but also consistent with the economic theory suggesting that scarce resources are preferably allocated to activities that yield higher marginal returns. When KSh 10000 are available, allocation of around 20% of the hired labour for weeding to the poorest field becomes an option (note also that this field has a slope of > 20% and weeds may cover the soil and reduce erosion).

3.1.3 Maize production and soil erosion

For each of the three scenarios of initial cash reserves there was a range of increasing maize yield values that did not result in an increase in soil erosion (Figure 9). As in the previous analysis, better investment capacities allowed greater maize production to be achieved at farm scale. Above a certain threshold that varied for each scenario, there was a clear trade-off between increased yields and larger soil losses, but the nature of the trade-offs (i.e., the slope of the curve) differed markedly between the scenario of KSh 2000 and the other two. For the scenario of low initial cash reserves, soil losses by erosion increased abruptly beyond a certain maize production (c. 4 t farm^{-1}) due to less capacity to invest in erosion control. In the trade-off curves between N losses and maize production (cf. Figure 6), there were practically no differences between the minimum rates of N losses achievable for the different scenarios. In this case, however, the minimum achievable rates of soil loss by erosion varied among scenarios (Figure 9). For a certain maize production level, the rate of soil erosion was less when the availability of cash was higher, due to an increased capacity to invest in erosion control. These differences in soil loss rates, however, that were in the order of 1 - 2 t ha^{-1} yr^{-1} may not result in significant differences in reality, given the uncertainties in other parameters. In the zone of the curves corresponding to the greatest maize production, soil losses tended to increase, though at a clearly different incremental rate for the three scenarios.

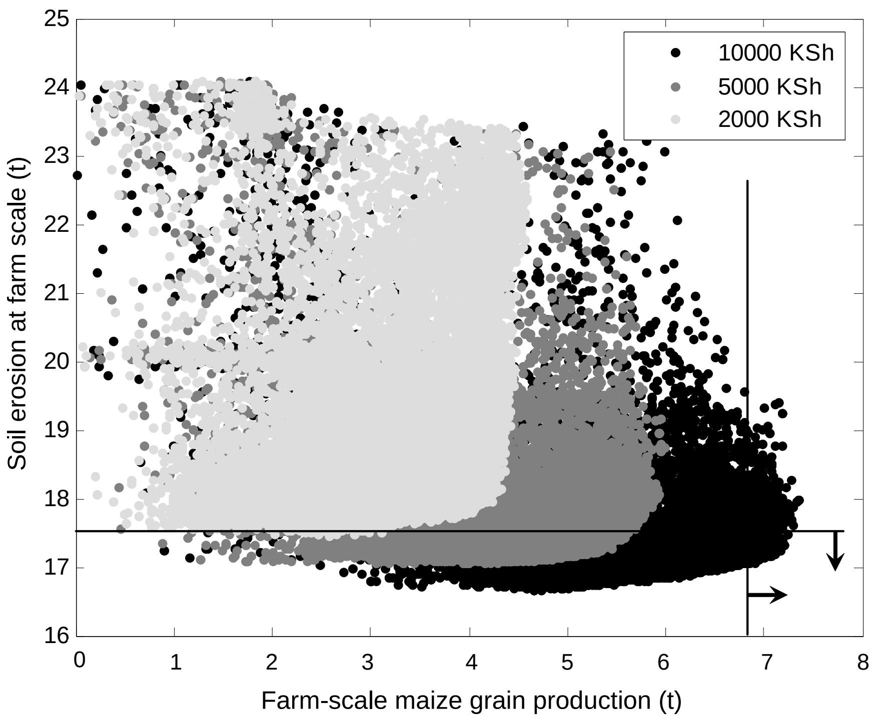


Figure 9: Results of the optimisation of the objectives 'maximising maize production at farm scale' and 'minimising soil losses by erosion at farm scale' for the three scenarios of investment capacity (2000, 5000 and 10000 KSh ha^{-1}). The vertical and horizontal lines indicate, for the high investment scenario (10000 KSh ha^{-1}), the subset of solutions that satisfy both objectives. The selected subsets were those with maize production larger than 6.8, 5.6 and 4.2 t farm^{-1} and soil erosion losses smaller than 17.5, 18.0 and 18.5 t farm^{-1}, respectively.

Larger yields associated with increased rates of soil erosion appear to be counter-intuitive, as larger biomass production would offer a better cover of the soil surface. This happened in the scenario of low initial cash reserves due to two main reasons: (i) the scarce labour available was mostly allocated to land preparation and weed control and almost nothing to erosion control; and (ii) given the poor yields, all fields had to be cultivated to achieve more than 4 t farm^{-1} of grain, leading to late planting of the poor-fertility field (>20% slope) without ridging. Larger initial cash reserves allowed more investment in labour to control erosion and therefore larger yields could be obtained reducing the cost of soil losses. Thus, the effect of cash availability was characterised by a shift from one trade-off curve to another; increasing cash investments were necessary for the system to 'jump' from trade-off situations of greater soil losses and smaller yields to more favourable ones. Thus larger maize yields were associated with smaller soil losses, but not through a direct relationship.

3.2 Compromise between food production and resource conservation

Further, we analysed compromise cases in terms of attaining food production and resource conservation objectives by isolating for each scenario the subset of solutions leading to the maximum maize yields with the minimum soil losses by erosion. The subsets of solutions selected comprised those with maize production larger than 6.8, 5.6 and 4.2 t farm^{-1} and soil erosion losses smaller than 17.5, 18.0 and 18.5 t farm^{-1} (equivalent to average soil losses of 8.0, 8.2 and 8.4 t ha^{-1}) for the scenarios of KSh 2000, 5000 and 10000 of initial cash reserves, respectively. Such a subset is indicated in Figure 9 for the KSh 10000 scenario; i.e. the subset of points along the Pareto set comprised in between the vertical and horizontal lines drawn in the graph (lower-right corner). The average rate of soil losses by erosion that can be expected under forest vegetation in this type of environment may be as high as 5 t ha^{-1} year^{-1} (M. van Noordwijk, pers. comm.), suggesting that the selected thresholds may be considered conservative for arable land. For each of these subsets of optimal solutions, the average value and standard deviation of the primary objective indicators, model parameters and complementary indicators achieved at farm scale were calculated (Table 5). For the same subsets of solutions, average indicators and allocation parameters and their standard deviation were calculated for each land quality unit within the farm system (Table 6; note that these values are expressed as per land quality unit and that the area of each of them within the farm varies, cf. Table 2).

For the scenario of high initial cash reserves, increased N leaching as a consequence of larger rates of N application (1.0, 3.8 and 26.8 kg N ha^{-1}) leads to a lower productivity of the applied N (Table 5). However, the productivity of the applied N was larger but also highly variable for the scenario of the lowest initial cash reserves, indicating that crop yields in this case varied from high apparent responses to applied N to virtual crop failure. When the availability of N in the soil was calculated from the values in

Table 2 and included in the calculation of the gross N use efficiency [= grain yield / (soil N + fertiliser N)], the average figures at farm scale indicated a more efficient use of the natural resource base with increasing investments. However, the gross N use efficiency varied widely across soils of different quality (Table 6). With increasing investments, more fertiliser was used in the poor-fertility fields, although the applied N was less efficiently used, leading to larger N losses. The most efficient use of N was achieved in the average fields, as determined by the greater response to N applications in those fields. Under the scenario of the highest initial cash reserves, the allocation of fertiliser to the best fields was less favoured due to the better yields that can be achieved in those fields without N application. Under the same scenario, the optimum rate of fertiliser use in the poor-fertility fields varied widely.

Table 5: Average values and standard deviation of farm-scale indicators and model parameters when harmonising food production and resource conservation objectives (cf. Fig. 9).

Indicator/parameter	Scenario		
	KSh 2000	KSh 5000	KSh 10000
Objective indicators			
Maize production (t farm^{-1} season^{-1})	4.3 (0.0)	5.7 (0.1)	7.1 (0.1)
N losses (kg N farm^{-1} season^{-1})	84 (1)	87 (2)	109 (3)
Soil erosion (t farm^{-1} season^{-1})	18 (1)	18 (0)	17 (0)
Summary of model parameters			
Total N fertiliser used (kg farm^{-1})	5 (3)	18 (8)	128 (16)
Labour used (man-days farm^{-1})			
Ploughing and planting	49 (1)	53 (1)	63 (4)
Weeding	21 (1)	34 (1)	43 (2)
Ridge cropping and mulching	21 (1)	26 (2)	38 (4)
Total	91 (1)	113 (2)	145 (3)
Investment in N fertiliser (KSh season^{-1})	187 (94)	673 (321)	4787 (624)
Total investment in labour (KSh season^{-1})	4151 (122)	10250 (333)	16872 (668)
Complementary indicators			
Rainfall use efficiency (kg grain mm^{-1})	12.6 (0.3)	16.6 (0.2)	20.6 (0.2)
N productivity (kg grain kg N applied^{-1})	1913 (6411)	531 (957)	75 (7)
Gross N use efficiency (kg grain kg N available^{-1})	18 (70)	23 (86)	24 (3)
Value of production (KSh season^{-1})[1]	59340	78660	97980
Gross benefit (KSh season^{-1})[1,2]	55040	67730	76230
Return to labour (KSh man-day^{-1})[1,2]	618	605	548
Benefit/cost ratio[1,2]	12.8	6.2	3.5
Daily gross benefit (KSh family^{-1} day^{-1}) [1,2]	151	186	209
Gross benefit per capita (KSh person^{-1} day^{-1}) [1,2,3]	22	27	31

[1] Calculations done considering the average values for the objective indicators and model parameters
[2] Calculations done considering only the direct costs of N fertiliser use and labour hired in; fixed costs and/or other variable costs such as buying seeds were not considered.
[3] Calculated assuming the local average family size of 6.8 members per household.

Table 6: Selected field-scale indicators and allocation strategies when harmonising food production and resource conservation objectives for the three scenarios of financial liquidity: KSh 2000, 5000 or 10,000 available for investment during the long-rains season on one farm (cf. Fig. 9). Average values for the subset of selected solutions are presented followed by their standard deviation between brackets.

Scenario/ land quality uint	Area (ha)	Maize production (t field^{-1})	Maize yield (t ha^{-1})	N balance (kg field^{-1})	Change in soil N stock (%)	Soil loss rate (t field^{-1})	Fertiliser use (kg field^{-1})	Gross N use efficiency*	Fraction of total labour allocated	Fraction of total cash allocated
KSh 2000										
Fertile	0.5	1.4 (0.1)	2.8 (0.2)	+4 (0.5)	+ 10 (3)	0.1 (0.0)	2 (0.5)	17.3	0.2 (0.0)	0.2 (0.0)
Average	1.3	2.7 (0.1)	2.1 (0.1)	-38 (0.5)	- 42 (9)	2.7 (0.1)	1.5 (1.0)	34.0	0.7 (0.1)	0.6 (0.1)
Poor	0.4	0.2 (0.1)	0.5 (0.3)	-22 (0.2)	- 85 (21)	15.4 (0.1)	1.5 (1.1)	2.4	0.1 (0.0)	0.2 (0.1)
KSh 5000										
Fertile	0.5	1.5 (0.1)	3.0 (0.2)	+5 (1.0)	+ 12 (4)	0.1 (0.0)	5.4 (3.6)	18.2	0.2 (0.0)	0.2 (0.1)
Average	1.3	3.6 (0.1)	2.8 (0.1)	-38 (0.7)	- 42 (9)	2.5 (0.1)	3.6 (1.8)	44.8	0.7 (0.1)	0.6 (0.1)
Poor	0.4	0.6 (0.1)	0.6 (0.4)	-21 (0.6)	- 81 (20)	15.3 (0.0)	9.0 (3.5)	6.9	0.1 (0.0)	0.2 (0.1)
KSh 10000										
Fertile	0.5	1.8 (0.0)	3.6 (0.1)	+8 (1.8)	+ 17 (5)	0.1 (0.0)	25.6 (12.8)	19.6	0.2 (0.0)	0.2 (0.0)
Average	1.3	4.2 (0.1)	3.2 (0.2)	-29 (3.3)	- 32 (9)	2.1 (0.1)	51.2 (13.0)	41.1	0.6 (0.1)	0.6 (0.1)
Poor	0.4	1.1 (0.1)	2.8 (0.6)	-16 (1.9)	- 61 (18)	15.2 (0.0)	53.1 (52.0)	10.3	0.2 (0.0)	0.2 (0.1)

* In kg grain per kg of N available (soil + fertiliser); calculations done using the mean values of maize production and fertiliser use.

Most of the total labour available on the farm for each scenario was used for land preparation and planting, particularly in the scenario of low initial cash reserves (Table 5), and the largest fractions of the total labour and cash resources were allocated to the average-fertility fields (Table 6), as influenced also by their larger area within the farm. The returns to labour calculated from the gross monetary benefit (= value of production – investments in N and labour) did not differ much between scenarios because of the larger investment in labour when the initial cash reserves were larger. The benefit:cost ratio was larger when less cash was invested on a seasonal basis. The gross benefits obtained from these modelling results, simplistically assuming that all the maize produced was sold, represent US$ 2 to 2.8 a day for the household (1 US$ = 75 KSh), barely US$ 0.3 to 0.4 per capita (for the local average of 6.8 family members – cf. Table 1). According to the modelling results for this simplified farm system, improving the gross benefit potentially achieved by the family by growing maize would require boosting the yields in the poor outfields of the farm from about 0.5 t ha^{-1} to almost 3 t ha^{-1}. However, the improved management associated with larger investments also led to more favourable values for some of the indicators related to long term sustainability. For example, the N capital of the system was reduced more drastically when less cash was invested, as reflected by the changes in the soil N stocks (Table 6). Grain production per unit of N lost varied from 60 – 80 kg grain kg N $lost^{-1}$ in the average and fertile fields to 10 – 30 kg grain kg N $lost^{-1}$ in the poor fields. The average values at farm scale were 46, 59 and 62 kg grain kg N $lost^{-1}$ for the investment scenarios of KSh 2000, 5000 and 10000, reflecting different environmental and sustainability costs.

4. Discussion

This inverse modelling exercise allowed us to analyse trade-offs between different farmers' objectives and to compare potential resource allocation strategies to achieve them. The underlying soil quality of the different fields of the farm affected the efficiency of resource capture and use, and hence the results of the optimisation in terms of investment and allocation strategies (cf. Table 6). The allocation of N fertiliser favoured the more fertile fields located closer to the homestead, where the efficiency of N capture was greater. Threshold yields were identified for the various fields and at the farm scale, above which N losses and soil erosion increased abruptly (Figs. 6 and 9); these thresholds were largely affected by the capacity to invest in erosion control or in applying fertiliser to the crops in the fertile fields (where the N capture efficiency was larger, as illustrated by the positive N balances in Table 6). A certain degree of substitution between labour and nutrient use was possible due to the relatively good fertility of these soils (cf. Table 2). However, soils in the area of Kakamega in western Kenya are normally regarded as resilient and of high potential for agricultural production (Shepherd et al., 1996). Our results, which suggest that investment should favour labour for crop management over nutrient use or soil erosion control, are not likely to be equally relevant for regions with poorer soils, with more fragile physical attributes or situations with different price-cost ratios, presumably. Irrespective of the amount of labour used, crops are likely to yield little on poor soils when no nutrient inputs are used.

As pointed out by Thornton and Herrero (2001), the assessment of the feasibility of proposed management alternatives for smallholder farmers requires a clear understanding of the management aspects of the household in relation to the biophysical aspects of the production system. The inverse modelling approach used here for analysing conflicting objectives at farm scale combined good detail on the underlying crop and soil biophysical processes, and their feedbacks, with the possibility of accounting for a number of likely farmers' goals (i.e. increasing food production, reducing erosion) through optimisation. In this respect, our approach has an advantage over linear programming approaches (e.g. MGLP), which do not account for biophysical feedbacks (Brown, 2000). However, the biophysical, dynamic component of the optimisation tool should be kept as simple as possible, since the performance of inverse modelling decreases when the number of parameters to calibrate is large (i.e., the number of parameters should not exceed c. 40 – Vrugt, 2004). On the other hand, when several processes of different nature (decisions, biophysical parameters) are considered simultaneously, the system under analysis becomes complex and then linearity is more often the exception than the rule. Thus, while MGLP approaches coupled with dynamic technical coefficient generators are useful at the scale of analysis necessary for land use studies (i.e. village, water catchments, regions) (e.g. Hengsdijk et al., 1999; Baijukya et al., 2006), the analysis of decision making at farm scale could be better accomplished by using inverse modelling, embracing the complexity, heterogeneity and feedbacks within the system.

One of the weakest points of the approach used here probably was the definition of labour demand functions on the basis of field exercises involving farmers, which involved a substantial degree of linearity. This was a necessary assumption in view of the limited knowledge available on the relationship between labour use for different practices and crop performance for these smallholder systems (Giller et al., 2006). Currently, such relationships are being analysed in the framework of a coordinated project in eight African countries (AfricaNUANCES, 2004) by establishing field experiments designed to quantify the relationship between weed pressure, labour applied to control weeds, and the effect on crop production. The build-up of weed populations, depending on the types of weeds considered, may also be seen as an indicator of the sustainability of the system in the long term. When strategic management decisions are considered, instead of operational decisions as analysed here, the processes affecting this indicator should be modelled in more detail.

In real-life applications of this approach, such as in aiding decision-making on resource allocation, more complex formulations than the simplified case analysed here would be necessary, including other on- and off-farm activities and/or income sources in the model, and considering longer time spans of the simulations. Since our optimisation exercise was conducted for a single enterprise within a simplified, relatively wealthy farm and considering a limited number of objectives over one season, these results cannot be regarded as 'optimal' in a practical sense (e.g. long-term farmers' objectives such as education of their children, or returns from other activities on the farm, were not considered).

The results from this exercise on a simplified farm system suggested that cropping with few external nutrient inputs on soils of heterogeneous quality as observed in these systems requires large investments in labour and proper management skills. Comparing the investment strategies (Figure 7) with the trade-off curves (Figure 6) reveals that up to almost 6 t farm^{-1} of maize (average yield 2.7 t ha^{-1}) could be produced on the farm investing barely (0.1 x 5000 =) 500 KSh ha^{-1} in mineral N fertilisers (equivalent to about 10 kg of N fertiliser), when timely planting and weeding are ensured by hiring sufficient labour (assuming that N is the only limiting nutrient). The average N fertiliser use intensity in the area was 24 kg per farm (Tittonell, 2003), representing an investment of KSh 890 at current (2005) prices. Maize production levels higher than 6 t for this case study, relatively wealthy farm were only obtained under the financial scenario of KSh 10000 initial cash reserves, with cash investments in N fertiliser ranging from 1800 to 3500 KSh ha^{-1}, representing between 50 and 100 kg of N fertiliser (equivalent to application rates of barely 23 and 46 kg N ha^{-1}). These small application rates suggest that intensification of the system to more than double the current local average maize yields of 1 – 1.5 t ha^{-1} could be achieved with relatively small investments in nutrient inputs, provided that labour is available to ensure that nutrient capture is efficient (e.g. reduce erosion losses) and that the nutrients are converted (through a reduction in weed competition, for example) into crop yield. However, other constraints not considered here, such as access to fertiliser, the opportunity costs of labour and/or farmers knowledge and experience in their use, are important in explaining the gap between average yields observed and those predicted by the model for this case study farm.

Although these fertiliser application rates are small, they represent substantial investments for poor farmers; for example, the average labour wage paid in the study area ranges around KSh 150 a day, whereas in nearby areas of even higher population densities (e.g. Vihiga district) the daily wage can be as low as KSh 50 a day. Simplistically, considering an annual food requirement in grain equivalents of 170 kg person^{-1} and the average household size for the area (6.8 family members), around 1.2 t of maize grain is necessary to achieve a baseline of food security. Assuming that an investment of 500 KSh ha^{-1} *coupled with proper management* would lead to producing 6 t of maize in one season on our case study farm, a surplus of 4.8 t of maize would be available for sale to the market (i.e. about 50 bags). Depending on the time of the year this surplus maize production represents income of between KSh 40000 and 80000. In spite of these figures pointing to a presumably high profitability of farming with few external inputs, the use of mineral fertilisers by smallholder farmers is limited in most of sub-Saharan Africa (Bationo et al., 2004). The lack of investment in fertilisers may be ascribed to several reasons, including their cost, their availability in local markets and the lack of knowledge on their types and uses. However, this also points to questioning whether our current understanding of smallholder systems allows us to capture farmers' *real* objectives.

Even for farmers who are experienced in using fertilisers, the decision whether or not to buy fertiliser at the beginning of the season is more strongly affected by financial liquidity at that specific time (e.g. in March – cf. Table 3), rather than by the cost of the fertiliser *per se*. The results of the optimisation indicate that as the availability of cash at the beginning of the season increased, the absolute amount, and also the fraction of the available cash invested in N fertiliser increased (i.e. 4, 6 and 22% of the total) (Table 5). The use of mineral N fertiliser may improve land and labour productivity at farm-scale provided that simultaneous measures are taken to improve N capture within the system, although these may represent trade-offs between short- and long-term farmers' objectives. Larger investments in labour and N fertiliser in our analysis led to more efficient use of the environmental resources (i.e. rainfall) as well as of some of the production factors (i.e. land, assets, management). For other production factors the selected indicators suggested somewhat better results for the scenario of poor investment capacity, e.g., labour productivity, returns to capital invested in N fertiliser. This suggests that caution should be exercised when selecting indicators to use in trade-off analysis. For example, in these low-input systems the sensitivity of the benefit:cost ratio to the variable costs is often large. This may lead to improper conclusions when investments in input-based technologies are compared with respect to current practices (characterised by no or little input use). In reality, farmers are normally more interested in obtaining large maize yields and less in rates of N loss or benefit:cost ratios.

On the other hand, different indicators pertaining to the sustainability of the system as a whole should be considered simultaneously, provided that relevant thresholds for each indicator can be identified. The identification of such thresholds can be done through participatory exercises including several stakeholders with their respective objectives (e.g. Solano et al., 2001), and defining the proper scale of analysis in each case. An interesting, emerging indicator that may be used for comparison across farming systems and/or environments is the dispersion of the 'cloud' of feasible strategies obtained after optimisation; this is illustrated by our results in Figures 7 and 8. Under the scenario of high investment capacity, the spread in acceptable parameter combinations was smaller, the model output was more sensitive to the strategy chosen, and therefore more clearly delimited farming strategies could be derived from the analysis. Conversely, when less cash was available to invest in labour and nutrients, the set of parameter combinations (i.e. possible strategies) was larger, indicating a higher rate of substitution between alternative allocation strategies leading to the same result (less sensitivity).

This provides an important insight into the highly variable investments and management strategies of smallholder farmers that is often observed. If conditions for investment are unfavourable, many different management strategies (but not necessarily many different decisions) lead to the same or similar results in terms of productivity and sustainability of the farm system. This relates also to the concept that variation in optimal solutions may not explain variation in non-optimal solution – i.e., those observed in reality. In our study, the comparison was done between different financial scenarios. The same type of analysis could be done across agroecological zones, climatic situations, varying socio-economic conditions, market opportunities and/or policy environments. At least two preliminary hypotheses can be derived from this. The first hypothesis is related to the idea that the spread of feasible solutions at farm scale is affected by farm characteristics, which in turn varies across farms of different social status and is affected by location-specific factors (e.g. landscape, markets). The second challenges the concept of ‘blanket’ management recommendations, as the set of resource allocation strategies leading to Pareto-efficient results is much wider when farming conditions are less favourable. By contrast, the concept of technical recommendations works better in subsidised farming systems relying on high external input use and/or price control policies – i.e. more stable conditions, as demonstrated by the fact that most farmers in such systems use the same varieties, plant at the same time, apply the same type and amount of fertilisers and biocides, use the same commercialisation channels, etc. Therefore, technological interventions to target smallholder farming systems such as those in western Kenya should be designed by considering farm heterogeneity and its drivers, and by building farmers’ decision-making capacities through deeper knowledge and understanding of the systems they manage, instead of simply recommending specific management practices.

Notes

The terms ‘resource’ and ‘efficiency’ have a very specific meaning in disciplines such as economics. Here we use these terms broadly, defining resources as labour, cash, nutrients and other biophysical factors (e.g. solar radiation) used for farm production, and efficiency as the ratio between the amount of output obtained from per unit of input added to a process taking place within a well delimited (sub-)system and over a certain time span (the season in our case); with inputs and outputs expressed in their different units (e.g. labour productivity in kg of grain produced per man-day of labour invested in cropping, or N productivity in kg of grain per kg of fertilizer N applied to the soil).

Chapter 7

Targeting nutrient resources for integrated soil fertility management[†]

[†] Adapted from:
Tittonell, P., Corbeels, M., van Wijk, M.T., Vanlauwe, B., Giller, K.E., 2007. Targeting nutrient resources for integrated soil fertility management in smallholder farming systems of Kenya – explorations using the crop and soil model FIELD. Agronomy Journal, submitted.

Abstract

Studies on integrated soil fertility management (ISFM) options for sub-Saharan Africa indicate synergies and/or additive effects of combined applications of mineral fertilisers and farmyard manure. Such studies are often conducted under controlled experimental conditions, frequently on-station, and using input rates that are far beyond the reach of most smallholder farmers. Realistic evaluation of ISFM technologies should consider key features of smallholder farms: 1. Management-induced spatial soil heterogeneity; 2. Long term system dynamics and inter-annual variability; 3. Limited availability of manure of poorer qualities than often tested in controlled experiments; 4. Limited access to mineral fertilisers; and 5. Competing uses for crop residues on the farm. We used a simple dynamic simulation model, FIELD (Field-scale resource Interactions, use Efficiencies and Long term soil fertility Development), to explore long-term management strategies for the allocation of realistic rates of mineral fertiliser and manure, using soil and manure quality parameters measured on case-study farms in western Kenya. The model was calibrated and tested against four datasets including long-term crop and soil dynamics, and capturing within-farm variability in crop responses to fertilisers. Patterns of responsiveness to increasing application rates of N fertiliser from 0 to 180 kg N ha^{-1} (+/- 30 kg P ha^{-1}) distinguished: poorly-responsive fertile fields (grain yields ranged from 4.1 to 5.3 t ha^{-1} without P and from 7.5 to 7.5 t ha^{-1} with P) from responsive fields (c. 1.0 to 4.3 t ha^{-1} and 2.2 to 6.6 t ha^{-1}) and poorly-responsive infertile fields (c. 0.2 – 1 t ha^{-1} and 0.5 – 3.1 t ha^{-1}). While the poorly responsive fertile fields can be managed with minimum 'maintenance' fertilisation, the infertile fields should undergo rehabilitation through restitution of soil organic matter. Soils receiving combined manure and fertiliser applications over 12 consecutive years stored between 1.1 to 1.5 t C ha^{-1} year^{-1} when 70% of the crop residue was retained in the field, and between 0.4 to 0.7 t C ha^{-1} year^{-1} when only 10% of residues were retained. Degraded outfields could not be rehabilitated with manures of average quality for farms in western Kenya (e.g., 23 – 35% C, 0.5 – 1.2% N, 0.1 – 0.3% P) applied at a (realistic) rate of 1.8 t dm ha^{-1} season^{-1} for 12 consecutive years, without fertilisers. Application of the best quality manure found in the region (39% C, 2.1% N, 0.2% P) led to an increase in c. 1 t C ha^{-1} year^{-1} in the poorest fields. Different qualities of manure, initial soil conditions and combinations of manure plus mineral fertilisers induce a different degree of hysteresis of soil restoration. Mineral fertilisers may contribute in the initial phases of soil rehabilitation to induce restoration of biomass productivity that will lead to higher potential C inputs to the soil.

Keywords: Sub-Saharan Africa, Soil organic carbon, maize production, mineral fertilisers, hysteresis of soil restoration

1. Introduction

Although western Kenya is regarded to be a region of high potential for crop production, current yields of the major crops in smallholder farms are much less than yields achieved under controlled, on-station experimental conditions. These 'yield gaps' are largely the result of nutrient limitations, weed infestation, pests and diseases and poor agronomic management that together reduce the efficiency of use of available nutrients and water (Tittonell et al., 2007a,c). Given the small farm sizes, the problems of poor soil fertility, and the scarcity of labour and nutrient resources in this highly populated region, mineral fertilisers are one option to increase both land and labour productivity. However, the use of mineral fertilisers within smallholder systems should be designed judiciously to ensure their effectiveness and to avoid negative environmental externalities. Far from being a solution *per se* to poor land and labour productivity, mineral fertilisers are a useful and necessary means to improve productivity when strategically allocated to specific 'niches' within complex and dynamic farming systems. The design of such strategies should not overlook the effects of farm heterogeneity and long-term sustainability of farming practices.

Use of mineral fertilisers face high transaction costs in rural markets (Barrett et al., 2002): they are retailed at higher prices than in urban wholesale markets and often not labelled, so that farmers are unable to verify their composition. Moreover, decisions on purchasing fertilisers are made before planting, at a time of high demand for other important household expenditures (e.g. paying school fees), or when farmers have already sold their harvest from the previous season. As a result, the amounts of fertilisers that farmers can access are small, and therefore it is crucial that these are targeted to fields within their farm that allow the highest marginal returns to investments (Van Keulen and Breman, 1990). Within smallholder farms, fields can be identified that exhibit different patterns of responsiveness to applied nutrients: poorly-responsive fertile fields, poorly-responsive unfertile fields, and responsive medium- to infertile fields (Tittonell et al., 2007d; Zingore et al. (2007b).

Strategically-targeted fertiliser use together with organic nutrient resources to ensure fertiliser use efficiency and crop productivity at farm scale are basic principles of integrated soil fertility management (ISFM) (Vanlauwe and Giller, 2007). In particular, poorly-responsive infertile fields require long-term rehabilitation to build up soil fertility before crops respond and efficient use of applied nutrients can be ensured. In mixed crop-livestock systems, the combined application of animal manure and mineral fertilisers is one option to achieve this. Positive synergies and or additive effects have been observed in field experiments testing different combinations of manure and mineral fertilisers (e.g., Vanlauwe et al., 2001; Bationo et al., 2004). However, the application rates and the quality of the manure used in most experiments are superior to those that farmers can achieve in practice. But even manures with poor nutrient contents may be useful to build up soil C and supply micronutrients to crops, when applied over successive years. Such long term strategies to build up soil fertility are especially necessary on poorly responsive unfertile fields, to achieve significant crop responses to applied nutrients. It is within this context, of limited access to fertilisers, poor soil fertility and poor quality and availability of manure, that options for soil fertility management within heterogeneous farms should be explored.

Simulation modelling can help in identifying options, and in understanding the trade-offs between short- and long-term benefits of ISFM. A simple, dynamic crop-soil simulation model, FIELD (Field-scale resource Interactions, use Efficiencies and Long term soil fertility Development, Tittonell et al., 2007b), was developed to explore crop/soil management strategies within the existing heterogeneous conditions of smallholder farms and to assess a range of indicators of resource use efficiency. FIELD is the crop-soil module of a farm-scale model (NUANCES-FARMSIM), in which it operates linked to livestock, manure management and household decisions modules to analyse resource and labour allocation strategies in African farming systems. A relatively simple modelling tool is necessary to perform such analyses, given: (i) the scarcity of biophysical data (of the type needed to parameterise most crop growth simulation models) for most African farming systems; and (ii) the multiple interactions between crop management factors operating at farm-scale (e.g., labour allocation to weeding), which may have a larger impact on crop productivity than the processes that are being modelled.

FIELD is built around the concept of resource use efficiencies (i.e., radiation, water and nutrient use efficiencies) for the assessment of crop production. The model conserves the key attributes of the approach taken in QUEFTS (Janssen et al., 1990) to account for nutrient interactions, but incorporates long-term plant-soil feedbacks and the interactions with other relevant drivers of farm heterogeneity (i.e. management decisions, water availability). FIELD simulated maize and soyabean responses to N, P and manure applications reasonably well on clayey and sandy soils in Zimbabwe (Tittonell et al., 2007b).

The objective of this study was to analyse options for ISFM within heterogeneous smallholder farms. We first calibrated and tested the model FIELD against a number of experimental datasets and then used it to analyse: (i) the effect of current soil fertility status on crop responsiveness and the efficiency of mineral fertiliser use; (ii) the potential of different ISFM strategies to maintain or build up soil fertility in the long term; and (iv) the capacity of different categories of fields to support responses in productivity when restorative measures are put in place. In search of options for targeting ISFM technologies, the following research questions were formulated:
(1) How does maize – the major food and cash crop in the region – respond to increasing rates of applied N and P (little response to K has been observed in the trials, cf. Tittonell et al., 2007d) within spatially heterogeneous farms?

(2) How does maize respond to realistic, minimum rates of mineral fertilisers in the presence of different types of manure within spatially heterogeneous farms?
(3) If part of the crop residues are retained in the fields after harvesting, is it possible to maintain adequate levels of organic carbon in the soil through increased biomass production as a consequence of mineral fertiliser applications (with and without manure applications)?
(4) Assuming that an increase in soil organic matter would lead to improved resource use efficiency, better use of applied mineral fertilisers, and crop productivity, what is the capacity of different management interventions to restore soil productivity through soil organic matter build up for fields with different intensity of soil degradation?

This 'capacity of soil restoration' or rehabilitation rate brought about by different management practices is referred to as '*hysteresis* of soil restoration', in analogy to the path-dependent process of hysteresis occurring in natural systems (e.g., in drying-and-re-wetting soils – Scanlon et al., 2002)[‡]. Although not strictly similar, we believe that the behaviour of soils that undergo degradation and rehabilitation resembles the phenomenon of hysteresis (see also: Lal, 1997), on the basis that: when soil C or crop yields are followed in time for a soil undergoing degradation they tend to follow a concave decline; when measures are put in place to restore productivity, these indicators tend to follow an upward, convex trajectory.

2. Materials and methods

2.1 System characterisation and background

The study sites in western Kenya comprise highland and midland agroecological zones that receive 1300 to 2100 mm of annual rainfall in a bimodal pattern; in 'normal' years 60 to 70% of it occurs during the long-rains season, between February and June, while the rest falls during the short rains between August and November. Farms sizes are small (0.5 to 2 ha), and although soil types vary within the landscape, soils are in general inherently fertile (70% of the area is considered to be of high agricultural potential). Differential long-term management of the fields within the farm has led to strong heterogeneity in soil productivity within individual farms (Tittonell et al., 2005c). In general, current soil fertility is poor due to continuous cultivation with low rates of nutrient inputs through organic and/or mineral fertilisers and to soil water erosion. Cultivation without inputs is the result of poor availability of or limited access to nutrient resources (Table 1). For farmers who own cattle, manure application rates vary (on average, between 0.9 to 4 t fresh weight ha^{-1}) across farms of different

[‡] In a deterministic system with no hysteresis and no dynamics, it is possible to predict the output of the system at a given moment in time, knowing only the input to the system at that moment. If the system has hysteresis, in order to predict the output it is necessary to consider also the path that the response follows before reaching its current value.

resource endowment and across localities where different livestock management systems prevail (e.g. free grazing vs. stall feeding).

Table 1: Nitrogen use in farms from different wealth classes in western Kenya as derived from analysis of resource flow maps (adapted from Tittonell, 2003). Area cropped, livestock owned and potential availability of manure and C, N and P for application to crops.

Village*	Resource endowment	Land cropped (ha)	Livestock heads (TLU's)	Potential manure availability (t $year^{-1}$)	Potential application rates (kg ha^{-1})** C	N	P
Ebusiloli	Higher	2.1	4.0	8.4	960	38	6.1
	Medium	1.1	2.2	3.6	785	31	5.0
	Poorer	0.5	0.8	1.1	528	21	3.3
Among'ura	Higher	2.3	2.3	3.5	212	8	1.3
	Medium	2.2	2.0	2.9	218	9	1.4
	Poorer	1.0	1.7	2.0	408	16	2.6

*Ebusiloli (Vihiga district) is located in a highly populated area (ca. 1000 Inhabitants km^{-2}), closer to urban centres with easier access to markets; intensive (zero grazing, Friesian) livestock production systems predominate. Among'ura (Teso district) area is less populated (200-300 Inhabitants km^{-2}), land is available for fallow, markets are far, and the local (zebu) livestock graze in communal land. TLU: tropical livestock unit (250 kg live weight).
**Calculated over the total area of cropped land, assuming optimum manure handling and an average dry matter content of 80%, C content 30%, N content 1.2% and P content 0.19%

Despite the scarcity of animal manure, only a relatively small number of farmers use mineral fertilisers in limited amounts. For example, in the case of N fertilisers, the wealthiest farmers in the region may apply up to 60-80 kg N ha^{-1} on small portions (10 to 40%) of their cropped land (Tittonell et al., 2005c). Among the poorest farmers, those who use fertilisers only apply them to less than 10% of their land area with N application rates below 20 kg ha^{-1}. Crop productivity in the region is mostly limited by N and P; localised K deficiencies were also reported (Shepherd et al., 1996).

2.3 Overview of the model FIELD

FIELD is the crop-soil module of the bio-economic model NUANCES-FARMSIM (FArm-scale Resource Management SIMulator; www.africanuances.nl), which simulates household objectives and constraints, resource allocation patterns, labour and economic balances and nutrient flows at farm level (Figure 1 A). FARMSIM is designed for analysing trade-offs between farming systems and the environment, focusing on strategic decision-making and embracing the spatial and temporal variability of smallholder systems. FARMSIM consists of a crop-soil (FIELD), a livestock (LIVSIM) and a manure (HEAPSIM) module that are functionally integrated to allow capturing feedbacks between these identities at farm scale, as affected by farmers' management decisions. FIELD simulates long-term changes in soil fertility (C, N, P and K), interactions between nutrients that determine crop production, and crop responses to management interventions such as mineral fertiliser and/or manure applications. Different fields within a farm represent combinations of crop types and sets of soil properties, which are simulated as different instances of the FIELD module. Simulation of livestock productivity, growth and herd dynamics is done with LIVSIM, while nutrient cycling through manure is simulated with HEAPSIM (Rufino et al., 2007a,b).

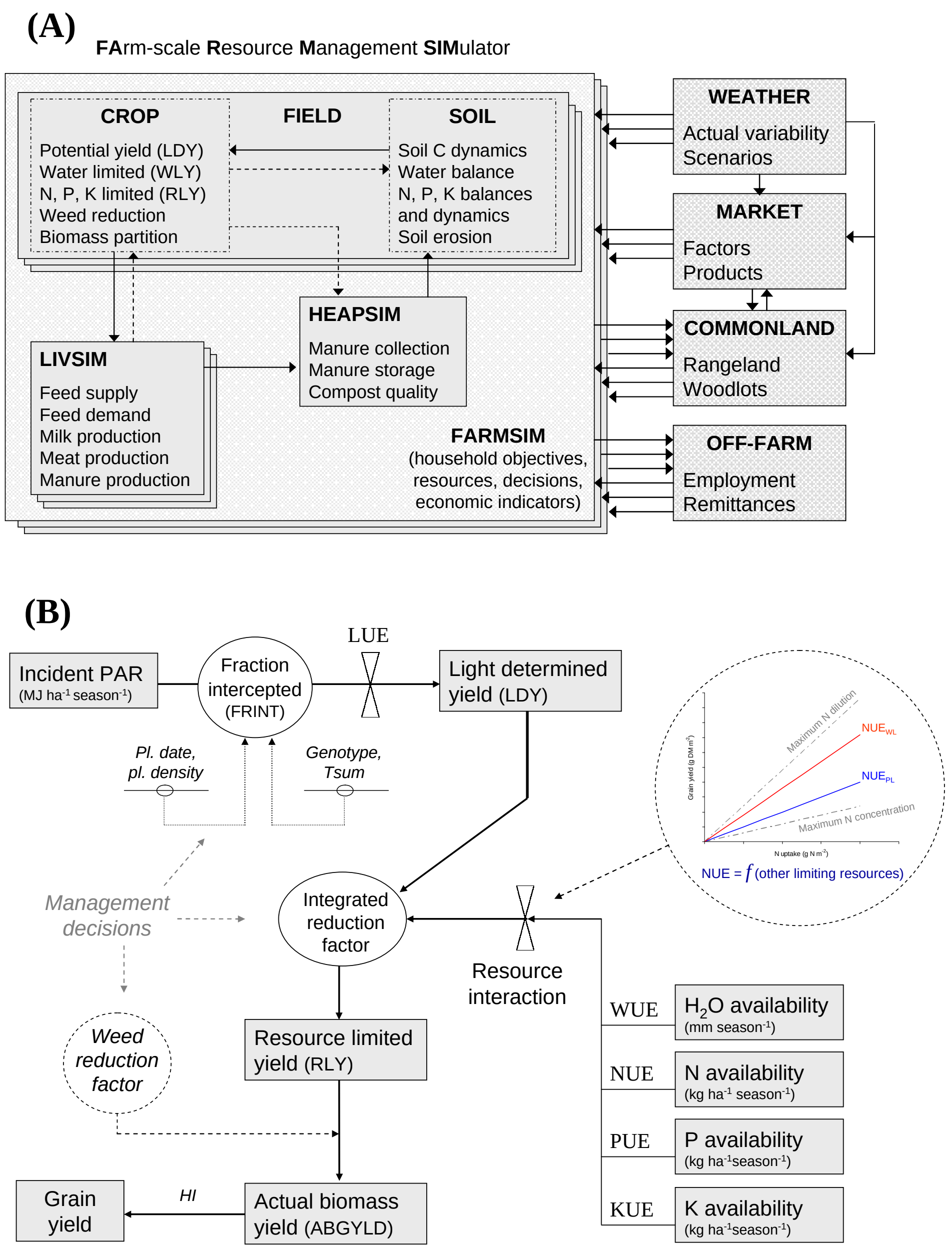


Figure 1: (A) Schematic representation of the relationships between different modules of the model FARMSIM (FArm-scale Resource Management SIMulator); (B) the crop production module of the sub-model FIELD (Field-scale resource Interactions, use Efficiencies and Long-term soil fertility Development). See text for further explanation.

Here, we used a stand-alone version of the model FIELD. The simulation of soil processes in FIELD was described by Tittonell et al. (2007b – Appendix 7.1). The approach used to simulate crop production is illustrated in Figure 1 B. Total dry matter and grain yields are calculated on the basis of seasonal resource (light, water and nutrients) availabilities and use efficiencies, according to the generic conceptual model:

Crop production = Resource availability × Resource capture × Resource conversion efficiency

From the total amount of incident photosynthetically active radiation (PAR) during the growing season, only a fraction is intercepted by the crop (FRINT), and this is converted into crop biomass using a light conversion efficiency coefficient. It calculates the 'light-determined' yield that is affected by management factors such as cultivar choice, planting date or stand density (and thus it cannot be considered to be the 'potential' yield in a strict sense). Water-limited crop production is calculated on the basis of seasonal rainfall and a site- and crop-specific water use efficiency coefficient. The estimation of this coefficient depends on availability of data for each case study. When sufficient data are available, more detailed models simulating soil nutrient balances can be used to generate functional relationships (e.g., fraction of rainfall infiltrated vs. runoff as a function of soil texture and slope) that are then built into FIELD (see Section 2.3.2). When no data are available, rainfall use efficiency coefficients (i.e., yield per mm of rain) derived from literature and/or experiments are used to estimate water-limited yields. Crop yields measured on plots receiving full-nutrient treatments in controlled experiments are considered to be close to the water-limited yields for a given site, and can thus be used to calibrate the rainfall capture and conversion (or transpiration) efficiency coefficients for the given crop at that site.

Nutrient availabilities and use efficiencies determine nutrient-limited crop production. Nutrient capture efficiency results from the partitioning of available nutrients between crop uptake and other processes that act as nutrients sinks (e.g. leaching and gaseous losses of N and immobilisation into the soil organic matter). Nutrient conversion efficiencies are the inverse of the weighted average nutrient concentrations in the crop and range between crop-specific minimum and maximum values (Nijhof, 1987). Resource-limited crop production in FIELD is then calculated as the minimum of water-limited production and the production determined by the availability and use efficiency of N, P or K and their interactions following Liebscher's Law of the Optimum (van Keulen, 1995). Actual crop production is finally calculated by applying a reduction factor for weed competition. Actual grain yield is then determined by multiplying actual biomass production with a harvest index coefficient. More details on how resource interactions are simulated in FIELD can be found in Appendix 7.2.

2.3 Model set-up, calibration and testing

In this section (2.3) we describe how FIELD was calibrated and tested for the conditions of the study area, using four independent datasets. We first used a dynamic crop growth simulation model running on a daily time step, already tested for maize in western Kenya, to derive functional relationships that describe radiation and water use efficiencies. Then, we calibrated FIELD against long-term datasets on changes in soil C without and with manure applications, and finally tested the model to simulate crop responses to applied manure and mineral fertilisers. Once the model was calibrated and tested, we run scenarios of ISFM strategies that are described in the next section (2.4).

2.3.1 Data sources

The different datasets were used in the various steps of model calibration and testing include:
1) Data on soil organic C dynamics, from a chronosequence of agricultural fields of different age following forest clearance (up to 100 years of continuous crop cultivation) around the Kakamega National Forest Reserve in western Kenya (Solomon et al., 2007).
2) Soil organic C and crop biomass data from a long-term experiment (1989-2003) on effects of manure application (5 and 10 t ha^{-1} $year^{-1}$) in maize-based cropping systems at Machang'a, Kenya (Micheni et al., 2004).
3) Data on maize responses to increasing rates of manure application (0, 1.2 and 4 t C ha^{-1}) with and without mineral N applied at a rate of 120 kg ha^{-1} (in the presence of P and K fertilisers) from an experiment that was conducted during two consecutive growing seasons (long and short rains of 2005) at two localities in Aludeka and Nyabeda (c. 20 km from Emuhaya) (unpublished).
4) Crop biomass and soil fertility data from an on-farm N-P-K (100:100:100 kg ha^{-1}) nutrient-omission trial with maize conducted on 18 farms in three localities in western Kenya: Aludeka, Emuhaya and Shinyalu (Vanlauwe et al., 2006).

2.3.2 Deriving functional relationships using dynamic crop growth models

Many of the current parameters and functions describing resource use efficiency within FIELD are directly derived from empirical measurements in experiments. To make the model more generic and yet maintain a low level of complexity in its formulation and parameterisation, functional relationships for key processes in FIELD were developed using more detailed, dynamic simulation models that have a shorter time step of integration. For example, in a earlier study (Chikowo et al., 2007) we used of the crop-growth model APSIM (Keating et al., 2003) to generate relationships such as rainfall capture efficiency as a function of field slope or soil clay content. In the present study, we used the crop-growth model DYNBAL (DYnamic Nutrient

BALances) to generate a set of functional relationships for FIELD, in the cases in which field data was not available. DYNBAL has been calibrated and tested for maize under the conditions of western Kenya (Tittonell et al., 2006). For the purpose of this study, we parameterised DYNBAL using the soil data from the nutrient-omission experiments (dataset 4) and ran it with daily radiation and rainfall data to simulate light-determined and water-limited yields (i.e. with the N module of DYNBAL switched off). Daily rainfall was recorded at each location during the nutrient omission experiment, totalling 641 mm in Aludeka, 654 mm in Emuhaya, 716 mm in Shinyalu. Daily global radiation was measured at Maseno Experimental Station (western Kenya) and used to calculate the total amount of photosynthetically active radiation (PAR) reaching the crop throughout the experiment (on average, 1200 MJ PAR m^{-2} $season^{-1}$). Examples of parameter values for FIELD derived by using DYNBAL are presented in Table 2. Figure 2 A and B illustrate how the FIELD parameters, seasonal fraction of intercepted radiation (intercepted/ incident PAR) and efficiency of water capture (transpiration/ rainfall), were derived from daily-step simulations with DYNBAL.

Table 2: Examples of parameters used in FIELD that were derived running the dynamic model DYNBAL. Average values presented for Emuhaya.

Parameter	Unit	Average value (Emuhaya)
1) Light-determined yield		
Incoming PAR (season)	MJ m^{-2}	1208
Fraction of PAR intercepted	-	0.58
PAR conversion efficiency	g MJ^{-1}	3.43
2) Water-limited yield		
Cumulative rainfall (season)	Mm	616
Rainfall capture efficiency	-	0.23
Rainfall conversion efficiency	kg ha^{-1} mm^{-1}	134

PAR: photosynthetically active radiation

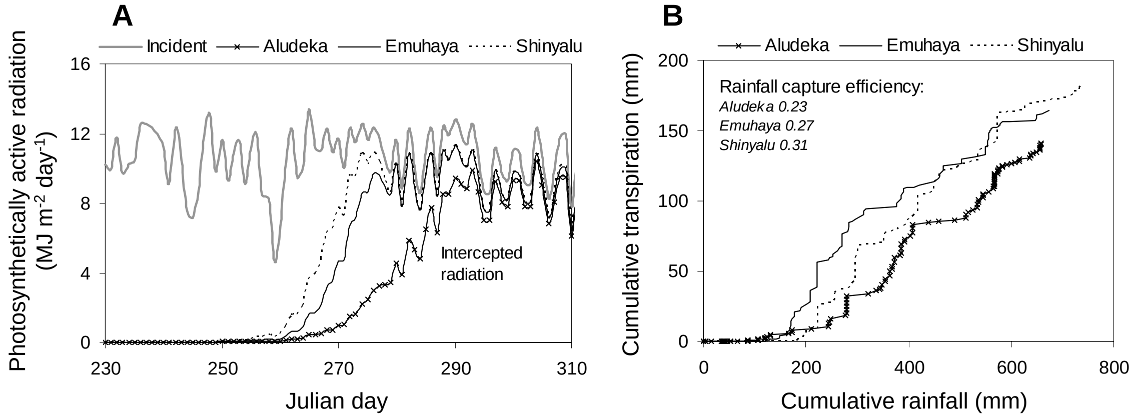


Figure 2: Simulations using the dynamic crop model DYNBAL. (A) Incident and intercepted radiation by maize and (B) cumulative crop transpiration vs. cumulative rainfall during the growing season at three locations in western Kenya.

2.3.3 Calibration of FIELD

The soil organic matter module of FIELD was calibrated against data from the chronosequence around Kakamega Forest (data set 1), simulating changes in soil C under continuous crop cultivation following forest clearance. Measurements of soil bulk density made in the forest and in farmers' fields were used to adjust soil bulk density values with decreasing soil C (*Bulk density = 1719.2 – 33.1 × SOC*, r^2 = 0.61). Values for soil input parameters were as follows: 46% clay, 19% sand, 11.8 mg kg^{-1}extractable P, 0.4 cmol$_{(+)}$ kg^{-1} exchangeable K; relative C losses by soil erosion were set at 0.01 year^{-1}. (To simulate soil K supply, the model was adapted as described in Appendix 7.3). The model run with average rainfall from historical 30-year weather data (1635+/-218 mm year^{-1}– FURP, 1994) simulated an exponential decrease in soil C in the upper 20 cm from 140 to 27 t ha^{-1} over 100 years, with an average net loss rate of 1.13 t C ha^{-1} year^{-1} (or 0.8% per year in relative terms) (Figure 3 A). The comparison of observed vs. simulated soil organic C (0-20cm) produced a relative mean squared difference of 2.3 t ha^{-1} and a root mean squared error of 13.3 t ha^{-1}, with r^2 = 0.94 (P < 0.01). Simulated maize grain yields decreased from 6.7 t ha^{-1} at the beginning of cultivation period (1 year after forest clearance) to 3.4 t ha^{-1} after 20 years of cultivation, 2.4 t ha^{-1} after 40 years and 1.4 t ha^{-1} after 100 years. With the same FIELD model parameters and inputs as above, but assuming an annual manure application rate of 5 t dry matter ha^{-1} (Maseno FTC manure – Table 3 B), equilibrium soil C was achieved after 60 years of cultivation with a C content of 71 t ha^{-1} in the upper 20 cm (c. 30 g C kg^{-1} soil). This is slightly greater than the soil C contents that are found in similar soils of continuously manured homegardens in the region (Tittonell et al., 2005c).

Using the 1989-2003 seasonal rainfall records, we calibrated FIELD against the long-term dataset on maize yields (two crops per year, in the long- and short rains) and changes in soil C contents at Machang'a (data set 2), simulating effects of an annual application rates of 0, 5 and 10 t dm manure ha^{-1}. Initial soil (chromic Cambisol) properties were set as follows: 31% clay, 13% silt and 56% sand, 5.9g kg^{-1} soil organic C (C:N ratio 12.7), 0.6 mg kg^{-1} extractable P. Mimicking the experiment, manure was applied at the start of the long rains season before planting of the maize crop (i.e., only once a year despite the double-cropping). The quality parameters of the applied manure are shown in Table 3 B. When compared with observed values, FIELD satisfactorily predicted crop biomass over the 26 growing seasons (overall RMSE 1.7 t ha^{-1}; r^2 = 0.51). By adjusting the annual humification coefficient for manure (0.27 year^{-1}), the model was able to fit simulated soil C to observed values (Figure 3 B) with RMSEs of 0.8, 2.1 and 3.8 t C ha^{-1} for the treatments receiving 0, 5 and 10 t manure ha^{-1}, respectively (overall r^2 = 0.66).

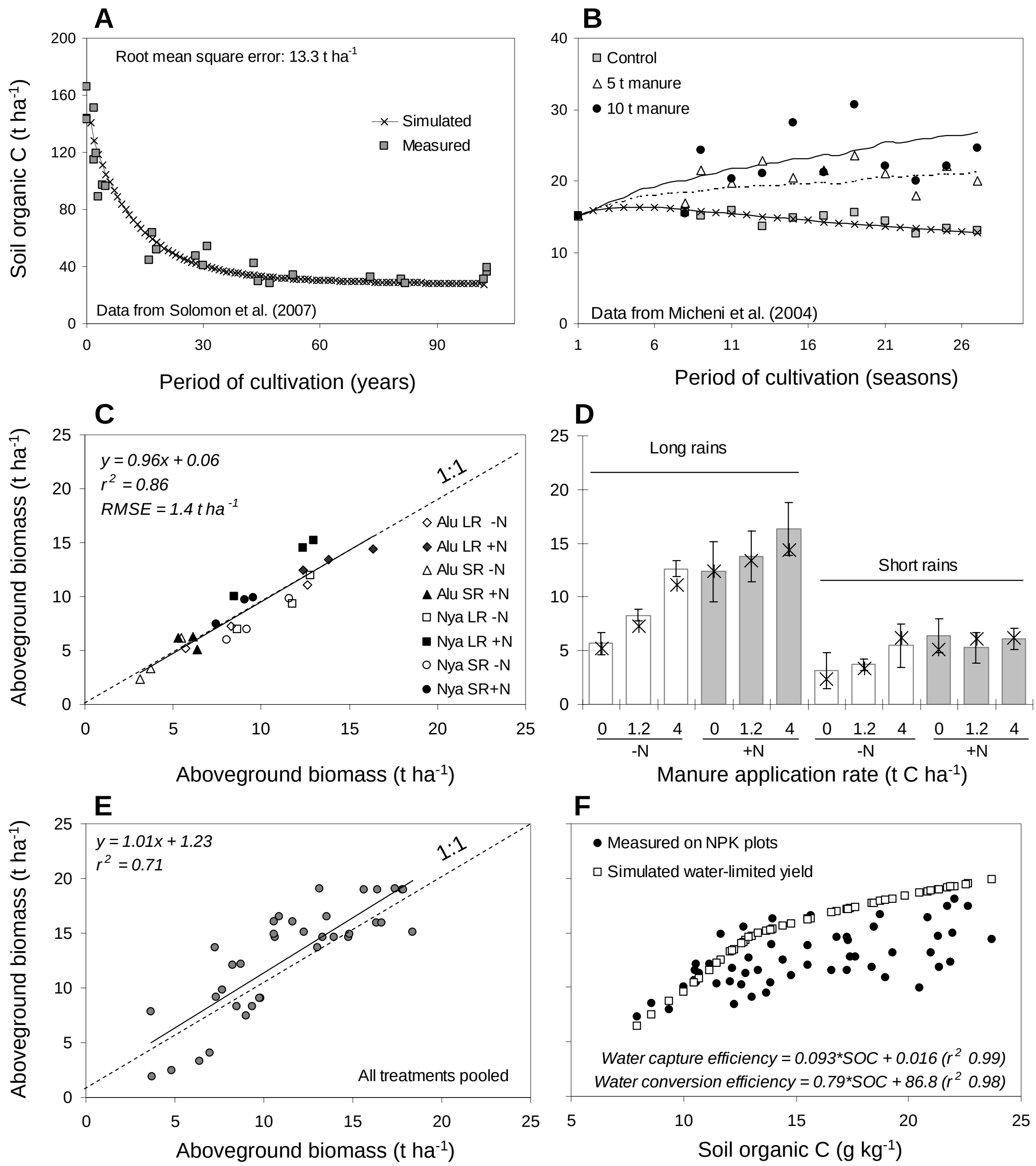


Figure 3: (A) Calibration of the model FIELD against soil C across a chronosequence of 100 years of cultivation around Kakamega Forest Reserve, western Kenya; (B) Simulated and measured soil C increase after 13 years (26 seasons) under 0, 5 and 10 t ha^{-1} manure applications in a Cambisol at Machang'a, central Kenya; (C) Observed (x-axis) and simulated aboveground biomass of maize in the long (LR) and short rains (SR) of 2005 with different rates of manure and mineral N in Aludeka (Alu) and Nyabeda (Nya), western Kenya; (D) Aboveground biomass production of maize with application of manure (0, 1.2 and 4 t C ha^{-1}), with and without application of mineral N (120 kg ha^{-1}), during the long and the short rains of 2005 at Aludeka – bars: measured values (plus standard deviation), asterisks: FIELD simulations; (E) Observed (x-axis) and simulated aboveground biomass of maize in the case study fields (Table 4) with all combinations of N, P and K in the nutrient-omission trial; (F) Measured biomass yield of all NPK treatments and simulated water-limited yields as a function of soil organic C.

Table 3: Parameters used in the model simulations. (A) Soil properties at the experimental sites of the manure application experiment; (B) Dry matter, C and nutrient content of manures from different sources

(A)

Locality	Clay (%)	Sand (%)	Soil organic C (g kg^{-1})	Total soil N (g kg^{-1})	Extractable P (mg kg^{-1})	Exchangeable bases ($cmol_{(+)}$ kg^{-1}) K	Ca	Mg	pH (water 1:2.5)
Aludeka	8	85	8.3	0.8	6.0	0.39	5.0	0.6	5.5
Nyabeda	58	29	15.4	1.4	2.4	1.01	4.9	1.8	4.9

(B)

Manure origin	Content (%) Dry matter	C	N	P	K
Machang'a experiment	80	26	2.0	0.48	n/a
Maseno FTC*	80	35	1.4	0.18	1.8
Experimental Dairy Farm	82	39	2.1	0.22	4.0
Farm A	56	30	1.2	0.32	2.0
Farm B	59	29	1.0	0.30	1.6
Farm C	77	25	1.0	0.10	0.6
Farm D	43	35	1.5	0.12	3.3
Farm E	41	23	0.5	0.10	0.6

*Manure from the farm at Maseno Farmer Training Centre, Maseno, western Kenya.
n/a: Not available

2.3.4 Testing FIELD to simulate effects of manure application

We then tested the model against the data on maize response to manure application (0, 1.2 and 4 t C ha^{-1}, corresponding to 3.4 and 11.4 t manure ha^{-1} year) in Aludeka and Nyabeda during the long and short rains of 2005 (data set 3). Soil properties at both sites are presented in Table 3 A. All treatments received 60 kg P ha^{-1} and 60 kg K ha^{-1}, while only *+N* treatments received 120 kg N ha^{-1}. Average nutrient contents of the manure used in this experiment are presented in Table 3 B (Maseno FTC), together with those of manures sampled from the experimental dairy farm of Maseno University and from five farms in western Kenya (Castellanos-Navarrete, 2007). The humification coefficient (HC) of the manure was calibrated to match the observed crop responses at both sites, minimising the value of the RMSE (resulting in HC = 0.53 $season^{-1}$, or 0.22 $year^{-1}$). We used this value as default for the other types of manure in Table 3 B. Although we acknowledge that manures of varying chemical composition will have different HC's, we lacked experimental data to derive a generic relationship between HC and manure quality. We thus assume that differences in simulated crop responses for the various types of manure are solely due to differences in their C and nutrient contents. Maize responses to increasing manure application rates were satisfactorily simulated by FIELD (Figure 3 C), although with a slight tendency to underestimate yields without N and overestimate response to N (Figure 3 D). In the long rains and at both locations, maize responded almost linearly to manure applications without N, while response to N with and without manure was only observed in the sandier soils of Aludeka, in both rainy seasons.

2.3.5 Testing FIELD to simulate crop responses to fertilisers on heterogeneous farms

Finally, we tested FIELD for simulating maize responses to mineral fertilisers using the soil and yield data from the on-farm fertiliser trials at Aludeka, Emuhaya and Shinyalu (data set 4). The model was parameterised for a combination of three localities × six farms per locality × three positions within the farm (home-, mid- and outfields) totalling 54 independent observations. The soil C module of FIELD was initialised by running 100-year simulations (approximately the period since land cultivation started in the older fields in the region) with different rates of manure inputs to represent the historical management that led to current ‘fertile’ and ‘poor’ fields, matching their observed soil C contents (cf. Tittonell et al., 2007b). The model was run to simulate the experimental treatment: control without fertiliser, full N-P-K fertilisation (100 kg N ha^{-1}, 100 kg P ha^{-1}, 100 kg K ha^{-1}) and three treatments with one of the nutrients (N, P or K) missing. Other crop and management parameters for the model (e.g., plant density, planting dates, length of growing period, harvest index) were defined as in the experiments.

Given the large variability in the data from the on-farm experiment, the performance of FIELD to simulate maize production was satisfactory (overall RMSE 2.8 t ha^{-1}; r^2 = 0.59), as illustrated in Figure 3 C for total aboveground biomass of maize under all treatments in the case study fields of Table 4. The water-limited yield calculated by FIELD using the summary functions derived with DYNBAL increased as a function of increasing soil C, as did the maize yields measured in the full-NPK plots (Figure 3 D). However, a large number of fields receiving full-NPK and having between 10 and 20 g kg^{-1} soil organic C produced yields that were smaller (up to 40% less) than the simulated water-limited yield. Yields under full-NPK are assumed to be close to water-limited yield levels, unless other factors that limit crop growth were present (e.g. micro-nutrient deficiencies or *Striga* infestations). This gap between simulated water-limited and measured full-NPK yields may on one hand suggest that DYNBAL overestimated water availability and therefore water-limited yields in soils with greater C content, or that the application rates of N, P and/or K in the experiment were suboptimal.

2.4 Scenario analysis

Once FIELD was parameterised and tested, the four research questions around ISFM posed in the Introduction were analysed. Three farms from three localities in western Kenya: Aludeka division in Teso district (0° 35’ N; 34° 19’ E), Emuhaia division in Vihiga district (0° 4’ N; 34° 38’ E) and Shinyalu division in Kakamega district (0° 12’

N; 34° 48’ E), and included in dataset 4 were used as case study for scenario analysis. These farms had been characterised earlier and visited in several occasions, and exhibited marked variability in soil quality, maize productivity and its response to mineral fertilisers from their home to their outfields. Soil properties, maize yields under farmer management and under controlled experimental conditions are presented in Table 4. In total, three case-study farms times three field types resulted in 9 fields being simulated. However, for clarity in graphs often only subsets of fields were plotted – those that showed typical patterns of responsiveness to management interventions (see later).

In the model simulations we used manure of different qualities, from the best quality sampled on the experimental dairy farm of Maseno University to the worst manure sampled on farm E (Table 3). For simplicity, and to represent common practices in the area, we assumed that through proper manure/compost management 1.8 t dm of manure were available for application to one hectare of cropland per season (cf. Table 1). Since concentrating the available manure in small portions of land is also common practice in the area (Tittonell et al., 2005c), high application rates of 5 t dm ha^{-1} to restore soil productivity were also simulated. The minimum mineral fertiliser application rates were set based on the assumption that a farmer was able to buy a bag 50 kg of DAP (18:46:0) and a bag of 50 kg of urea (46:0:0) to apply to one hectare of maize (equivalent to 32 kg N ha^{-1} and 23 kg P ha^{-1}). An application of (recommended) 60 kg N ha^{-1} and 30 kg P ha^{-1} was defined as ‘basal fertiliser’. Application of 140 kg N ha^{-1} and 40 kg P ha^{-1} was defined as ‘replacement fertiliser’, as this provides roughly the same amount of N and P as a combined application of basal fertiliser + 5 t ha^{-1} of manure of average quality. To illustrate the effect of rainfall variability the model was run for 12 years (or 24 seasons, the long and the short rains) using long-term rainfall records in the area. Coefficients of variability were calculated and multiplied by the average rainfall at each locality to generate 12 years of variable rainfall but with a similar pattern across localities to allow for comparisons (Table 4 B).

The following simulations were performed to address our research questions on ISFM:

(i) Application rates of 0, 30, 60, 90, 120, 150 and 180 kg N ha^{-1} with and without 30 kg P ha^{-1} for a single season to all the fields in Table 4 A.

(ii) Application of basal and replacement fertiliser rates, of good quality manure (5 t dm ha^{-1}) and of basal fertiliser + manure for 12 consecutive years to all fields in Table 4 A, with different proportions of crop residues retained in the field.

(iii) Application of manure (1.8 t dm ha^{-1}) of different qualities (Table 3) with and without application of minimum fertiliser rates (32N:23P) for 12 consecutive years to all fields in Table 4 A.

(iv) Runs of 12 years without nutrient inputs followed by 12 years of ‘rehabilitation’ applying manure (1.8 t dm ha^{-1}) of different qualities (Table 3) with and without application of minimum fertiliser rates (32N:23P).

Table 4: Scenario analysis. (A) Soil properties, crop management parameters and maize aboveground biomass yield under farmer management (first season – long rains) and in the experiment (second season – short rains) measured in three farms across sites; (B) Multipliers used to simulate rainfall variability (derived from measured data) throughout the 12 years of the simulation period.

(**A**)

Farmer (site)/ position within farm	Soil properties: Clay + Silt (%)	Organic C ($g\ kg^{-1}$)	Extractable P ($mg\ kg^{-1}$)	Exchang. K ($cmol_{(+)}\ kg^{-1}$)	Bulk density ($kg\ m^{-3}$)	Field slope (%)	Results under farmer management*: Biomass yield ($t\ ha^{-1}$)	Harvest index	Residue removed (%)	Residue biomass ($t\ ha^{-1}$)	Use of compost ($t\ ha^{-1}$)	Maize biomass in experiment: Control yield ($t\ ha^{-1}$)	NP yield ($t\ ha^{-1}$)	NPK yield ($t\ ha^{-1}$)
J. Obonjo (Aludeka)														
Homefield	44	12.2	13.4	0.39	1340	2.0	6.1	0.37	20	3.1	0	14.7	10.7	13.9
Mid-field	44	7.6	2.9	0.47	1470	2.5	4.0	0.20	0	3.2	0	4.8	11.7	11.9
Outfield	47	7.0	1.8	0.30	1440	1.5	2.5	0.28	0	2.5	0	3.7	11.4	10.5
D. Nakaya (Emuhaya)														
Homefield	50	20.8	15.3	1.96	1150	7.5	8.9	0.43	0	5.1	2.3	17.8	15.6	16.4
Mid-field	54	14.4	3.6	0.63	1340	9.0	8.3	0.43	60	1.9	0.5	7.3	16.6	16.3
Outfield	56	12.6	1.9	0.28	1400	3.0	6.9	0.43	100	0.0	0.0	9.0	10.6	14.8
S. Shivonje (Shinyalu)														
Homefield	76	24.0	13.6	0.49	1190	9.5	5.5	0.40	20	2.6	1.8	12.2	17.4	13.2
Mid-field	72	17.3	2.5	0.08	1200	29.5	4.2	0.32	80	0.8	1.0	8.2	13.5	10.9
Outfield	72	16.1	2.1	0.10	1070	11.0	3.0	0.26	20	1.8	0.0	3.7	11.6	10.6

(**B**)

	Year 1	2	3	4	5	6	7	8	9	10	11	12
Rainfall variability	0.66	1.20	0.76	1.23	1.02	1.04	0.61	1.25	1.31	0.83	0.85	1.23

*Results derived from participatory resource flow mapping and on-farm yield measurements; the amounts of crop residue and compost incorporated were calculated using farmers own estimations.

The results of the simulation (iv) were used to calculate the *hysteresis* of soil restoration in biomass yield units, and the number of years necessary for restoring the initial productivity of a certain field (i.e., the productivity at $t_1 = 0$, the beginning of the 12-year simulation). The effectiveness of fertiliser application was analysed through calculation of fertiliser use efficiencies (kg grain yield increase per kg applied nutrient), using the following equations:

Fertiliser N use efficiency = [Grain yield(N_iP_j) – Grain yield(N_0P_j)] / Applied N_i
Fertiliser P use efficiency = [Grain yield(N_iP_j) – Grain yield(N_iP_0)] / Applied P_j
N effect per unit P applied = [Grain yield(N_iP_j) – Grain yield(N_0P_j)] / Applied P_j

Where N_i (i = 15 – 180 kg N ha^{-1}) and P_j (j = 30 kg P ha^{-1}) indicate N and P application treatments; with N_0 = 0 kg N ha^{-1} and P_0 = 0 kg P ha^{-1}.

3. Results

3.1 Maize response to mineral fertilisers

Simulations using FIELD indicated different responses of maize grain yield to increasing application rates of N fertilisers across the three case-study farms, and even wider differences across the various fields of each individual farm (Figure 4). Considering the treatments that received only N (Figures 4 A, C, E), the three patterns of responsiveness can be observed: poorly-responsive unfertile fields (e.g. outfields at Aludeka), responsive fields (e.g. midfields at Shinyalu, homefields at Aludeka) and poorly-responsive fertile fields (e.g. homefields at Emuhaya). Crops in most fields responded to application of 30 kg P ha^{-1}, alone or in combination with N (Figures 4 B, D, F). In most cases and particularly in the homefields at the three locations the sole addition of P led to a doubling of yields. Adding P to the homefields caused a saturation of the response curve with N application rates of 60, 0 and 120 kg N ha^{-1} in Aludeka, Emuhaya and Shinyalu, respectively. Yields attained with N + P in the homefields of Emuhaya are close to the potential yields as observed under on-station experimental conditions in the area (cf. Tittonell et al., 2007d). The addition of P induced almost linear crop responses to N from 0 to 180 kg ha^{-1} in the outfields at the three locations. The recommended fertiliser rate of 60 kg N ha^{-1} and 30 kg P ha^{-1} led to widely different results across locations and fields, which varied between 1.1-5.9, 2.6-7.6 and 2.7-4.5 t ha^{-1} in Aludeka, Emuhaya and Shinyalu. The response to N applied at rates > 100 kg ha^{-1} in the presence of P indicates that, indeed, the N fertiliser rate applied in the on-farm experiment was suboptimal (cf. Section 2.3.5).

Calculated fertiliser use efficiencies varied widely across fields within the three case study farms (Table 5). In general, N use was more efficient in the presence of P (Table 5 A vs. B) and in the most favourable cases every kg of fertiliser P applied induced a response of c. 150 kg grain per kg N applied (e.g. outfield in Shinyalu with 180 kg N ha^{-1} – Table 5 C). Applying P with or without N led to positive responses in grain yields in most cases, with the weakest responses in the mid- and outfield of Aludeka at low N application rates, and the strongest responses in Shinyalu (Table 5 D). In the poorly responsive, fertile homefield at Emuhaya the largest relative P use efficiency was obtained without application of N, since increasing N application rates narrowed the differences between yields obtained with and without P (cf. Figure 4).

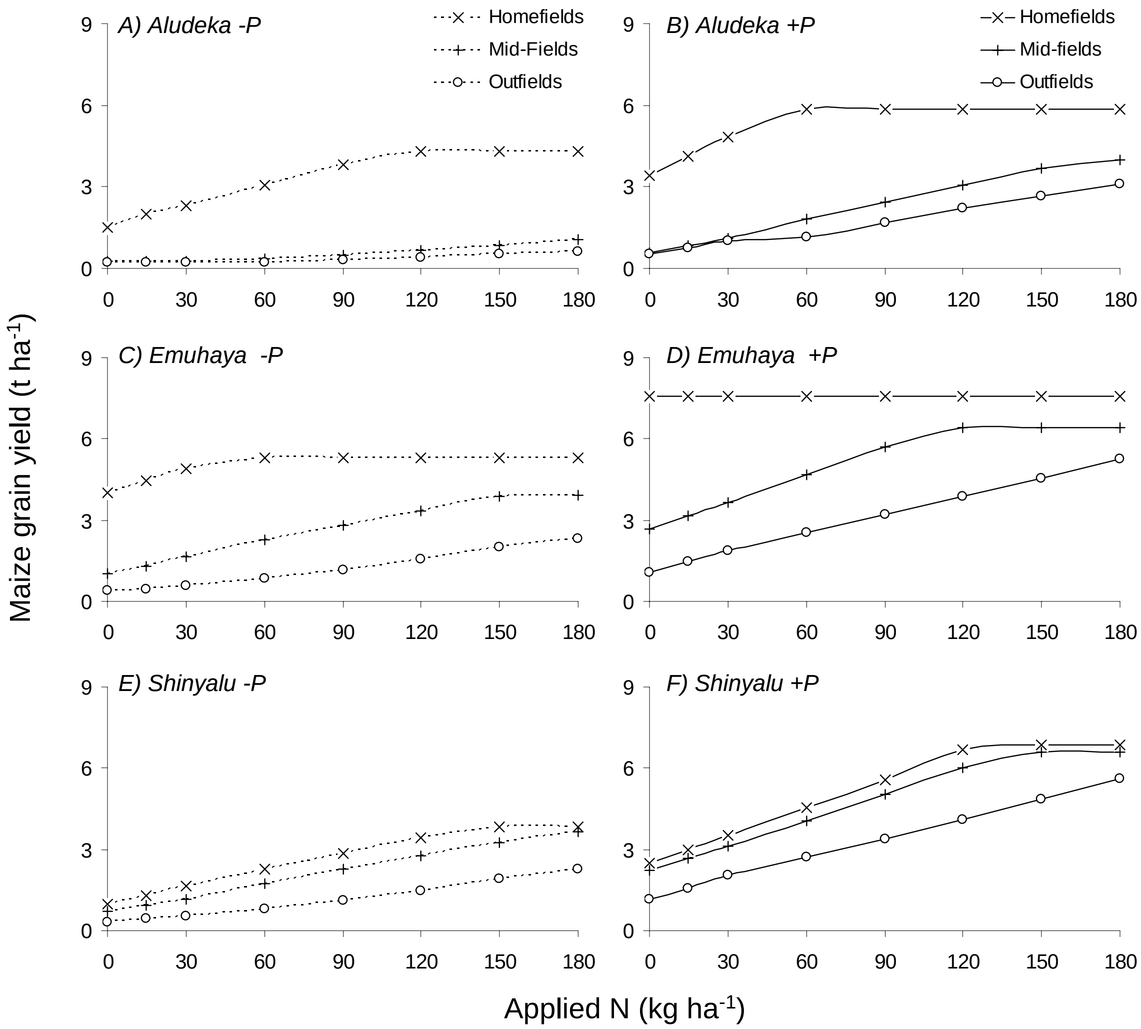


Figure 4: Simulated maize grain yields with increasing application of N (0 to 180 kg ha^{-1}), with and without application of P (-P = 0 and +P = 30 kg P ha^{-1}), as mineral fertilisers in home fields, mid-fields and outfields of three case study farms (cf. Table 4) in Aludeka (A, B), Emuhaya (C, D) and Shinyalu (E, F), western Kenya.

As reference for the interpretation of fertiliser use efficiencies, we calculated the fertiliser:grain price ratio (i.e., the kg of grain necessary to buy 1 kg of fertiliser), using varying wholesale and retail prices for calcium ammonium nitrate (CAN) fertiliser and maize grain, using prices from market surveys in western Kenya (Table 6).

Table 5: Simulated fertiliser N and P use efficiencies using FIELD (cf. Fig. 4) for one case study farm per site (cf. Table 4). Calculations were done with the results of simulating mineral fertilizer applications using equations I – III.

(**A**) Fertiliser N use efficiency without P added (kg grain kg N^{-1})

Site/ field type	N application rate (kg ha^{-1})							
	0	15	30	60	90	120	150	180
Aludeka								
Homefield	-	32	27	26	26	23	19	15
Midfield	-	0	0	1	3	3	4	4
Outfield	-	0	0	0	1	1	2	2
Emuhaya								
Homefield	-	29	29	22	14	11	9	7
Midfield	-	19	21	21	20	19	19	16
Outfield	-	5	7	8	9	10	11	11
Shinyalu								
Homefield	-	20	21	22	21	20	19	16
Midfield	-	14	15	17	18	17	17	16
Outfield	-	7	7	8	9	9	10	11

(**B**) Fertiliser N use efficiency with P added (kg grain kg N^{-1})

Site/ field type	N application rate (kg ha^{-1})							
	0	15	30	60	90	120	150	180
Aludeka								
Homefield	-	47	48	41	27	20	16	14
Midfield	-	19	18	20	21	21	21	19
Outfield	-	15	17	10	13	14	14	14
Emuhaya								
Homefield	-	0	0	0	0	0	0	0
Midfield	-	32	33	33	34	31	25	21
Outfield	-	25	27	25	24	23	23	23
Shinyalu								
Homefield	-	33	33	34	34	35	29	24
Midfield	-	30	30	31	31	32	29	24
Outfield	-	28	29	26	25	25	25	25

(**C**) Yield increase by N per unit of applied P (kg grain kg P^{-1})

Site/ field type	N application rate (kg ha^{-1})							
	0	15	30	60	90	120	150	180
Aludeka								
Homefield	-	24	48	81	81	81	81	81
Midfield	-	9	18	41	63	82	103	114
Outfield	-	8	17	21	39	56	71	86
Emuhaya								
Homefield	-	0	0	0	0	0	0	0
Midfield	-	16	33	66	102	124	124	124
Outfield	-	13	27	49	71	93	116	139
Shinyalu								
Homefield	-	16	33	67	103	139	145	145
Midfield	-	15	30	61	94	127	147	147
Outfield	-	14	29	52	75	99	123	148

(**D**) Fertiliser P use efficiency (kg grain kg P^{-1})

Site/ field type	N application rate (kg ha^{-1})							
	0	15	30	60	90	120	150	180
Aludeka								
Homefield	63	71	84	93	68	52	52	52
Midfield	10	20	28	48	65	80	94	98
Outfield	9	17	26	30	46	60	71	82
Emuhaya								
Homefield	118	103	89	75	75	75	75	75
Midfield	55	62	67	80	98	102	84	82
Outfield	23	33	43	57	67	76	84	97
Shinyalu								
Homefield	51	57	62	74	91	109	101	101
Midfield	50	58	65	77	91	109	112	98
Outfield	28	38	50	64	77	88	98	112

The most favourable ratio (of 2.2 kg grain to pay for each kg N) could be achieved by ‘wealthier’ farmers who produce maize surplus that can be sold locally (retail price) in times of food scarcity and who can buy a full 50 kg-bag of fertiliser from (often distant, semi-) urban markets at more convenient prices (Table 6). The worst ratio (17.6 kg grain to pay for each kg N) is often faced by most farmers in remote rural settings, when cash needs force them to sell their maize at the lowest price immediately after harvest (and to buy maize at other times of the year), and when small amounts of fertilisers are bought from local retailers (also often the wealthiest farmers in the community) at high prices. The simulation results show that when fertiliser N was applied without P in the case study farms (Table 5 A) the ‘break even’ threshold of 17.6 kg grain per kg N was only reached in about half of the cases.

Table 6: Fertiliser:grain price ratios (kg maize necessary to pay for 1 kg fertiliser) calculated for varying wholesale and retail prices in western Kenya (Source TSBF, 2006). Prices (in Kenya Shillings, 1 KSh = 72 us$) of fertilisers and maize fluctuate between rural and urban markets, and prices of maize also between periods of scarcity and abundance during the year.

Price of N fertilizer*		Price bag of maize (90kg)**			Price per *goro goro* (2 kg)***		
		780	1300	1820	20	40	60
Bag of 50 kg (KSh)	Price per kg N						
1530	67	7.7	4.6	3.3	6.7	3.3	2.2
1800	78	9.0	5.4	3.9	7.8	3.9	2.6
2070	90	10.4	6.2	4.5	9.0	4.5	3.0
Retailer price (KSh kg^{-1})							
50	109	12.5	7.5	5.4	10.9	5.4	3.6
60	130	15.1	9.0	6.5	13.0	6.5	4.3
70	152	17.6	10.5	7.5	15.2	7.6	5.1

*Calculated for calcium ammonium nitrate (CAN); N content 46%;
**Prices of 780, 1300 and 1820 are equivalent to 9, 14 and 20 KSh kg^{-1} maize;
***Local unit of trade, a tin of +/- 2 kg maize; prices of 20, 40 and 60 are equivalent to 10, 20 and 30 KSh kg^{-1} maize.

3.2 Combined application of manure and mineral fertilisers

Application of 5 t dm ha^{-1} of good quality manure (Experimental Dairy Farm – Table 3 B) led to substantially increased crop productivity in the mid to long term in four fields with different initial patterns of responsiveness to fertilisers (Figure 5 A, D, J, M). Simulated crop productivity was larger during the first 3 to 4 seasons with application of mineral fertilisers at the basal rate (60 kg N ha^{-1} and 30 kg P ha^{-1}) than with application of 5 t dm ha^{-1} of manure (of the best quality found in the region). In subsequent seasons, maize yields were greater with manure applications in the fields that were initially poorer (Figure 5 D, J, M), and did not differ from yields obtained with basal fertiliser in the homefield of Emuhaya (a poorly responsive, fertile field).

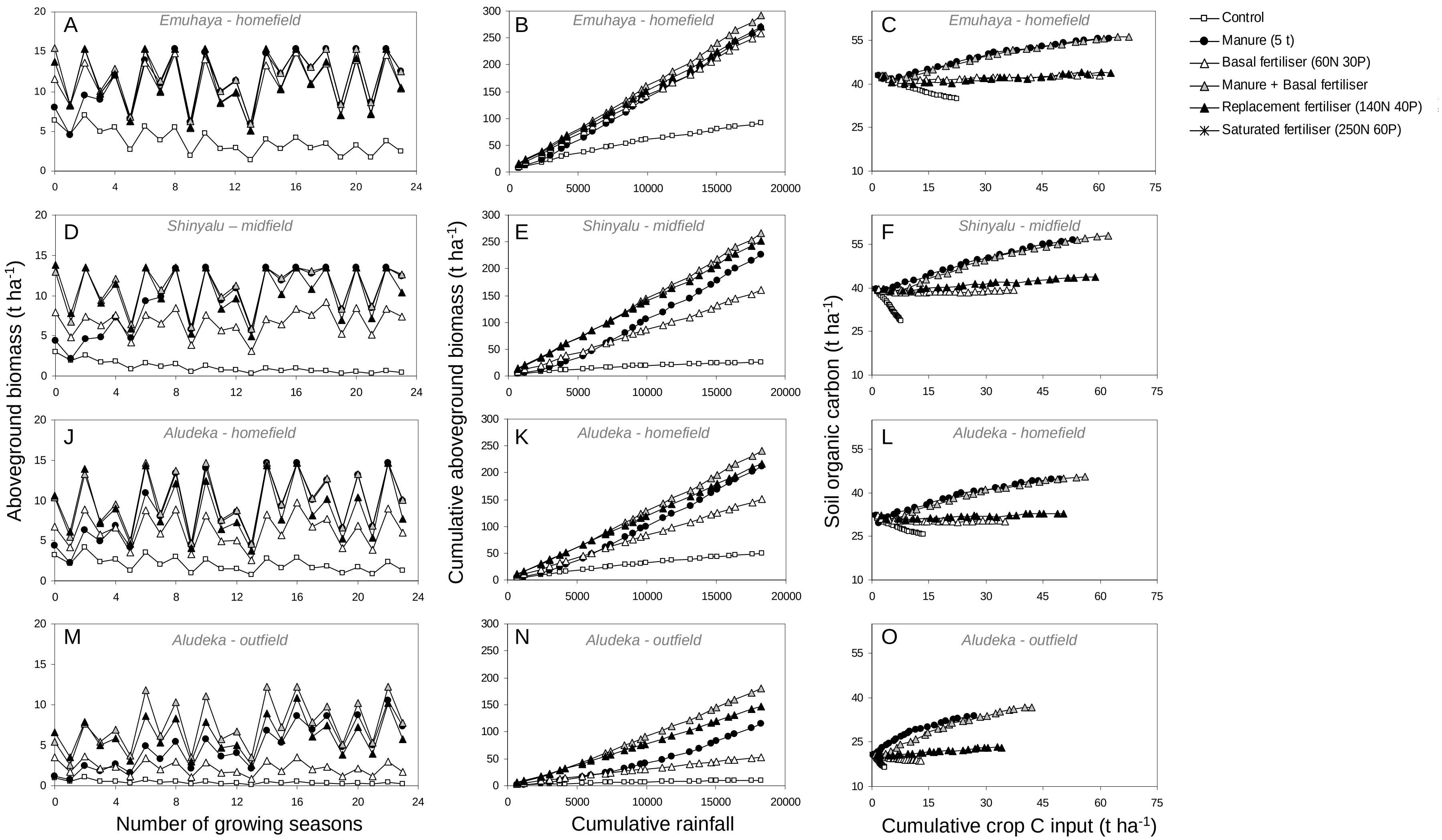


Figure 5: Simulation of maize production under various nutrient management strategies during 12 years (24 seasons) in fields with different patterns of responsiveness. A, B and C: Emuhaya homefield (non-responsive fertile field); D, E and F: Shinyalu midfield (responsive field); J, K, L: Aludeka homefield (responsive field); M, N, O: Aludeka outfield (non-responsive poor field). Left panes: aboveground biomass against time; Central panes: cumulative aboveground biomass against cumulative rainfall; Right panes: soil organic carbon against. cumulative crop C inputs to the soil (roots + stover).

Positive interactions between combined basal fertiliser and manure were only observed during the first season in the responsive fields (Shinyalu midfield and Aludeka homefield), while virtually the same performance as basal fertiliser was observed in the non-responsive fields (Figure 5 A, D, J, M). However, the combination of mineral fertiliser and manure led to the highest long term crop productivity in the degraded outfields of Aludeka – three times larger than crop productivity with basal fertiliser alone. Replacement fertiliser, i.e. application of the same amounts of N and P as in manure + basal fertiliser, led to similar productivity levels in the responsive and fertile fields in wetter seasons, but less in drier seasons or in all of the seasons in the poor Aludeka outfield.

Larger long-term maize productivity as a consequence of improved nutrient management is reflected in higher rainfall productivities (Figure 5 B, E, K, N), which in the case of the homefield in Emuhaya (Fig. 5 B) reached values of c. 15 kg biomass ha^{-1} mm^{-1} of seasonal rainfall. Calculations for western Kenya using the dynamic crop model DYNBAL indicated maximum attainable water-limited yields in the order of 20 kg aboveground biomass ha^{-1} mm^{-1} of seasonal rainfall (Tittonell et al., 2006). Simulated yields attained under the control treatment without inputs (as under farmers' management) ranged between 1 and 5 kg biomass ha^{-1} mm^{-1}. Thus, a crop productivity of c. 15 t dm ha^{-1}, as simulated for the wetter seasons in Figure 5 A, D and J, represents a potential yield that is however hardly achieved in reality (e.g., Kipsat et al., 2004). Assuming such potential yields, C inputs to build up soil organic matter can be derived from the amount of crop residues (above and belowground) that are retained in the field (Fig. 5 C, F, L, O). The various treatments simulated varied in the rate at which they contributed to build up soil organic C when 100% of the crop residue was retained in the fields, basically due to their large differences in crop productivity. In the non-responsive, fertile homefield at Emuhaya both rates of mineral fertilisers without manure contributed almost the same amount of C from crop residues (Fig. 5 C). Application of fertiliser at replacement rates led to more C contributed to the soil than basal fertiliser in the rest of the fields, and more than manure applications in the outfield (Fig. 5 O).

Since farmers have many different uses for crop residues, including livestock feeding/bedding, fencing or using them as fuel, they normally remove a large part of the residues from the fields after harvest (also to facilitate tillage in these double-cropping systems). Our simulation results indicate that the initial soil C contents can be practically maintained with basal fertiliser rates if 70% of the crop residue is retained in the field (assuming alternative uses for the remaining 30%), except in the poorly responsive fields (Figure 6 A). In the latter, replacement fertiliser rates increased soil C by 2.3 t ha^{-1} after 12 years (24 growing seasons) with respect to the initial value at $t_1 = 0$. It must be noted, however, that maintaining the initial soil C contents of poor fields is undesirable. Soil C needs to be increased in such fields and this was only achieved with manure application every season (twice a year). Wider differences in soil C build up between the various treatments simulated were observed in Shinyalu midfield, characterised by abrupt slopes and clayer soils (cf. Table 4). If farmers remove most (90%) of the crop residue, as they commonly do, soil C is only built up by manure and root C inputs (Figure 6 B). In such case, the use of fertilisers is insufficient to build soil organic matter; since a slower soil organic matter build up also leads to less crop productivity, root C inputs to the soil are also less.

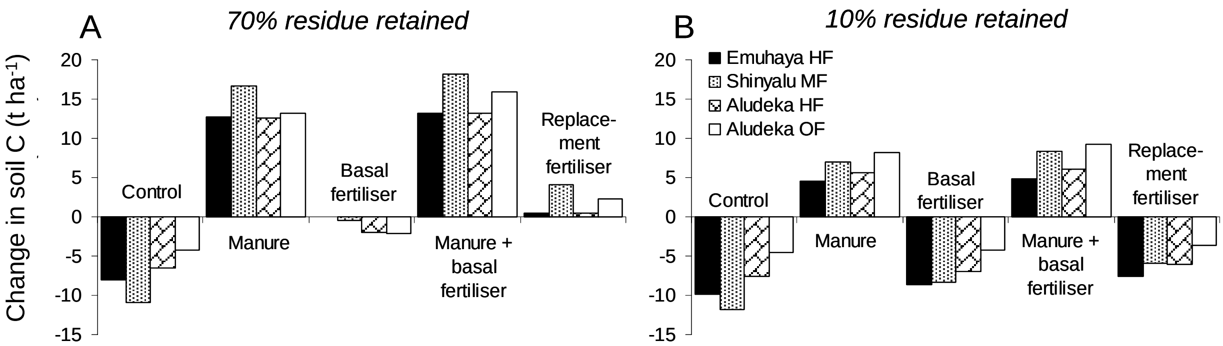


Figure 6: Simulated changes in soil organic C after 12 years of maize cultivation under different management strategies with retention of 70% (A) or 10% (B) of crop residues in the field after harvest, in fields with different responsiveness: non-responsive fertile field (Emuhaya homefield), responsive fields (Shinyalu midfield and Aludeka homefield) and non-responsive infertile field (Aludeka outfield).

3.3 The attractiveness of soil improving technologies

Often the implementation of ISFM technologies represents a trade-off between the immediate concern of increasing yields and the long-term sustainability of the system. The combined application of manure and fertilisers may be attractive, as this may induce positive interactions in responsive fields (cf. Figure 5 D and J) in the short-term and maintain soil C in the long term. However, that may not be the case in the poor outfields during the first seasons (cf. Figure 5 M), and especially not when more realistic manure application rates and average manure qualities are considered. For example, in the outfield at Aludeka, where soil C build up is deemed necessary, application of 1.8 t dm ha^{-1} of manure of the various qualities sampled in western Kenya (Table 3 B) led to different simulated long-term results in terms of restoring productivity and soil organic C (Figure 7 A and B). With the sort of manures qualities as sampled from case study farms in western Kenya, soil C can only be maintained – at most – with this rate of manure application.

Farmers' decisions on technology adoption are often conditioned by attractive results in terms of short–term crop yield responses. Zooming-in to the first four years, Figure 7 C and D show simulated maize grain yields on the outfield at Aludeka with repeated manure applications, with and without application of a minimum fertiliser rate (32 kg

N ha^{-1} and 23 kg P ha^{-1}). The crop residue was retained in the field. Beyond the variability induced by seasonal rainfall, yields in the second year (and increasingly thereafter) were substantially larger with all manure types in the presence of fertiliser, achieving larger grain yields than after four years without fertilisers. However, the response to fertilisers without manure (‘control’) was poor in the first seasons (see also Figure 5 M). Without such relatively small amounts of mineral fertilisers to boost crop productivity in the second year, soil C contents could not be improved with any of the manure qualities sampled in western Kenya farms (Farms A to E) applied at the (quite realistic) rate of 1.8 t dm ha^{-1}.

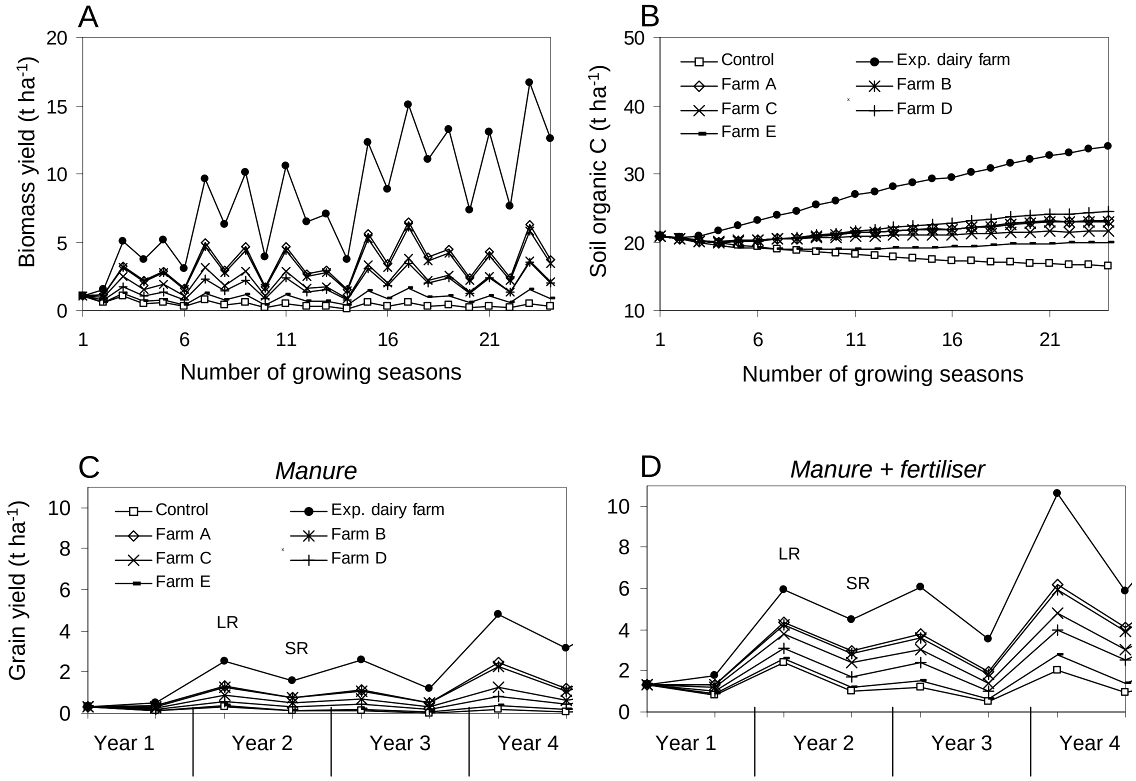


Figure 7: Rehabilitation of non-responsive fields (outfield at Aludeka) with application of 1.8 t dm ha-1 manure of different qualities (Table 3 B). (A) Simulated aboveground maize biomass and (B) soil organic carbon during a 12-year period. Zooming-in to the first 4 years of the simulation, (C) grain yield increase with application of different manure types and (D) with manure plus of a minimum fertiliser rate (32 kg N ha^{-1} and 23 kg P ha^{-1}).

3.4 ‘Hysteresis’ of productivity restoration

By analogy to the phenomenon of hysteresis in dynamic systems, we defined the ‘hysteresis of restoration’ as the capacity of the system to react to ISFM interventions aimed at rehabilitating soils, restoring their productivity. Figure 8 shows FIELD simulations of crop productivity during 24 years: 12 initial years without inputs and 12 subsequent years with application of manure, mineral fertilisers or manure + mineral fertilisers (at rates of 32 kg N ha^{-1} and 23 kg P ha^{-1} and 1.8 t dm ha^{-1} of good quality manure), for a non-responsive fertile field (Emuhaya homefield), a responsive field (Aludeka homefield) and a non-responsive infertile field (Aludeka outfield). For simplicity, average instead of variable rainfall was used in these simulations. In Figures 8 A, C and E the 'rehabilitation' phase (*r*) has been plotted reversing the time axis, to illustrate the magnitude of the hysteresis (*h*).

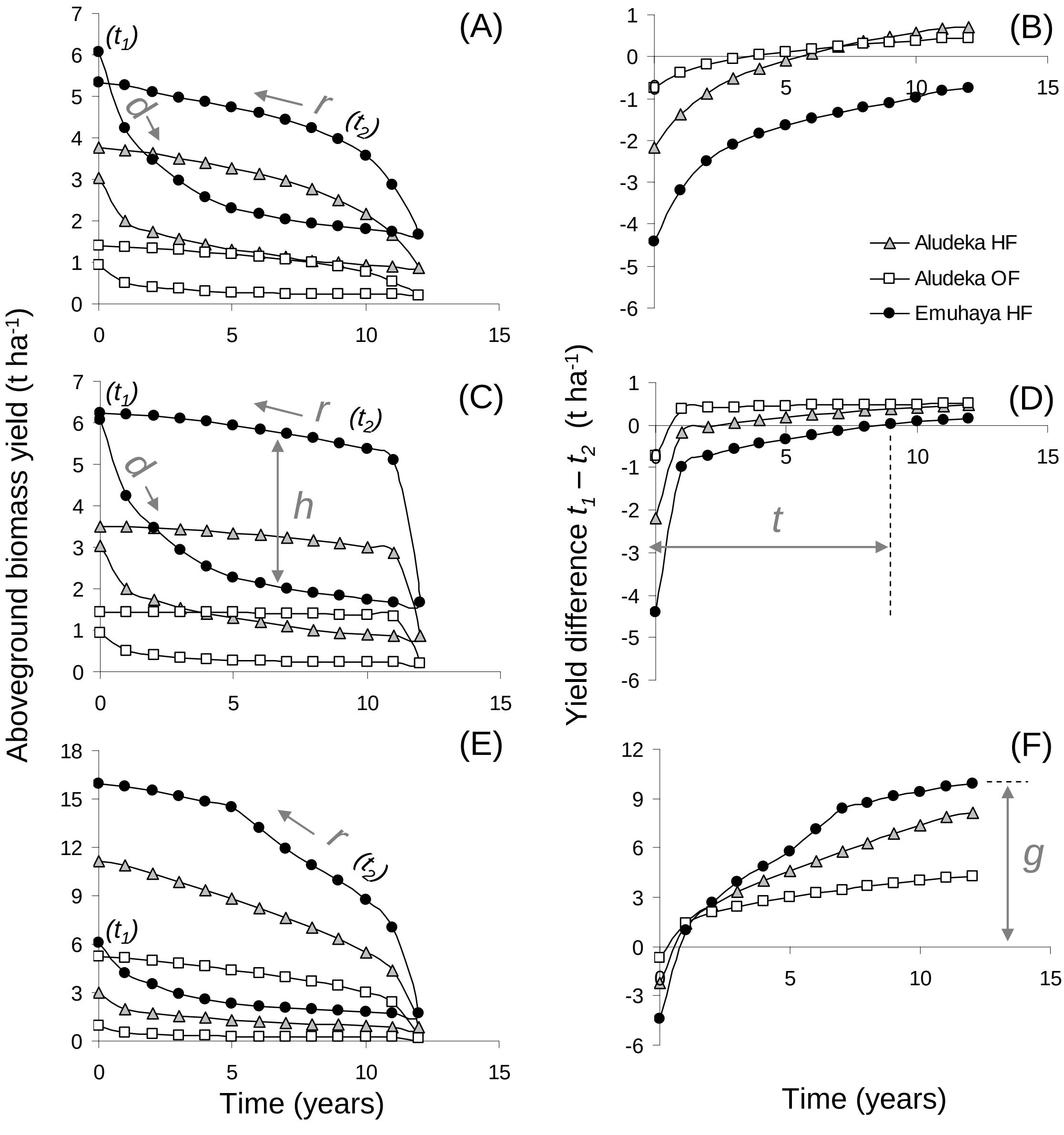


Figure 8: Hysteresis of soil restoration. (A, C, E) Simulated biomass yields during the degradation (*d*) and rehabilitation (*r*) phases and (B, D, F) absolute difference with respect to the initial yield (at t_1) over the years of rehabilitation (t_2), indicating the time needed to achieve initial yield levels (*t*) and the net productivity gain (*g*), for three fields in western Kenya (HF: homefield, OF: outfield). In A, C and E the rehabilitation phase was plotted inverting the direction of the time axis to indicate the magnitude of the hysteresis (*h*). Rehabilitation treatments included application of manure (A and B), N-P mineral fertilisers (C and D) and combined manure + fertilisers (E and F).

Figures 8 B, D and F show the number of years (*t*) necessary to achieve the initial production levels with the respective interventions, and the net productivity gains (*g*) that may be achieved. The rate of restoration was faster with mineral fertilisers (Figs. 8 A and B) than with manure (Figs. 8 C and D) – at the simulated application rates – and much faster with combined manure and fertilisers (Figs. 8 E and F) (note the differences in the scale of the *y*-axes). Taking the initial productivity as the threshold, however, is not always appropriate. In the case of the poor outfield of Aludeka, the low initial productivity is achieved after 3 years of manure application or after one year of fertiliser application. Likewise, the initial high productivity of the fertile homefield in Emuhaya is not achieved after 12 years of manure application. In these cases, a ‘desirable’ or ‘achievable’ threshold yield (cf., Tittonell et al., 2007b) should be defined and used in the calculations.

In general, the hysteresis of restoration will depend on the type of technology implemented to restore soil productivity (mineral and/or organic fertilisers, rotations with legume crops, soil erosion control measures, improved crop germplasm, etc.), on the inherent properties and initial condition of the soil, and on complementary management measures such as retaining crop residues in the field (or e.g. water harvesting measures in drier areas). Table 7 presents calculations of the hysteresis of restoration of the three fields with different responsiveness plotted in Figure 8 after 12 years of cropping without inputs, using the various manure qualities in Table 3 B applied at 1.8 t dm ha^{-1}, with and without minimum fertiliser rates (32 kg N ha^{-1} and 23 kg P ha^{-1}), and retaining crop residues in the field. The degree of hysteresis measured in biomass units varied strongly for the various types of manure, with little reaction of the three systems to application of poor quality manures without fertiliser, and greater reactions to mineral fertilisers than to all manures.

Table 7: Hysteresis of rehabilitation (t dm ha^{-1}) brought about by application of 1.8 t ha^{-1} of manure of different qualities with and without addition of mineral fertiliser to fields of different initial fertility (responsiveness)

Field		Manure quality type					
	No manure	Exp. Dairy Farm	Farm A	Farm B	Farm C	Farm D	Farm E
No fertiliser							
Emuhaya HF	-	2.46	1.20	1.13	0.72	0.51	0.17
Aludeka HF	-	1.98	0.68	0.63	0.44	0.33	0.06
Aludeka OF	-	0.94	0.32	0.29	0.15	0.12	0.02
32 kg N ha^{-1} + 23 kg P ha^{-1}							
Emuhaya HF	3.73	12.26	7.51	7.18	5.97	5.79	4.52
Aludeka HF	2.14	8.89	4.35	4.18	3.65	3.70	2.75
Aludeka OF	1.15	4.62	2.47	2.38	2.04	2.11	1.50

The effect of soil properties on the hysteresis of restoration is illustrated in Figure 9 A-C, depicting the results of FIELD simulations of 12 years of degradation followed by 12 years of rehabilitation for all the fields in the on-farm experiment (dataset 4; *n* = 54) with application of best quality manure (1.8 t dm ha^{-1}). For a wide range of initial soil C contents the hysteresis of the system remained below 2 t ha^{-1} (Figure 9 A); the few cases above that threshold correspond to fields where available (Olsen) P was larger. While fields with slopes between 0 and 10% could experience either low or high hysteresis, fields on abrupt slopes showed consistently poor capacity of reaction to rehabilitation with manure applications. Combination of manure and minimum fertiliser rates led to positive interactions in most fields (particularly in those with less soil C), as illustrated for Aludeka in Figure 9 D: the simulated hysteresis of rehabilitation of fields with soil C < 10 g kg^{-1} with manure+fertiliser combined was larger than the sum of the hysteresis with sole manure and sole fertiliser.

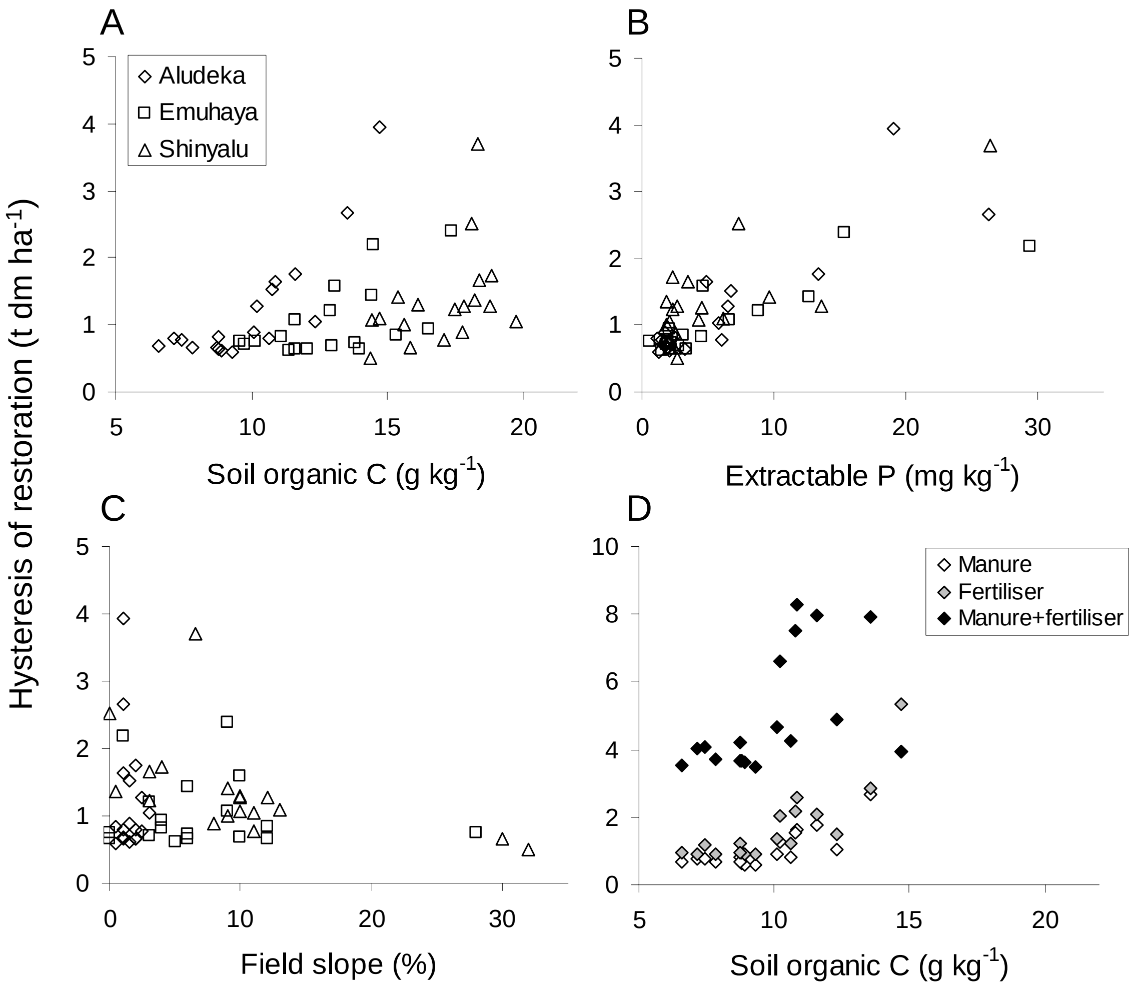


Figure 9: Hysteresis of soil restoration (i.e., the value of *h*, cf. Fig. 8) with repeated applications of animal manure calculated for all the fields in the nutrient-omission experiment and plotted against their initial (A) soil organic carbon, (B) extractable P contents, and (C) their topographic slope. (D) Hysteresis of soil restoration with application of animal manure, mineral fertiliser and manure + mineral fertiliser shown only for the fields at Aludeka (cf. Fig. 9 A).

4. Discussion

The application of a given rate of mineral fertiliser produced widely variable yield responses of maize across the various fields of individual farms (cf. Figure 4, Table 5), confirming experimental results of different studies across sub-Saharan Africa (e.g., Carter and Murwira, 1995; Wopereis et al., 2007). Nutrient use efficiencies varied widely, between 1 – 48 kg grain kg^{-1} N applied, and between 9 – 118 kg grain kg^{-1} P applied. This variability in the response to fertilisers – often reinforced by other interacting factors that determine resource use efficiencies (Tittonell et al., 2007c,d) – may partly explain the limited use of mineral fertilisers by smallholder farmers in western Kenya. In addition, some farmers in the region believe that fertilisers 'spoil the soil' or make their soil 'hungry' (Misiko, 2007). Possible reasons for this perception may arise from the fact that greater crop yields when N and/or P fertilisers are applied induce greater rates of extraction of other nutrients – particularly when crop residues are removed from the fields – which may lead to multiple nutrient deficiencies in the long-term.

Within the boundaries of its agroecological requirements, maize is a well suited crop to build up soil organic matter through crop residue C inputs due to its large biomass production and responsiveness to applied nutrients (Figure 5). However, the competing uses that farmers have for maize stover cannot be overlooked. Under the most favourable scenarios (combined manure and fertiliser applications - cf. Figure 6), the simulations with FIELD indicated that soils stored up to 1.5 t C ha^{-1} $year^{-1}$ when 70% of the crop residue was retained in the field. The average simulated C accumulation across fields and treatments was 0.37 t C ha^{-1} $year^{-1}$ (cf. Figure 6). The maximum 'C capture efficiency' in the soil for the 12-year period simulated was 0.18 (i.e., increase in soil C/ total C input), whereas average C losses attributable to heterotrophic respiration and soil erosion were around 4.6 t ha^{-1} $year^{-1}$. Kapkiyai et al. (1999) measured differences in total C in the order of 6 t C ha^{-1} in the upper 15 cm of the soil between control plots and plots that received fertilisers (120 kg N ha^{-1}, 52 kg P ha^{-1}) and manure (10 t dm ha^{-1} year, 20.5% C) during 18 years in central Kenya. In that experiment, which was conducted under controlled, on-station conditions average maize grain yields were 1.5 and 5 t ha^{-1} $year^{-1}$ for the control and fertiliser+manure treatments, respectively, and crop residues were removed from the control plots.

To build up soil C and nutrient stocks through fertiliser use it is necessary to either retain the crop residue in the field or to replace these inputs with other organic amendments, such as animal manure, green manures or through transfer of plant biomass from outside the field. Continuously manured soils receive C inputs that are crucial in building up soil organic matter when the crop residue is not retained (Figure 6). In contrast to mineral fertiliser use, continuous application of animal manure, even if in small amounts (Table 1), would allow building up more balanced soil nutrient stocks and a larger capacity of the soil to retain nutrients (and water) by increasing soil organic matter in the long-term. Continuous application of manure may also contribute to mitigate other potential soil fertility problems, such as micronutrients deficiencies, soil acidity or soil physical impediments, which have been less frequently reported for western Kenya (Braun et al., 1997). 'Fortifying' mineral fertilisers by addition of more nutrients in their composition can partly solve this problem (e.g., the Mavuno compound fertiliser currently promoted in Kenya), although C inputs to the soil are not guaranteed.

The use of animal manure as soil amendment is strongly conditioned by the lack of sufficient quantities at farm scale (Table 1). Moreover, manure application in farmers' fields often gives poorer responses than those measured in controlled experiments, basically due to the wide differences in manure qualities across different farms (Table 3 B, Figure 7). Castellanos-Navarrete (2007) measured efficiencies of N cycling in crop-livestock systems of western Kenya of around 30% on average. This implies that per every 100 kg N fed to livestock (e.g. in 10 t of maize stover) only 30 kg would be available for application to crops (e.g. in 2.5 t of manure), of which probably a half becomes available to the crop in the first season. Considerable N (and C) application rates could still be reached if this amount of manure is concentrated in a small field (e.g. 0.25 ha). However, under the current productivity levels of western Kenya an equivalent of about 10 ha would be necessary to produce 10 t of maize stover.

The combination of small amounts of mineral fertilisers and realistic application rates animal manures looks most promising as ISFM strategy, as indicated by the simulations of FIELD (Figure 7, Table 7). These results suggest that when manures are poor in nutrients, the presence of fertiliser is essential to increase soil organic matter. Even the poorest quality manure (cf. Farm E in Table 3 B) in combination with minimum amounts of mineral fertilisers induced some response in crop yield that can make the investment attractive to farmers. However, different types of farmers experience different fertiliser:grain price ratios, according to their capacity to overcome transaction costs or to react to price fluctuations throughout the year (Table 6).

ISFM technologies should be designed to shift non-responsive infertile fields into responsive fields in the mid- to long-term, for example, by targeting the limited amounts of manure to their rehabilitation. Non-responsive fertile fields (e.g. homefield in Emuhaya – Table 5) may be managed with 'maintenance fertilisation' rates (mainly with mineral P) to sustain their current productivity. Organic matter allocation studies on sandy soils in Zimbabwe (Mtambenengwe and Mapfumo, 2005) indicated the existence of minimum soil C thresholds for substantial responses to mineral fertilisers by maize. In our case, however, soil C explains only part of the magnitude in the crop response to fertilisers, while soil P availability seems to play a most important role (see also Tittonell et al., 2007d). Soil P availability determines not only the short-term crop response to applied nutrients but also the capacity of the system to react to restoration measures in the longer term (i.e., available P had a tighter relationship with the hysteresis of restoration than soil C – Figure 9). Most soils under cultivation are extremely deficient in available P (< 2 mg kg^{-1}) in western Kenya (Tittonell et al., 2007c).

The concept of hysteresis of soil restoration provides an integrative measure of the capacity of reaction/response of the system to restorative ISFM interventions in the long term – as much as the response of crops to applied nutrients does in the short term – reflecting both the effect of system properties (e.g. soil condition, rainfall variability, type of crops) and the performance of different rehabilitation technologies. In our case, the simulated reaction of degraded soils to the application of mineral fertilisers (Figure 8 C and D) indicated almost immediate responses in the first year. This might, however, overestimate the actual capacity of reaction of the system. In reality, it may take longer to restore soil productivity when degraded soils exhibit other limitations (e.g., physical degradation or acidity) that were not simulated by FIELD. The calculated values of hysteresis are only relevant within the system (or set of systems) under study, and extrapolations outside these boundaries are of little value. Here, the hysteresis of restoration was measured in crop productivity units, but it could also be expressed in soil C units, annual crop C inputs to the soil, value of production (at constant prices), etc. If calculated with comparable methods and with standard assumptions, the concept of hysteresis of restoration could be used in scenario analysis across farming systems within different biophysical and socioeconomic environments; for example, comparing the impact of certain interventions across regions differing in agroecology or under varying market situations, using a common indicator.

A disadvantage in the implementation of this concept is the need of long term data, either to calculate the hysteresis of restoration directly from measured changes in the relevant indicators, or to calibrate/parameterise simulation models to calculate changes in the long term. Availability (and accessibility) of data from long-term experiments to calibrate models constitutes a bottleneck for studies involving exploration of strategies/ scenario analysis in sub-Saharan Africa. In the present study, for example, reliable data was lacking for parameterisation of the capacity of animal manures of variable quality to release nutrients through decomposition. We overcame this by using the same humification coefficient for all manures. However, the effect of manure composition, application rates, as well as soil properties and (micro)climatic conditions on the humification coefficient can be significant. In the light of such shortcomings, we and others (e.g. Smaling et al., 1997; Andrén et al., 2004) maintain that simulation models for scenario exploration in data-scarce environments should be kept simple. By taking a seasonal time step as in FIELD, processes can be summarised into functional relationships that capture key aspects of the dynamics of farming systems relevant to the research questions raised.

5. Conclusions

Mineral fertilisers are a clear option for soil fertility management by smallholder farmers in areas of high population densities (small farm sizes) and generalised soil degradation such as western Kenya. In rehabilitating degraded soils, small amounts of mineral fertilisers can be used to kick-start the system, to jump to a higher level of productivity that will generate favourable feedbacks within the system. Larger biomass production brought about by fertiliser use leads to larger C inputs to the soil and long-term increase in soil organic matter; presumably requiring less fertiliser in the future. However, greater crop productivity induced by the use of mineral fertilisers does not translate into better soil fertility in the long term when large amounts of C and nutrients are removed every season from the fields after harvest. To the contrary, this practice may lead to faster decline in the availability of other nutrients in the soil, in line with the negative perception that some farmers have about the long-term effect of mineral fertilisers. In this sense, and under current circumstances, the speculation on the capacity of smallholder farmers in Africa to commercialise their crop residue as raw materials for biofuels would have serious consequences for the sustainability of these systems (e.g., see: www.africa-ata.org/aatf for the call by the Director General of the UN Industrial Development Organisation to make Africa a world leader in biofuel production).

Animal manure is commonly used by farmers to manage soil fertility in mixed crop-livestock systems. The amounts of manure available to smallholder farmers are limited, and their quality often poor compared with manures from commercial farms (i.e., those that are normally used in field experiments). When manures of poor quality are applied at realistic rates with respect to their availability on smallholder farms, their contribution to restoring the productivity of degraded soils is so restricted that it may discourage farmers to invest efforts in soil rehabilitation. Manure application in combination with small amounts of fertilisers may generate more attractive responses in the short term and a more balanced build up of C and nutrient stocks in the soil in the long term. However, soils that underwent severe degradation or are inherently infertile will exhibit low hysteresis of restoration, and will require major long-term investments to restore their productivity (that might not be recovered over several years).

The targeting of technologies for ISFM in the context of African smallholders should encompass these key features of smallholder systems: strong management-induced soil heterogeneity, limited availability of poor quality manure, competing uses for crop residues within the farm, lack of labour and limited access to mineral fertilisers. Approaches for *truly*-integrated soil fertility management must not overlook these facts.

Acknowledgements
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Chapter 8

Exploring the physical feasibility of options for the intensification of crop-livestock systems[†]

[†] Adapted from:
Tittonell, P., van Wijk, M.T., Herrero, M., Rufino, M.C., de Ridder, N., Giller, K.E., 2007. Inefficiencies and resource constraints – exploring the physical feasibility of options for the intensification of smallholder crop-livestock systems in Vihiga district, Kenya. Agricultural Systems, submitted.

Abstract

Farmers' goals, aspirations and experience are key elements in the design of more sustainable farming systems. During participatory prototyping activities conducted in Vihiga, western Kenya farmers designed what they considered to be the ideal farm (Waithaka et al., 2006): one in which high productivity would be achieved through optimising crop-livestock interactions. Three major observations were derived: 1. Participating farmers had an optimistic view on the contextual boundary conditions (i.e., climate and market dynamics) in which the ideal systems would operate; 2. They tended to overestimate the size of the flows that determine crop-livestock interactions (e.g. the amount of fodder produced to feed livestock or the amount of manure available to fertilise crops); 3. The productive structure of the ideal farm prototypes resembled, to a large extent, the current configuration of the wealthier farms in the area. The objective of our study was to analyse the physical feasibility of shifts in the productive structure of the majority of farms in the area necessary to move them closer to the ideal prototype, having the current wealthier farms as reference. We selected four case study farms which represented four main types of local households and quantified all relevant physical flows through and within them. With this information we parameterised a dynamic, farm-scale simulation model (NUANCES-FARMSIM) to investigate: (i) the current differences in resource use efficiencies and degree of crop livestock interactions across farm types; and (ii) the impact of different interventions on producing the desired shifts in productivity towards the ideal farm. Simulations were run for periods of 10 years using historical weather data from the area. Changes in the current farming systems were introduced stepwise, as both intensification of input use and qualitative changes in the configuration of the farms. Results indicate that improving resource use efficiencies must go hand-in-hand with removing resource constraints, and *vice versa*, and that household food self-sufficiency (expressed in energy units) can be achieved in all farm types through input intensification. However, the feasibility of implementing such interventions on a large number of farms is disputable. The impact of livestock on the recycling of nutrients and on the efficiency of nutrient use at farm scale can be large, provided that enough nutrients are present in (or enter) the system to be redistributed. Our results suggest that the trajectory of change towards the ideal farm is hardly feasible for a majority of farmers in the region, which implies that the ideal farms may be indeed just an 'ideal'.

Keywords: Sub-Saharan Africa, Farming systems design, Smallholder farms, Farm-scale modelling, Food security, Resource use efficiency

1. Introduction

Sustainability assessments in much of sub-Saharan Africa (SSA), through calculation of nutrient balances or chronic poverty analysis, inform us that smallholder farming systems are highly inefficient, face severe resource degradation processes, and are vulnerable to changes in external driving variables (e.g. Smaling et al., 1996; Barrett et al., 2002; Tomas and Twyman, 2005). External factors threatening the systems include political/institutional instability, changes in the biophysical environment, market volatility, and demographic pressure with consequent degradation or extinction of common resources. Areas of high population density – originally of high agricultural potential – represent severe cases of ongoing deterioration of often-century-old smallholder systems. These areas are common in the most fertile highland and midland agroecological zones of SSA, of which western Kenya is probably one of the most conspicuous examples (Braun et al., 1997). The design of sustainable systems should aim to make these systems more stable, reliable and adaptable in face of external changes. Due to economic and environmental reasons, systems design should also aim to improve the efficiency of resource utilisation.

The design of more sustainable and equitable agricultural systems should rest on, minimally: (i) proper diagnosis of the baseline situation and understanding of the causes that render the systems unsustainable; (ii) social desirability (community involvement) and compatibility with the local culture; (iii) ability to foresee, predict or simulate (internal and external) changes in time and their consequences, in terms of the trajectories of change (achievability) and the long-term stability of the newly-designed systems. Diagnosis and monitoring require proper indicators, which must be easy to measure, sensitive to the changes being monitored, easily understood and meaningful for communication (López-Ridaura, 2005). Thornton and Herrero (2001) proposed the use of integrated crop-livestock simulation models to aid the (re-)design of sustainable farming systems, by means of *ex-ante* evaluation or exploratory studies that search ways of balancing crop-livestock interactions to capitalise synergies (win-win) and improve resource use efficiencies at farm scale. Recent experimental approaches to promote development in rural areas, however, have relied on intervention without rigorous *ex-ante* evaluation. In western Kenya, for example, an entire rural community (village) has been delimited as a benchmark and since 2004, became a pilot site for the simultaneous implementation of multiple (input-based and agroforestry) technologies, complemented with social promotion activities, aiming at quantifying the level of investment necessary to meet the UN Millennium Development Goals – i.e. the "Millennium Village" (www.unmillenniumproject.org).

This study builds on a wealth of previous studies in the highlands of western Kenya – a region that has been the focus of extended research. A key study that guided our questions is the evaluation of what farmers perceived as *ideal farms*, a recent application of participatory prototyping in the design of viable farms by Waithaka et al. (2006). The viability of such prototypes has been evaluated by integrating, for one 'average' season, the results of a livestock-feeding simulation model and a household-level model that used linear programming techniques to optimise farmers' objectives, relying on technical coefficients calculated from field data by the IMPACT platform (Integrated Modelling Platform for Animal-Crop Systems – Herrero et al., 2007). A similar approach was taken by Castelán-Ortega et al. (2003) for the analysis of peasant systems in the highlands of Mexico and by Zingore et al. (2007b) to analyse smallholder farms in Zimbabwe. In none of these cases were the different models/ tools functionally integrated, the long term dynamics of the systems and the trajectory towards the ideal farm considered, nor was the effect of within-farm soil heterogeneity on crop production simulated. The 'ideal farms' would have 'ideal soils', and thus the reciprocal effects of management on soil fertility and *vice versa* could not be captured. In designing the ideal farms, the participating farmers assumed socio-economic and biophysical environments that were highly conducive.

We propose an approach in which (relatively simple) crop, soil and livestock models are dynamically and functionally linked into the farm-scale modelling shell FARMSIM (Farm-scale Resource Management SIMulator) which has been developed within the AfricaNUANCES project (www.africanuances.nl). The model is then used to simulate the dynamics of simplified but realistic systems chosen to represent farms with different resource endowments and livelihood strategies (i.e. *Farm Types*) derived from a typology of households in western Kenya. The shift towards the ideal farm should be pursued through sustainable intensification. Potential pathways to intensification of smallholder systems analysed include increased (nutrient) input use intensity – a 'green revolution' type of approach – or changes in the configuration of the systems that demand more labour, management intensity and investments – i.e., *qualitative* changes. Using the integrated analytical tool, our objectives were to evaluate: (i) the biophysical performance of these simplified farms in terms of key flows determining resource use efficiency at farm scale; and (ii) the potential impact of options for the sustainable intensification of crop-livestock interactions in the poorer farms. Emphasis was placed on identifying realisable physical frontiers for the intensification of crop-livestock interactions through innovative management within these systems. Thus, the role of farm labour and the financial constraints for and consequences of the implementation of different management strategies were not quantitatively analysed in this case.

2. Materials and methods

2.1 The study area

Despite its relatively high agroecological potential, Vihiga is one of the poorest districts in Kenya, with an average of 58% of the households living below the poverty line. The area is densely populated (i.e. 800-1100 people km^{-2}) and most of the land is used by smallholders farming very small pieces of land (i.e. 0.5 ha on average; Kiptot et al., 2007). Rainfall is bimodal, totalling 1850 mm $year^{-1}$, and allowing two cropping seasons (the long and the short rains) a year. Dominant soil types include deep reddish Nitosols, Ferralsols and Acrisols distributed in the upper positions of a heavily dissected plateau (Tittonell et al., 2005b). Farms are predominantly integrated crop-livestock (maize-cattle) systems; crops provide feed and bedding material (fodder, crop residues, weeds) for the cattle while these provide manure to fertilise the crops (cf. Chapter 3). A survey by Waithaka et al. (2002) indicated that 77% of the agricultural households in Vihiga kept cattle, of which 42% owned only zebu, 42% zebu and cross and/or pure breed, and 16% had solely cross or pure breeds. Cattle productivity is poor, with average ages of first calving around 41 months, calving intervals of 663 days and milk production of 2.7 litres cow^{-1} day^{-1}, associated with poor disease control, housing and management, and inadequate feeding. The land is allocated mostly to food crops, with about 10% allocated to cash crops (tea grown by the wealthiest farmers and vegetables by others), 11% to fodder crops (mostly Napier grass, *Pennisetum purpureum* Schumach), 12% to compound fields and fallow land, and 5 to 10% to eucalyptus woodlots. Off-farm income is a major income source for the households in the region. The sources of off-farm income to which households have access, and the regularity of this income, have strong impacts on the choice and performance of farming activities (Crowley and Carter, 2000).

2.2 The prototypes, research questions and scenario analysis

As social desirability is one of the key elements in the design of sustainable farming systems, we based our analysis on the participatory prototyping conducted in the area by Waithaka et al. (2006). The *ideal farms* designed by groups of farmers participating in four localities of Vihiga district had the following characteristics:

- They consisted of basically the same enterprises that can be seen today in typical farms of Vihiga; farmers placed emphasis on having dairy livestock and tea as a cash crop and had little diversity of food crops; their size varied between 0.4 and 0.8 ha;
- Most of the farm area in the ideal farm was allocated to the staple crop maize – even if it was amply available on the market – consistent with the fact that farmers had food security as their primary household objective. Having a surplus of food crops to sell on the market was also highly desirable;
- Intensification would be achieved through managing crop-livestock interactions, applying manure to fertilise crops and using their residue to feed cattle. There was a limited understanding of input-output relationships, however, so that farmers had high expectations of crop yields with minimal nutrient inputs, and/or the daily requirements of fodder per lactating cow were grossly underestimated;

- In general, crop and milk yields estimated for the ideal farms were much larger than those achieved in the real farms. The reasons for not achieving good yields of crops and milk were ascribed to the lack of land, of technical skills, of access to markets, of livestock breeding facilities, of capital to purchase high cost inputs (e.g. fertilisers, artificial insemination) and labour (e.g. late planting, poor weeding), and to cultural conventions (e.g., keeping low-yielding Zebu cattle to pay dowries).

In summary, the major enterprises and the land use and management patterns of these ideal farms do not differ considerably from what can be observed today in farms of high resource endowment in Vihiga (Tittonell et al., 2005b). Thus, while these prototypes do not seem to be illusory or unachievable, their realisation would imply a shift of the current systems towards higher degrees of resource endowment. Such a shift cannot include increasing the area cropped, since this is prohibitive in densely-populated areas such as Vihiga. Are there feasible technological options to operate such shifts through intensification, provided that the necessary investments are available? Major differences between the ideal and the current farms were the tighter management of crop-livestock interactions, that the ideal farms seemed to exist in an environment of more favourable input/output price ratios, and that farmers had an optimistic view on their biophysical productivity. Do these ideal prototypes constitute a realisable improvement of the current farm systems within a reasonable time frame? To explore the type of interventions that would be necessary to favour an upwards shift of the current farm systems we used the farm-scale model to analyse:

(i) the current production structure of representative case study farms of different resource endowment to quantify the 'distance' between poor and wealthier farms in terms of resource cycling and use efficiency;

(ii) possible pathways of intensification of crop-livestock interactions through use of external inputs or qualitative changes within the systems.

In different simulation scenarios, intensification was pursued through: (1) increased use of external nutrient inputs; (2) changes in land allocation between food and fodder crops and; (3) changes in the productivity and efficiency of the livestock subsystem.

2.3 Overview of the model

NUANCES-FARMSIM constitutes a farm-scale decision making shell, where household objectives, constraints and resource (including labour) allocation patterns are simulated and economic balances calculated, linking the simulation results from different sub-models (Figure 2 A; Appendix 8.1). Crop and soil modules are combined at field plot scale in the model FIELD (Field-scale resource Interactions, use Efficiencies and Long-term soil fertility Development – Tittonell et al., 2007b). Different combinations of crop types and soil properties can be simulated to explore the interactions occurring within the farm for different field types (e.g. infields and outfields, annual and perennial crops, etc.). LIVSIM (LIVestock SIMulator – Rufino et al., 2007b) is a model that simulates animal production and nutritive requirements of different livestock breeds, categories, and feed characteristics and availability (Appendix 8.2). The dynamics of nutrients through manure collection, storage and use as well as changes in quality due to management are simulated by HEAPSIM (Rufino et al., 2007a), in which a fuzzy-logic approach is used to estimate C and nutrient transfer efficiencies through manure collection and storage under different livestock production systems and management (Appendix 8.3). The variability in weather and market conditions, the dynamics of resource availability from common lands and the inflow of cash or kind from off-farm sources constitute inputs to FARMSIM that are accounted for and/or modified for scenario simulation, or simulated using auxiliary models.

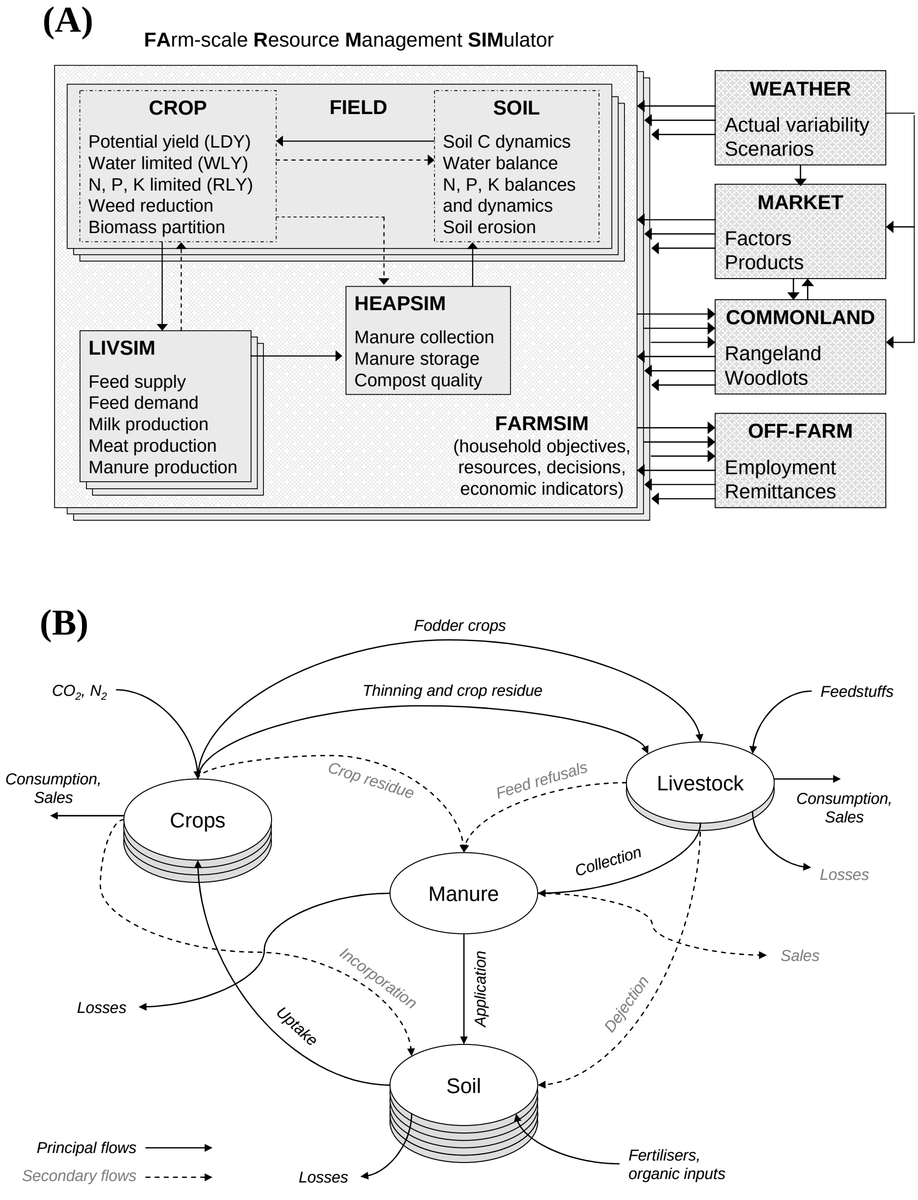

Figure 1: (A) Schematic representation of the various components of the model FARMSIM (FArm-scale Resource Management SIMulator); (B) A more detailed representation of components and flows within the crop-livestock system, the unit of analysis in this study, as implemented in the model.

Experimental data and, when possible, calibrated process-based models are used to generate functional relationships that are built into the various sub-models of FARMSIM. For instance, functional relationships that are built in FIELD, such as the effect of plant spacing on the fraction of radiation seasonally intercepted, have been derived using the model APSIM (Chikowo et al., 2007). Thus, these sub-models constitute summary models that incorporate processes and interactions in a descriptive rather than an explanatory way, and operate with different time steps: monthly for livestock and manure, seasonal for annual crops, and in steps defined by cutting intervals for fodder crops (e.g. 60 to 80 days for Napier grass). For exploration of medium- to long-term changes in crop productivity and soil quality such summary models may suffice (Bouman et al., 1996). The data requirements of these models can be relatively easily satisfied for most of the African farming systems under study, and their results can be used for exploration of long-term management strategies since the dynamic character of the combined FARMSIM model allows simulation of interactions and feed-backs. Figure 1 B illustrates the main linkages between the different physical modules of FARMSIM. A detailed description of the various components of the farm-scale model can be found in van Wijk et al. (2007) – www.africanuances.nl.

Table 1: Functional typology for household categorisation applied in western Kenya by Tittonell et al. (2005b).

Farm Type	Resource endowment* and production orientation	Main source of income	Family structure**	Major constraints
1	High to medium resource endowment, mainly self-subsistence oriented	Permanent sources of off-farm income (e.g. salary, pension, etc.)	Variable age of the household head, small families	Mostly land availability (lack of family labour compensated by hiring-in)
2	High resource endowment, market-oriented	Cash crops and other farm produce sold on the market	Aged household head, numerous family (land subdivision starts)	Mostly labour (hired-in) due to large farm areas
3	Medium resource endowment, self consumption and (low-input) market-oriented	Marketable surpluses of food crops or annual cash crops	Young to mid-aged household head, expanding family	Mostly capital and sometimes labour
4	Predominantly low to medium resource endowment, self-subsistence oriented	Mostly non-farm activities (e.g. ox-plough service, handicrafts) plus marketable surpluses	Young to mid-aged household head, variable family size	Availability of land and capital
5	Low resource endowment, self-subsistence oriented	Selling their labour locally for agricultural practices	Variable age of household head and family size, often women-headed farms	Land and capital, (becoming labour-constrained due to selling labour)

*Referring to assets representing classical wealth indicators (i.e. land size, livestock ownership, type of homestead, etc.). **In relation to the position of the household in the ‘farm development cycle’ (Crowley and Carter, 2000)

2.4 Model simulations

Biophysical feedbacks and interactions taking place in the long term were simulated linking the dynamic models for the various components of the farm systems. Figure 1 B depicts what was defined as the crop-livestock system (CLS), the unit of analysis in this study. Tittonell et al. (2005b) classified farming systems in western Kenya into five farm types, of which Types 1 to 4 owned cattle (Table 1). The model explorations were run on four simplified farm systems representing Farm Types 1 to 4, as illustrated in Figure 2. In brief, these four strategies can be characterised as: Type 1 – subsidised; Type 2 – self-sufficient; Type 3 – expanding; Type 4 – subsisting. The fifth category, Type 5 – dependent, represents the poorest households often without bovine livestock. Considering the results of the participatory prototyping described earlier we assumed that farms of Type 1 and 2 represent two alternative models of the *ideal farm*; one in which off-farm income allows inflows of nutrients as feeds and fertilisers, and one in which cycling of own farm resources allow less dependence on external nutrient inputs, respectively (Table 1). Using the farm-scale model, we explored nutrient management and farm design alternatives to shift farms of Types 3 and 4 towards the 'ideal' farm configurations, with emphasis on biophysical crop-livestock interactions.

2.4.1 Characterisation of simplified crop-livestock systems

Relatively wealthy, market-oriented dairy farmers of Type 1 and 2 keep improved cattle breeds in roofed and hard-floored zero grazing units, where Napier grass is fed in combination with concentrates and crop residues. While farms in Type 2 tend to be self-sufficient in fodder production and sometimes are able to market surpluses, farms of Type 1 obtain fodder and other feeds from the market. These farmers often also have zebus grazing in the compound fields. Mid-class, semi-commercial farms of Type 3 often keep their cross-bred or local cattle tethered in the compound, where they complement their grazing with Napier grass and crop residues; in times of scarcity poor quality fodder such as dry maize stover or banana leaves are offered to the animals. Poor, subsistence-oriented farmers that can afford to own cattle normally have local zebu breeds of small frame (+/- 200 kg body weight) tethered in their compound, grazing standing crop residues in the crop fields and/or herded around to graze in communal patches of grass. Intermediate situations and/or combination of the above systems are of course common.

To represent Farm Types 1 to 4, four case study farms were selected in Emuhaya, Vihiga district and quantitatively characterised in the field (Karanja et al., 2006; Casellanos-Navarrete, 2007) (Tables 2 and 3). Household nutritional requirements and labour availability throughout the simulation period were calculated using IMPACT (Herrero et al., 2007). Fertilisers were not used, or used at low rates, in all farms (cf. Chapter 3). Most of the crop residue (i.e. 90%) was removed from the fields to feed the livestock in Farm Types 3 and 4, and about half of it remained in the field in Farm Types 1 and 2, where about half of the area was allocated to fodder production (c. 20% or less was allocated to fodder in farms of Type 3 and 4). Improved, cross-bred dairy cattle were kept in Farm Types 1 and 2 and zebu breeds in the rest. To reflect these differences in livestock breed, and based on farm measurements, maximum milk productivity was set, respectively, at 6500 and 3200 L year^{-1} at the peak of the lactation curve, equivalent to peaks of c. 18 and 9 L day^{-1} during that period. These values were used to parameterise *potential* milk production in LIVSIM (see Appendix 8.2), but are hardly reached in these systems in reality (cf. Bebe et al., 2003).

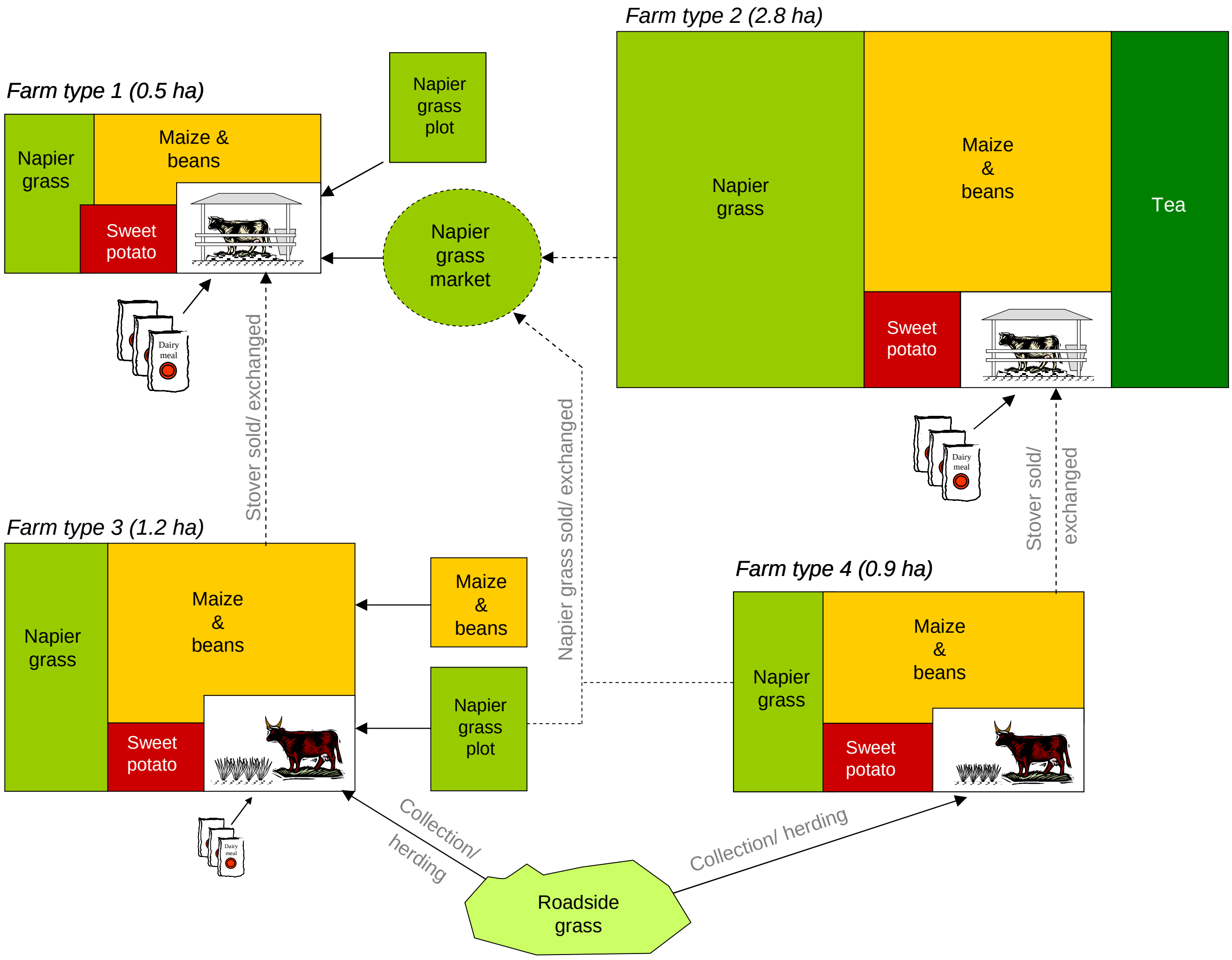

Figure 2: Schematic representation of the four case study farms belonging to Farm Types 1 to 4 described in Table 1. Dotted lines indicate intermittent flows (e.g., occasional exchange of crop residues or fodder between farm types). The configuration of cropping activities does not represent the actual shape, number and distribution of fields, but simply their relative importance in terms of area. External boxes represent fields that are rented outside the farm to increase production. The livestock production system in Farm Types 1 and 2 is more complex than in Types 3 and 4, including zero-grazing stalls, improved dairy cattle breeds and more intensive use of concentrates (represented by bags in the drawing).

Concentrates were used regularly for categories such as early lactating cows by Farm Types 1 and 2 and only occasionally by the rest. Decisions on buying extra fodder to complement the diet were taken based on the difference (ΔF) between fodder on offer during a certain month and fodder requirements, as a function of potential intake calculated in LIVSIM. However, farmers may decide not to cover the full requirement but only part of it, enough to maintain the animals alive. This was implemented by multiplying ΔF times a correction factor ($0 < CF < 1$) that accounted for whether farmers cover the full requirement ($CF \sim 1$) or just sufficient to keep the animals alive ($CF \sim 0$) when purchasing fertilisers (i.e., a $CF = 0.3$ means that farmers covered 30% of the deficit with respect to the *potential* requirement). The minimum values of CF were obtained through trial and error, by running the model repeatedly for each Farm Type and ensuring that the simulated amounts of fodder bought were in agreement with field observations (Castellanos-Navarrete, 2007) for these case study farms.

Roadside grasses, weeds, banana stalks and residues from outside fields (Figure 2) were used to complete the diet in Farm Types 3 and 4. Manure was collected frequently after cleaning the shed and piled in a heap, protected from direct sun in Farm Types 1 and 2. Poorer farmers tend to throw the collected manure into a pit together with other household waste and crop residues; when animals are tethered either within or outside the boundaries of the farm, manure is collected less frequently from night stalls. Manure cycling efficiencies as affected by collection and storage conditions were calculated using a fuzzy-logic approach parameterised with field data as described by Rufino et al. (2007a). Less efficient use of on-farm nutrient resources and mineral fertilisers led to poorer current nutrient stocks and heterogeneity in Farm Types 3 and 4 (Figure 3). The strongest negative gradients of soil fertility were observed for P and K, decreasing sharply at increasing distance from the homestead. All fields in Farm Type 4 and most in Farm Type 3 had available P values below the threshold for crop responses of 10 mg kg^{-1} found earlier in western Kenya (Vanlauwe et al., 2006). N availability (not shown) followed a similar trend within farms as soil C in Figure 3.

2.4.2 Assumptions

Since our objective was to explore the biophysical boundaries to the intensification of the CLS, the analysis concentrated on physical flows and assumed that (i) labour was available and that (ii) all necessary investments in inputs and assets could be made. In Section 3.3 we discuss the consequences and limitations of this approach. Further studies using FARMSIM will focus on labour and financial constraints to intensification. To perform the analysis, the five Farm Types were simplified in the following way:

- Most fields of the farms were planted to maize/beans, Napier grass and sweet potatoes. Tea was only grown in Farm Type 2 and not considered as part of the primary productivity of the farm. Garden crops such as local vegetables, bananas or fruit trees, and woodlots were not dynamically simulated but rather treated as ‘black boxes’; their contribution to primary productivity was also disregarded; crop rotation or spatial rotation of activities within the farm were not considered; the contribution of livestock other than cattle was not considered;

- The number of fields per farm was reduced by grouping fields under similar land use and location within the farm/ landscape;
- Labour requirements and allocation to different activities has been optimised for all these systems (van Wijk et al., 2007). These values were kept constant for all of the simulations;
- Resource allocation patterns were derived from resource flow mappings (Tittonell et al., 2005c) and general management decisions, such as the amount of the total manure produced allocated to each field, were kept constant throughout the baseline scenarios;
- Although conception is simulated stochastically in LIVSIM (Rufino et al., 2007b - Appendix 8.2), we kept calving intervals constant (provided that the body condition of the cows allowed conception and gestation) to represent the baseline situation observed on the case study farms (Castellanos-Navarrete, 2007).

We believe that the assumptions made in simplifying the real systems still allow a fair representation of key resource flows and their interaction as they happen in reality. Simulation results are presented for periods of 10 years, due to a number of reasons. First, longer simulation periods would imply possible shifts of farms from one type to another (e.g. following their trajectory throughout the farm developmental cycle – Chapter 1). Second, the lifetime of a dairy cow in the highlands of Kenya is about 12-13 years; in scenarios where a dairy cow was brought into the system the first two years of its life were not considered to allow analysis of the system in a stable productive phase. Finally, in ten years from now we will be past 2015, the target year for achieving the UN Millennium Development Goals, a relevant time horizon to evaluate the impact of interventions.

2.4.3 Baseline model runs

In the baseline runs the configuration of Farm Types 1 to 4 were kept as current (Figure 2; Tables 2 and 3) and the results compared in terms of productivity, resource use efficiency, degree of crop-livestock interaction (i.e., size of flows, connectivity) and soil fertility status. A historical rainfall dataset (Jaetzold and Schmidt, 1982) and weather data collected at the site between 1993 and 2003 (Chapters 3 and 7) were used to run the simulations. Although the various modules of FARMSIM run with different time steps, all results were summarised and presented on a seasonal basis.

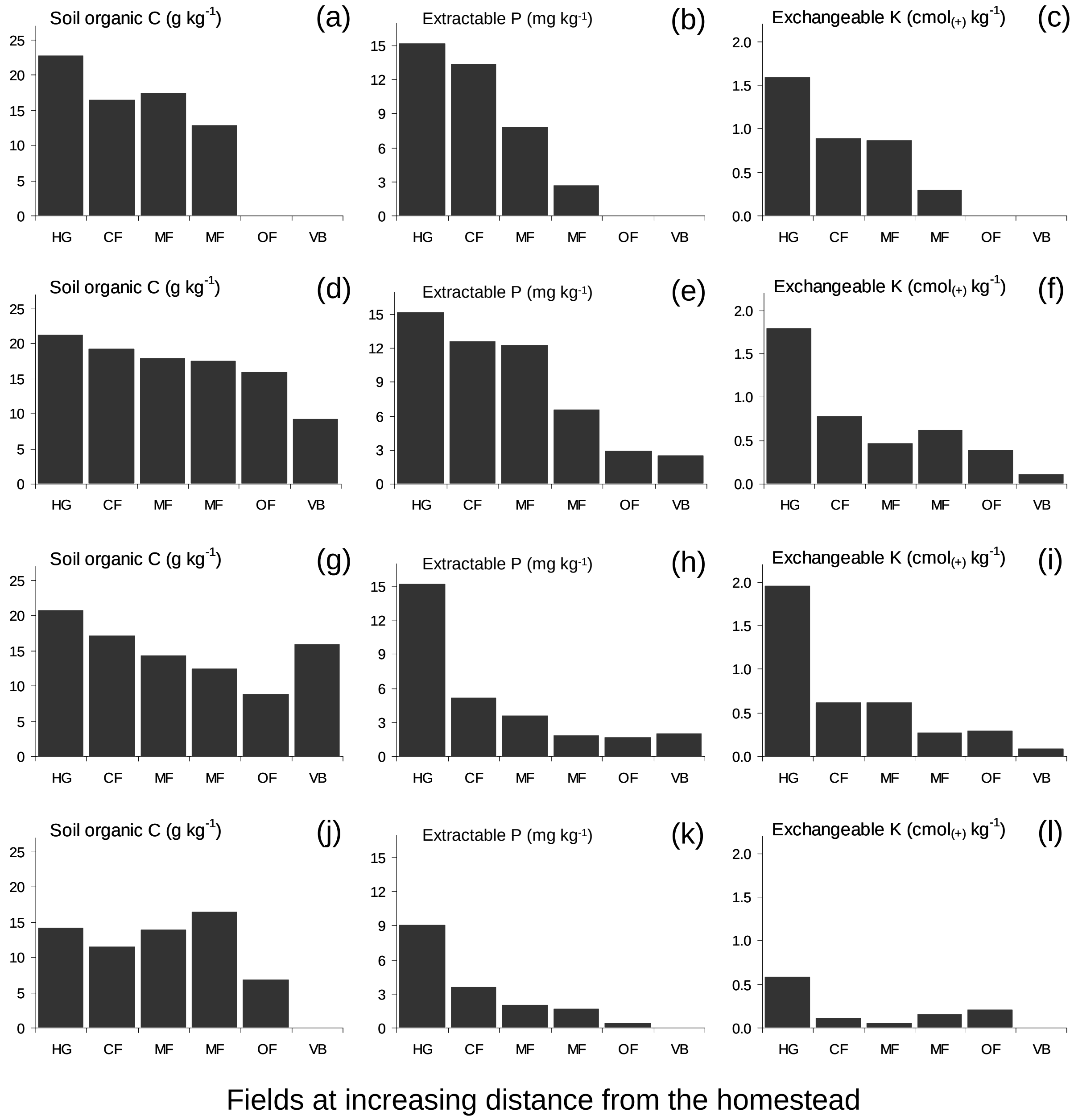

Figure 3: Soil fertility indicators measured in the various fields of the four case study farms. (a-c) Farm Type 1, (d-f) Farm Type 2, (g-i) Farm Type 3, (j-l) Farm Type 4. Fields are ordered according to their approximate distance from the homestead: HG: home gardens, CF: close fields, MF: mid-fields, DF: distant fields and VB: valley bottomland.

2.4.4 Model runs with N and P fertiliser applications

Small rates of mineral N and P fertilisers were applied to maize/bean fields in the case study farms of Type 3 and 4 following the allocation strategies presented in Table 3 B. N and P application rates simulated for the various fields were intended to mimic realistic rates already in use by farmers Type 1 and 2 (cf. Table 3 A). At the Fertiliser Summit held in 2006 in Abuja, Nigeria, African state authorities set the challenging goal of achieving fertiliser use intensities of 50 kg nutrients ha^{-1} across sub-Saharan Africa. If a household farming 1 ha of land receives a bag of 50 kg of di-ammonium phosphate (DAP, 18:46:0) and a bag of 50 kg of calcium ammonium nitrate (CAN, 46:0:0) per season, N and P could be applied at rates of 46 kg ha^{-1} and 9 kg ha^{-1}, respectively. Simulated application rates remained within such ranges, combining applications of 0 to 60 kg N farm^{-1} with 0 to 15 kg P farm^{-1}. The rest of the management parameters in the model were kept as in the baseline.

Table 2: Main characteristics of the four case study farms who keep livestock in western Kenya, and are representative of Farm Types 1-4.

(A) Household

Farm Type	Family size	Consumption units*	Energy required (MJ d^{-1})	Protein required (g d^{-1})	Labour available (man-days farm^{-1})	Farmed area (ha)	Land:labour ratio (man-days ha^{-1})
1	6	5.6	63	247	3.5	0.52	0.15
2	9	8.4	90	365	4.0	2.20	0.55
3	5	4.4	45	160	2.5	1.22	0.49
4	6	5.0	53	208	3.5	0.89	0.25

(B) Livestock

Farm Type	Cattle head**		Total cattle live weight (kg farm^{-1})	Feeding system	Manure handling and storage
	Adults	Calves			
1	2	1	590	Zero grazing; use of concentrates	Heap under shadow; frequent collection
2	2	2	720	Zero grazing; use of concentrates	Heap under shadow; frequent collection
3	1	1	370	Tethered in compound fields	Waste/compost pit; frequent collection
4	1	1	270	Tethered in or outside the farm	Waste/compost pit; sporadic collection

(C) Soil fertility

Farm Type	Soil stocks per family member (kg person^{-1})					
	Soil organic C	Total soil N	Available P	Exch. K	Exch. Ca	Exch. Mg
1	3640	190	1.8	87	443	90
2	9490	690	3.0	134	1545	188
3	8160	695	2.5	127	1129	242
4	4410	495	1.5	30	471	94

*Calculated on the basis of household composition (age structure) using coefficients to account for gender and age developed for Kenya (Sehmi, 1993)

**Only female cattle were considered; males were assumed to be sold soon after birth

Table 3: Parameterisation of management decisions per field for the four simplified farm types. (A) Farm Types 1 and 2, with current fertiliser use indicated; (B) No fertiliser was currently used in all fields of Farm Types 3 and 4; scenarios of fertiliser allocation used in the simulation of management alternatives are presented instead.

(A)

Field	Area	Crop grown	Residue removed	Manure allocated		Current fertiliser use	
	(ha)		(%)	Fraction	kg ha^{-1}	kg N ha^{-1}	kg P ha^{-1}
Farm Type 1							
Home garde	0.27	Maize/ beans	60	0.3	1278	11.1	5.6
Mid field	0.12	Napier	n/a	0.3	2875	16.7	41.7
Outfield	0.05	Sweet potato	30	0	0	0	0
Valley bottom	0.08	Napier	n/a	0.4	5750	0	0
Farm Type 2							
Home garde	0.13	Maize/ beans	30	0.3	6346	0.0	11.5
Close field	0.45	Maize/ beans	50	0.2	1222	22.2	8.9
Mid field	0.50	Napier	n/a	0.2	1100	0	0
Mid field	0.45	Maize/ beans	50	0.1	611	55.6	24.4
Outfield	0.25	Sweet potato	20	0	0	0	0
Valley botto	0.42	Napier	n/a	0.2	1310	0	0

(B)

Field	Area	Crop	Residue removed	Manure allocated		N, P fertiliser allocation scenarios (kg farm^{-1})			
	(ha)		(%)	Fraction	kg ha^{-1}	7.5	15	30	60
Farm Type 3									
Home garde	0.14	Maize/ beans	90	0.4	2286	7.1	7.1	14.3	28.6
Close field	0.32	Maize/ beans	70	0.2	500	9.4	21.9	43.8	87.5
Mid field	0.12	Napier	n/a	0.2	1333	0	0	0	0
Mid field	0.36	Maize/ beans	50	0.2	444	8.3	19.4	38.9	77.8
Outfield	0.18	Sweet potato	20	0	0	0	0	0	0
Valley botto	0.10	Napier	n/a	0	0	0	0	0	0
Farm Type 4									
Home garde	0.16	Maize/ beans	90	0.6	1688	15.6	31.3	62.5	125.0
Close field	0.44	Maize/ beans	70	0.4	409	11.4	22.7	45.5	90.9
Mid field	0.10	Napier	n/a	0	0	0	0	0	0
Outfield	0.12	Sweet potato	50	0	0	0	0	0	0
Mid field	0.07	Napier	n/a	0	0	0	0	0	0

2.4.5 Model runs with increased areas under fodder

The area of the farm allocated to Napier grass production was increased in the case-study farms of Type 3 and 4 from 18 to 41% (0.22 to 0.50 ha) and from 19 to 37% (0.17 to 0.33 ha) of the farm area, respectively, reducing the area under food crops. Since more fodder was available, 75% of the crop residue was kept in the fields and incorporated. Small amounts of concentrates, maize thinnings, roadside grass, weeds, banana stalks and residues from outside fields are still used to complete the diet. Since Napier grass can be harvested more frequently and less is brought from the market, the average quality of the fodder fed to livestock improves (e.g. from 60 to 80 g kg^{-1} of crude protein content in Farm Type 3). This allows keeping an extra cow in Farm Type 3. Manure is collected more frequently and allocated to maize and Napier grass fields in a 50:50 ratio; the fractions allocated to the various fields (cf. Table 3B) are now: 0.1 to maize/beans field 1 (0.06 ha), 0.2 to maize/ beans field 2 (0.25), 0.2 to maize/ beans field 3 (0.30), 0.3 to Napier grass field 1 (0.30), 0.2 to Napier grass field 2 (0.20) and 0 to the sweet potato field (0.18) in Farm Type 3; 0.3 to maize/beans field 1 (0.10 ha), 0.2 to maize/ beans field 2 (0.37), 0.3 to Napier grass field 1 (0.18), 0.2 to Napier grass field 2 (0.15) and 0 to the sweet potato field (0.09) in Farm Type 4. These new configurations were run under baseline scenario (no fertilisers) and with application of N and P as described above. This is be referred to as the “Napier grass” scenario.

2.4.6 Model runs with improved livestock system

An improved, cross-bred dairy cow was introduced in the case-study farms of Type 3 and 4, keeping the new configuration of increased fodder production. Concentrates and extra fodder are bought on the market to cover the requirements of the new animals, on the basis of potential intakes calculated in LIVSIM. Calving intervals were shortened to 18 months, as in the wealthier farms. Manure collection and storage efficiencies were improved by assuming a more frequent collection from hard floored stalls (rather than open field, as currently) and by roofing the storage facilities. Concentrates were fed as necessary to all categories except dry cows (e.g., 1 to 2 kg dm day^{-1} to lactating cows, as commonly practiced by local dairy farmers), increasing the maximum allowed concentrate use in the model from 10 to 100 kg $farm^{-1}$ $month^{-1}$, and from 10 to 60 kg $farm^{-1}$ $month^{-1}$ for farms of Type 3 and 4, respectively. Road side grasses were not longer used to feed cattle under this scenario. This is referred to as the “Dairy cow” scenario.

3. Results and discussion

3.1 Current differences in the productive structure of the farms

3.1.1 Food and feeds

Wide differences in primary and animal productivity and in the size of C and nutrient stocks and flows can be seen in the averaged results of the 10-year baseline simulations with FARMSIM (Table 4 A-E). The four farms differed in their capacity to meet the energy requirements of the household with their respective on-farm food production (i.e., self-produced calories, SPC%). An indicator that may be derived from these simulation results is the relative number of seasons in which SPC < 100%; they were 0.9, 0.2, 0.7 and 1 for the case-study farms of Type 1 to 4, respectively (Figure 4). In these systems, the fact that a farm is not self-sufficient in food production does not necessarily imply that the household is food insecure. Farms of Type 1 derive most of their income from off-farm activities and often also produce for the market (e.g. milk or vegetables), while buying their staples on the market. In drier seasons even the wealthier case-study farm of Type 2 may produce less food than required, according to the simulation. Farms of Type 3 often hire land to increase food production and eventually meet their requirement, often with a small surplus for the market (production on annexed – hired or borrowed – land was not considered here). For protein requirements and self-production a similar pattern across farms was observed (not shown).

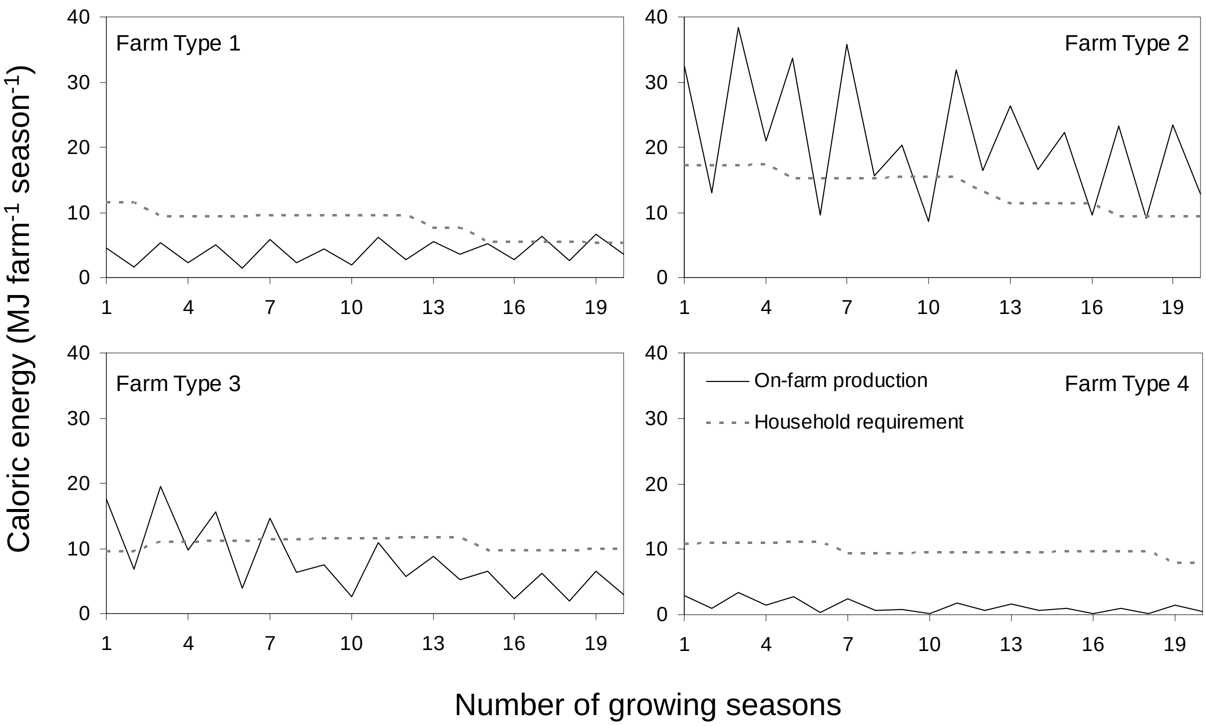

Figure 4: Simulated household energy requirement and self production of calories on farm during the 10-year baseline scenario. Variability in calorie production is due to rainfall variability. Changes in household requirements are due to assumed changes in family composition (i.e., ages of the family members were recorded and simulated, assuming that children left the household at 18 for females and at 21 for males). Due to the two cropping seasons per year, 10 years are equivalent to 20 seasons.

The primary production of farms of Type 1 and 2 consists largely of Napier grass produced as feed (Table 4 B). Crop residues, road side grass or weeds represent a relatively important part of the animal diet in farms of Type 3 and 4, in which concentrates are sparsely used (Table 4 B). Napier grass is bought regularly in farms of Type 1 and 2 and only to cover specific gaps in farms of Type 3 and 2 (cf. Type 1 and Type 3 in Figure 5).

Table 4: Indicators of productivity, resource use efficiency, crop-livestock interactions and carbon stocks and flows for the case studies of the four farm types under the 10-year baseline scenario. The values presented correspond to averages over the entire period of simulation expressed per season (sn).

(A) Crop production[1]

Farm Type	Primary productivity (t dm ha^{-1} sn^{-1})	Biomass yield (t dm ha^{-1} sn^{-1})	Food crops* (kg dm $farm^{-1}$ sn^{-1}) Maize	Beans	Sweet pot.	Edible energy (MJ ha^{-1} sn^{-1})	Edible protein (kg ha^{-1} sn^{-1})	SPC (%)
1	8.2	5.3	218	45	34	3254	32	53
2	6.1	6.0	1277	290	77	9543	91	137
3	2.8	3.8	484	124	32	6596	65	75
4	1.7	2.4	68	32	10	1392	17	12

(B) Fodder and feed

Farm Type	Napier grass (kg dm $farm^{-1}$ sn^{-1}) Produced	Bought	Fed	Extra resources fed to livestock (kg dm $farm^{-1}$ sn^{-1}) Crop residue	Concentr-ates	Weeds	Road side grass	Others
1	2071	1681	3338	463	28	28	370	84
2	8831	141	7206	935	112	171	501	251
3	1431	21	1166	304	1	188	201	69
4	997	26	823	77	0	43	143	143

(C) Livestock production[2]

Farm Type	Secondary productivity (t dm ha^{-1} sn^{-1})	No of animals	Live weight (kg $farm^{-1}$)	Weight gain (kg sn^{-1})	Milk production (L sn^{-1})	Milk yield (L ha^{-1} day^{-1})	Dry matter intake (kg dm sn^{-1})	Crude protein intake (kg sn^{-1})
1	1.4	3.3	901	52	650	6.9	3776	243
2	1.1	4.8	1971	81	2320	5.8	7329	660
3	0.2	1.2	360	14	200	0.9	1452	99
4	0.1	1.1	271	8	120	0.8	1098	79

(D) Manure handling

Farm Type	Excreted DM (kg sn^{-1})	Excreted elements (kg sn^{-1}) N	P	K	Urine N (kg sn^{-1})	Other inputs[3] (kg dm sn^{-1})	C in manure heap (kg sn^{-1}) Input	Output
1	1521	22.6	16.2	67.4	9.6	281	432	257
2	2531	66.7	33.5	130.8	33.6	1166	998	528
3	601	9.4	6.1	25.9	4.3	207	209	118
4	452	7.9	4.6	19.6	3.9	116	141	68

(E) Farm C stocks and flows

Farm Type	Soil C stock (t ha^{-1})	Rate of change in soil C (t ha^{-1} sn^{-1})	C fixed by crops (t ha^{-1} sn^{-1})	Soil C losses (t ha^{-1} sn^{-1})	Manure C application (t $farm^{-1}$ sn^{-1})	Crop residue C (t farm sn^{-1}) Available	Fed	Incorporated
1	37.4	-0.27	3.7	1.53	0.26	0.57	0.23	0.34
2	34.1	-0.37	2.7	1.11	0.53	1.24	0.62	0.62
3	26.6	-0.43	1.3	0.80	0.12	0.56	0.50	0.06
4	22.0	-0.42	0.8	0.62	0.07	0.17	0.15	0.02

[1]Primary productivity is the production of biomass by the simulated crops maize/beans, sweet potato and Napier grass over the entire farm area (biomass of tea and other perennial and garden crops not considered); Biomass yield is the average productivity of all individual fields irrespective of the crop grown; Food crops: dry weight of grains, pulses and tubers, respectively; Edible calories and proteins do not include milk

[2]Secondary productivity is the sum of milk production and animal weight change on a dry matter basis; number of animals expressed as tropical livestock units

[3]Other inputs of dry matter to the manure heap, including feed refusals, bedding material and crop residue entering the manure pool without being fed to livestock

SPC: self-produced calories

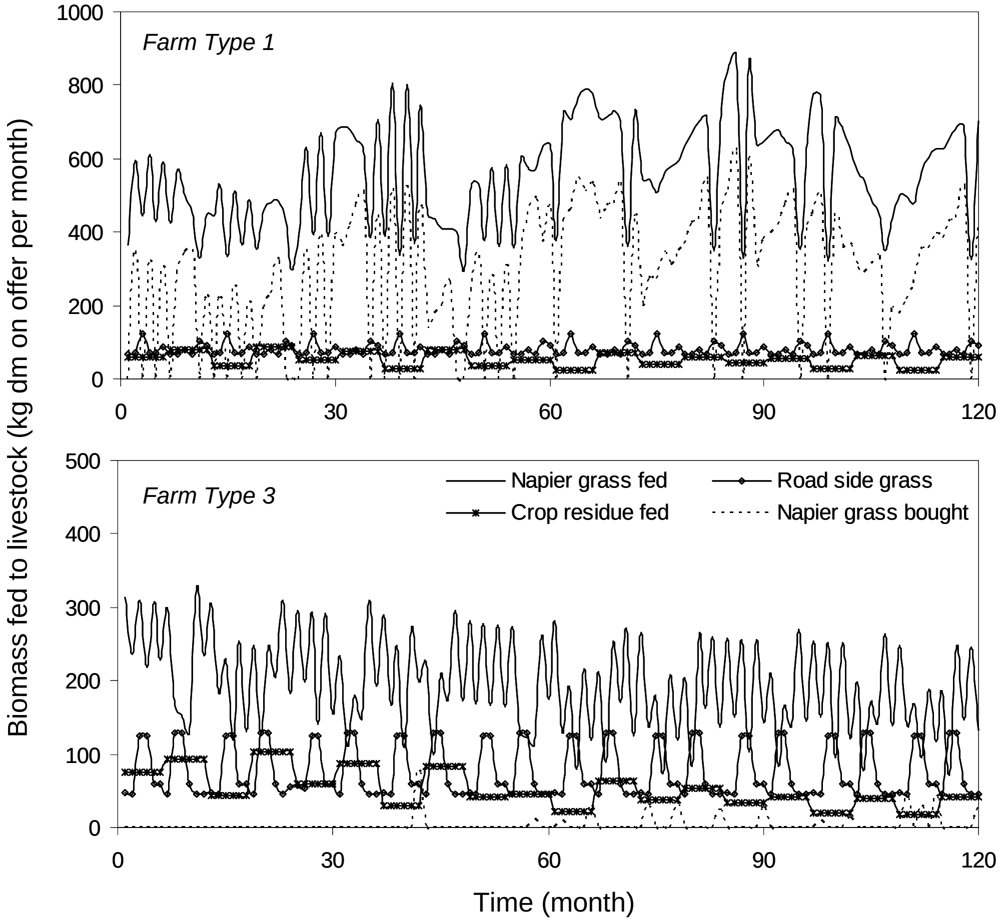

Figure 5: Simulated amounts of Napier grass, crop residue and roadside grass fed to livestock and amount of Napier grass bought on the market in the case study farms of Type 1 and 3 during the 10-year baseline scenario.

Although milk production is greater in Farm Type 2, Farm Type 1 produces more milk per unit area (Table 4 C). However, if the area necessary to produce all the extra Napier grass bought in Farm Type 1 was considered in the calculation of milk yields, these will be almost halved with respect to the current milk yields. Surveys in western Kenya (Waithaka et al., 2002) indicated an average *per capita* milk consumption of 105 L year^{-1} (125 L year^{-1} are recommended by the WHO). With this value as reference, the average on-farm production would be just about or below household consumption in Farm Types 3 and 4, with no surplus for the market.

3.1.2 Resource use efficiency

In spite of the variability from season to season, the primary production per unit area was two to three times larger for farms of Type 1 and 2 compared with 3 and 4, respectively, and the four case study farms showed different configurations with respect to the ratio of primary-to-secondary productivity (Figure 6 A and B), indicating a different degree of crop-livestock integration. The value of this ratio decreased with time during the 10-year simulation, as the overall primary productivity of the farms decreased, and at a different rate for each farm type. Such a trend is partly the result of not having automated the decisions on stocking or de-stocking in function of fodder and food production in the model, which farmers are likely to make in reality.

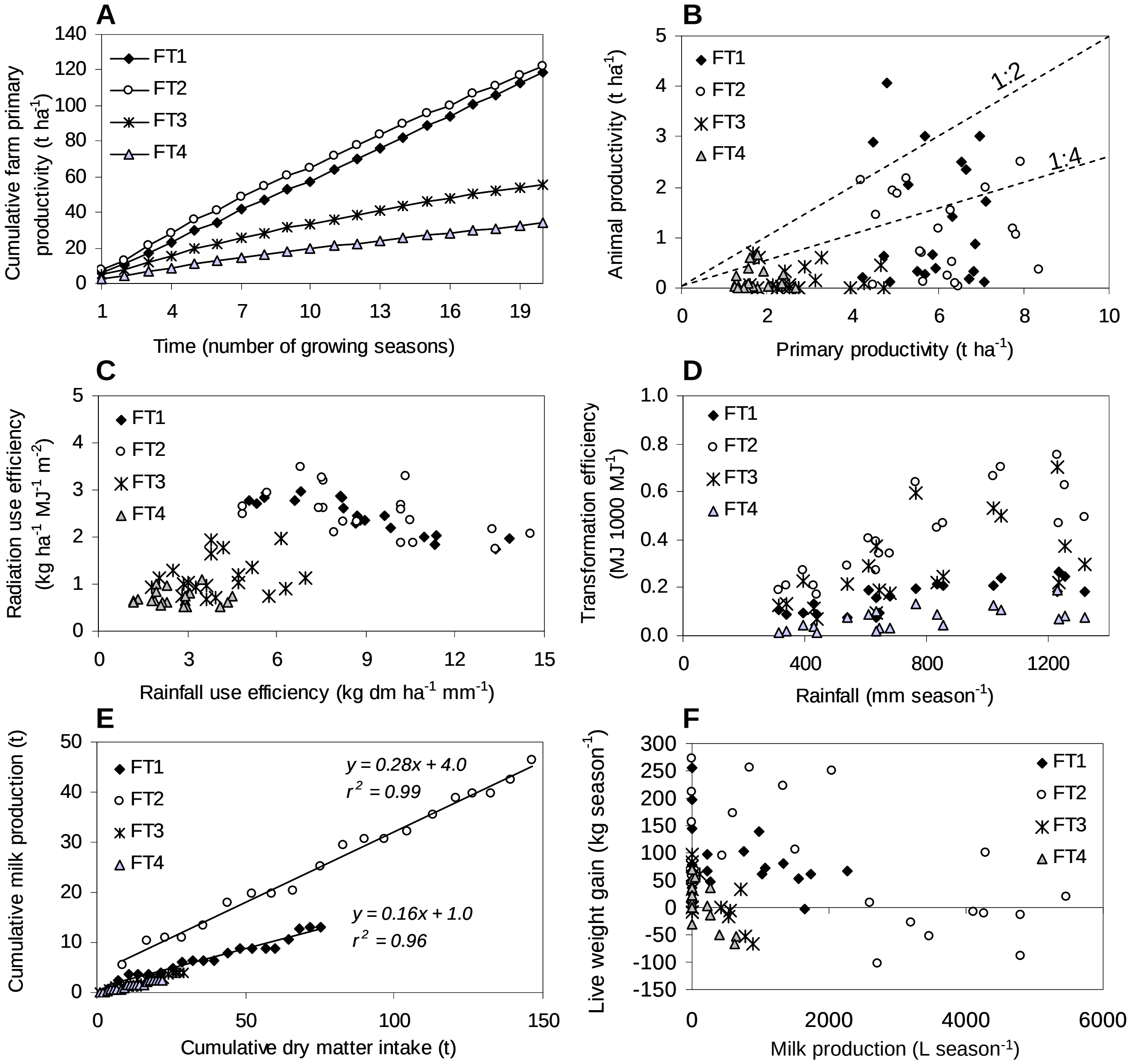

Figure 6: Farm-scale indicators of productivity and resource use efficiency derived from the 10-year baseline simulation for the four case study farms. (A) Cumulative primary productivity (crops and fodder) throughout the simulation; (B) Primary versus animal productivity (milk and weight changes), with dotted lines indicating the 1:4 and 1:2 productivity ratios; (C) Radiation use efficiency plotted against rainfall use efficiency at farm scale, expressed in units commonly found in literature; (D) The efficiency of transforming radiation into food calories at farm scale plotted against seasonal rainfall; (E) Cumulative seasonal milk production against cumulative seasonal dry matter intake by livestock; (F) Seasonal changes in live weight of the entire cattle herd plotted against seasonal milk production.

The four farm types differed also in their efficiency of use of natural resources and particularly in their capacity to transform solar energy into food energy (Figure 6 C and D). These values give an indication of the potential for improving resource use efficiency through system intensification; e.g., the current radiation and rainfall use efficiencies achieved on the poorest farms could in principle be doubled or tripled through intensification. As further reference, average rainfall use efficiency values of up to 20 kg ha^{-1} of maize biomass per mm of rainfall can be attained in western Kenya under optimum crop growing conditions (Chapters 5 and 7).

For resources cycled within the farm system, such as the conversion of fodder into milk (Figure 6 E), the four farm types differed both in the absolute amounts cycled (DM fed and milk produced) and in the efficiency of fodder utilisation during the 10 years of the simulation. During periods of feed scarcity, milk was produced at the expense of body weight and body condition (Figure 6 F). The extent to which this compensation takes place results from the mechanistics of partitioning and efficiencies as implemented in the livestock model (LIVSIM), which has been calibrated for improved cross-bred dairy cows in Kenya; little is known about such processes for local zebu cattle breeds (Rufino et al., 2007b). Weight gains took place at average rates of 3 – 5 % of the stock, decreasing from farms of Type 1 and 2 to Type 3 and 4 (Table 4 C).

3.1.3 Degree of crop-livestock interaction

Larger stocking rates, expressed as total cattle live weight per ha of farmland, were associated with greater average biomass yields (of all crops grown on the farm) as a consequence of higher rates of manure application to crops (Figure 7 A and B). Such relationships between cattle densities and crop productivity through manure availability are often observed in smallholder African farming systems (cf. Chapter 2). The total amount of manure cycled within the system and the consequent flow of C and nutrients back to the soil is small in farms of Type 3 and 4 (Table 4 D and E), also due to poorer efficiency and/or frequency of manure collection for storage or composting (Figure 7 C). However, it is in these farm types where most of the crop residue is removed from the fields and fed to livestock, representing 20-30% of the diet (Figure 7 D). Manure recovery efficiencies larger than 1, as depicted for Farm Type 2 in Figure 7 C, were possible due to the continuous addition of crops residues and feed refusals to the manure heap throughout the season. Of the total amount of N taken in by livestock in the diet around 30% enters the manure heap for storage and/or composting and from this between 25-50% is recovered for application to croplands (Figure 7 E and F).

The efficiencies of nutrient cycling during manure collection and storage were derived from measurements on these case study farms (Castellanos-Navarrete, 2007) and implemented in HEAPSIM through a fuzzy logic system that relates management aspects with factors that modify (multiply) decomposition and nutrient loss rates (Rufino et al., 2007a). Higher efficiencies of N recovery in the case-study farm of Type 1 were associated with a more frequent collection of manure from the stall and better conditions of storage (under cover). In all farms about 50% of the excreted N was in the urine, which was not collected in any of the systems (Table 4 D).

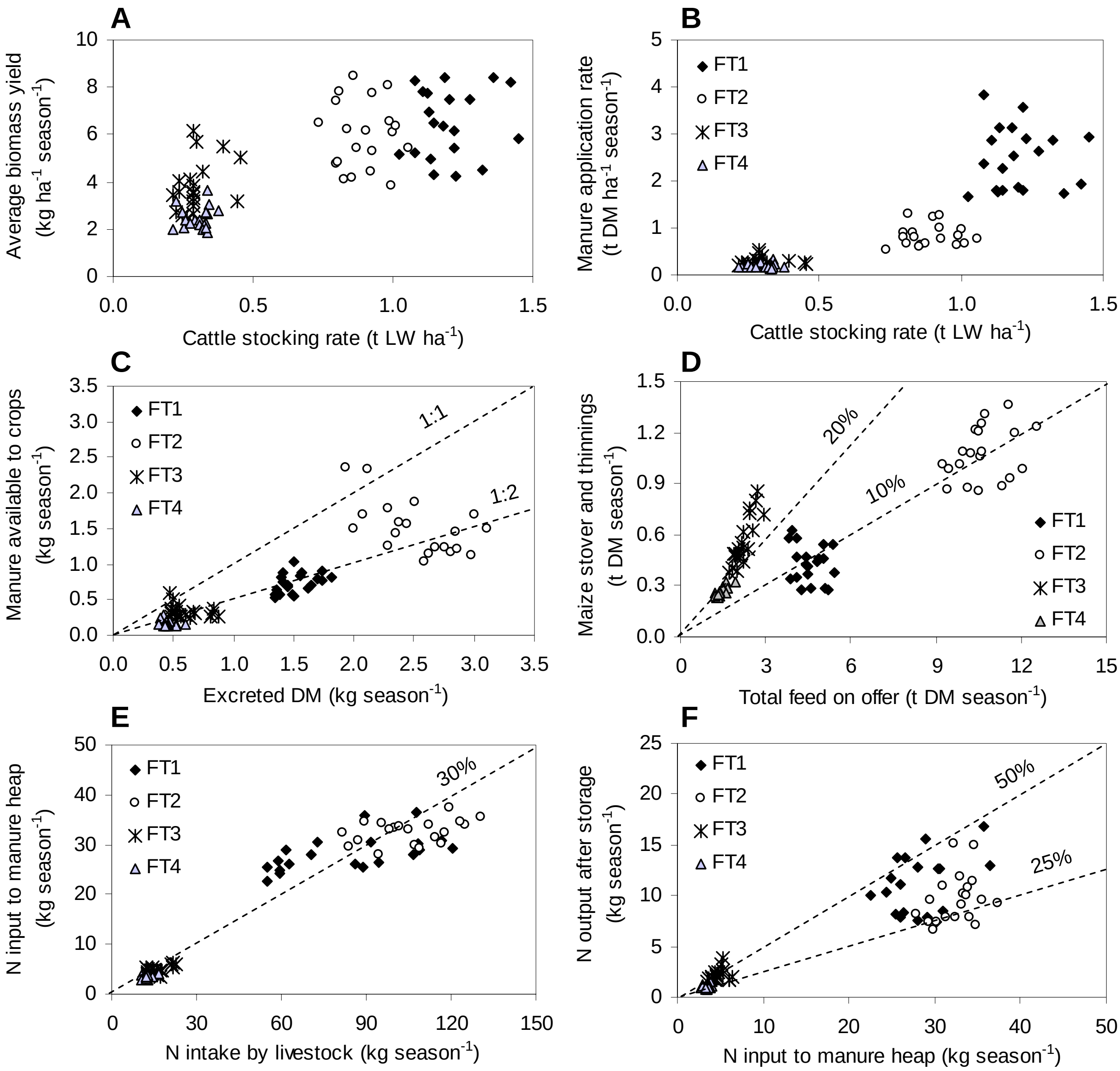

Figure 7: Farm-scale indicators of the degree of crop-livestock interaction derived from the 10-year baseline simulation for the four case study farms. (A) Average biomass yields of food and fodder crops and (B) average manure application rates plotted against cattle stocking rates expressed as live weight per area; (C) Dry matter of manure available for application to crops after storage vs. dry matter excreted, with dotted lines indicating 50 and 100% apparent efficiencies (i.e., other organic materials may be added to manure during storage); (D) Maize stover and thinnings fed to cattle over the total amount of dry matter on offer, with lines indicating 10 and 20% fractions; (E) Nitrogen input to the manure heap vs. N taken in by livestock on a seasonal basis, with 30% efficiency indicated; (F) N coming out of the manure heap after storage vs. N input to the heap, with 15 and 50% recovery efficiencies indicated.

It should be noticed that although the efficiencies of manure handling may vary or not between farm types, the absolute amounts of nutrients (N in this case) cycled within the farm systems are widely different. Even if enough labour and resources are allocated to improve nutrient cycling efficiencies within farms of Type 3 and 4, the impact on overall farm productivity will still be limited. An increase in N cycling efficiency through improved manure handling from 25 to 50% would imply ca. 10 kg season^{-1} of extra N cycled within the system in the case-study farms of Type 1 and 2, but only 1-2 kg season^{-1} extra in Type 3 and 4 (cf. Figure 7 F).

3.1.4 Nutrient cycling and soil fertility

The stock of soil organic C decreased in all farms during the 10-year simulations, at average rates of –0.28, –1.61, –1.03 and –0.75 t C year^{-1} from farms of Type 1 to 4, respectively (Figure 8 A); these rates correspond to differences in the average soil C content of –5.4, –7.3, –8.5 and –8.4 t C ha^{-1} between the initial and the final year (Table 4 E). Slower rates of soil C decrease in Farm Type 1 are the result of higher rates of manure application to its small crop fields (cf. Figure 7 B), resulting also in larger crop productivity and potential C input to the soil via crop residues and roots. The decrease in soil C stocks translates into lower farm food productivity, particularly in Farm Type 3 (Figure 8 C); in Farm Type 4 both soil C stocks and productivity are already poor at the beginning of the simulation. The capacity of these four case-study farms to store organic C in their soils also differed due to their capacity to fix atmospheric C into crop biomass C and retain it in the soil (Figure 8 C). Higher efficiencies of utilisation of light, water and nutrients allow larger rates of CO_2 fixation in farms of Type 1 and 2. In accordance with the trends in soil C stocks, C losses due to respiration and erosion are greater for these farms than for Type 3 and 4, but proportionally smaller with respect to what is fixed each season. The total amount of C fixed in crop residue available at the end of each season and the fraction of it that is effectively incorporated in the soil also differs widely across farms (Table 4 E). During manure handling and storage farms with higher stocking rates emit more CO_2-C per unit area (Figure 8 D); however, such losses represent 5 to 10% of what is fixed from the atmosphere in crop biomass.

The average soil C contents in all farms at the beginning of the simulation are close to the calculated and measured equilibrium soil C contents for these soils after 100 years of cultivation with little C input (Chapter 7; Solomon et al., 2007). However, increasing pressure on the land and shrinking communal grazing areas during the last years has led to faster rates of soil C decrease due to the complete removal of crop residues to feed livestock (Crowley and Carter, 2000). Under this situation, the new equilibrium soil C calculated by the model was as low as 22 and 18 t C ha^{-1} in the upper 0.2 m of the soil for Farm Types 3 and 4, respectively, after 10 years of simulation. (If the initial average mass-correction factors for these two farms are considered, these stocks would represent 21 and 25 t C ha^{-1} for the first 2000 t ha^{-1} of soil, equivalent to C concentrations of 1.0 and 1.3%, respectively. Soil C mass fractions around 1% have been often measured in the poorer fields of western Kenya farms – cf. Chapters 2, 3 and 4).

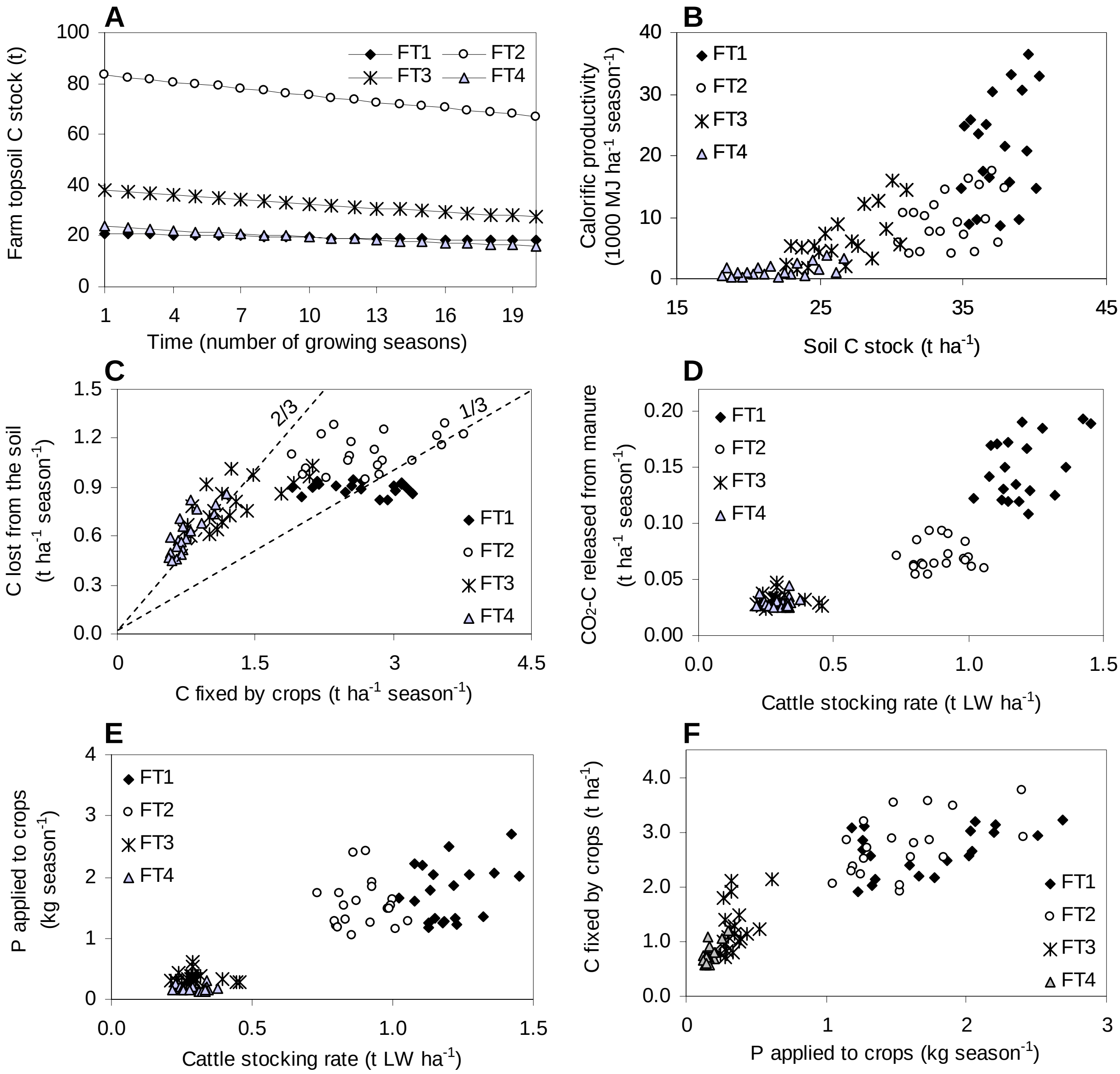

Figure 8: Farm scale indicators of C and nutrient stocks and flows derived from the 10-year baseline simulation for the four case study farms. (A) Changes in the stock of topsoil C at farm scale; (B) Production of food calories plotted against the stock of C expressed per unit of farm area; (C) Seasonal C losses in soil respiration and erosion vs. C fixed in crop biomass, with dotted lines indicating loss fractions of 33 and 66%; (D) Seasonal respiration C losses from the manure heap; (E) P applied to crops in manure plotted against cattle stocking rates expressed as live weight per unit area; (F) Seasonal rate of C fixation in crop biomass plotted against the total amount of P applied to crops in manure.

To maintain (or build up) of soil C stocks, crop productivity must be improved and crop residues kept in the field to input organic C to the soils. Crop productivity in western Kenya is largely limited by N and P, and more sporadically by K availability

(Shepherd et al., 1997 – cf. Chapter 5). Management-induced concentration of organic C and available P in a few fertile fields within individual farms has been repeatedly observed in these systems (Chapters 2, 4 and 5). When fertiliser use is infrequent, the main flow of P back to the soils occurs through application of manure or other organic resources. The higher the density of cattle in the system, the larger the chance that P will be returned to the soils (although often not to the same fields from where it has been removed). P and C are applied together when manure is applied, and fields that receive P produce greater crop yields and potentially larger C inputs to the soil via roots and crop residues, resulting in a favourable positive feedback (Figure 8 E and F). Such co-variation between management and consequent biophysical processes as a consequence of farmers' management decisions leads to the creation of gradients of soil fertility within these farms (Tittonell et al., 2005c).

3.2 Intensification pathways

The analysis presented above illustrates the wide gap in physical efficiencies achievable by the four farm types under baseline conditions. Assuming that farms of Type 1 and 2 represent two alternative models of the *ideal farm* (i.e., the farm prototype outlined by participating farmers in western Kenya), we explored means of intensification of Farm Types 3 and 4 to narrow their productivity gap with respect to Farm Types 1 and 2. This section presents simulation scenarios in which intensification of Farm Types 3 and 4 was pursued by increasing use of N and P fertilisers applied to food crops, allocating more land to fodder production while intensifying food production in smaller areas, and replacing the less productive local cattle breeds by improved, cross-bred dairy cattle.

3.2.1 Input intensification under the current farm configuration

Increasing rates of N and P fertiliser use at farm scale led to increasing farm primary productivity for Farm Types 3 and 4, eventually to cover all of the household energy requirement (Table 5). The application rates resulting from the amounts of N and P fertiliser used (0 to 60 kg N farm^{-1} and 0 to 15 kg P farm^{-1}) are within the range of maximum crop responses on these soils (cf. Chapter 7). Although little fodder was bought by these farm types, increasing maize productivity due to fertiliser use allowed more maize thinnings and stover to be used to feed cattle, reducing the need to buy Napier grass. Livestock productivity increased little with increasing fertiliser use; milk production increased by 10-20% on both farms, but given the small amounts produced under the baseline conditions the absolute increase was not substantial (not shown). The amount of manure returned to the soil increased considerably with fertiliser use with respect to the baseline conditions, but application rates remained very small. Rates of manure application in field experiments conducted to test the interaction between mineral and organic fertilisers are often higher. Such experiments often indicate that substantial responses in crop production can only observed with manure application rates as high as 10 to 20 t dm ha^{-1} (e.g. Kapkiyai et al., 1999; Zingore et al., 2007b).

Table 5: Changes in key indicators of farm productivity and efficiency in farms of Type 3 and 4 when N and P fertilisers are applied to food crops, without changes in land use. Averages over a 10-year simulation presented per season (sn).

Fertiliser use per sn. (kg farm^{-1})	Primary productivity (t ha^{-1} sn^{-1})	Self-produced calories (%)	Proportion of food secure sn's	Fodder bought (kg sn^{-1})	Manure application (kg farm^{-1})	Residue C incorporated (kg farm^{-1})	Farm CO_2 emission (kg farm^{-1})
Farm Type 3							
0N	2.8	77	0.25	20.8	292	127	977
15N	2.9	82	0.30	20.3	298	132	990
30N	3.0	88	0.30	18.7	303	136	1002
60N	3.2	100	0.50	18.0	314	145	1027
0N 7.5P	3.7	126	0.60	13.3	335	165	1066
15N 7.5P	3.8	136	0.75	11.7	344	172	1084
30N 7.5P	4.0	146	0.80	11.4	354	179	1103
60N 7.5P	4.3	168	0.80	9.8	373	194	1141
0N 15P	4.7	190	0.85	4.2	390	209	1170
15N 15P	4.9	209	0.90	2.6	405	223	1200
30N 15P	5.2	229	0.95	1.2	421	236	1230
60N 15P	5.8	269	1.00	0.0	454	263	1291
Farm Type 4							
0N	1.7	12	0	25.5	193	76	532
15N	1.8	16	0	24.4	197	80	541
30N	1.9	20	0	22.2	201	85	550
60N	2.1	29	0	18.5	210	94	569
0N 7.5P	2.2	31	0	14.4	209	97	569
15N 7.5P	2.3	39	0	12.3	218	106	586
30N 7.5P	3.0	73	0.25	0.0	241	136	638
60N 7.5P	3.0	73	0.30	0.0	241	136	638
0N 15P	2.7	57	0.10	3.4	226	122	612
15N 15P	3.0	74	0.30	0.0	240	137	638
30N 15P	3.4	94	0.45	0.0	258	154	665
60N 15P	4.2	137	0.75	0.0	291	190	722

On both farms, Type 3 and 4, mineral P application induced greater responses in terms of productivity than N application, in agreement with previous observations (cf. Chapters 5 and 7). Almost irrespective of the amount of N applied between 0 and 30 kg N farm^{-1}, the rate of replenishment of soil P stocks through fertiliser application determined the boundaries of food productivity of the farm system, as illustrated for the case-study farm of Type 3 in Figure 9 A. In this case, seasonal applications of 15 kg P farm^{-1} corresponded to replenishment rates < 2% per season. A positive synergy occurred when N was applied at 60 kg farm^{-1} together with 15 kg P farm^{-1}, as evidenced by the increase in farm primary productivity in Table 5. Higher soil organic contents were associated with higher food productivity, with decreasing crop yields as the simulation progressed under the baseline conditions (Figure 9 B and C). Applications of N fertiliser had a marginal effect on food productivity throughout the simulation (i.e., for the entire range of soil C contents). Applications of P fertiliser together with N allowed maintenance of higher amounts of soil C at farm scale and induced substantial responses in terms of food production.

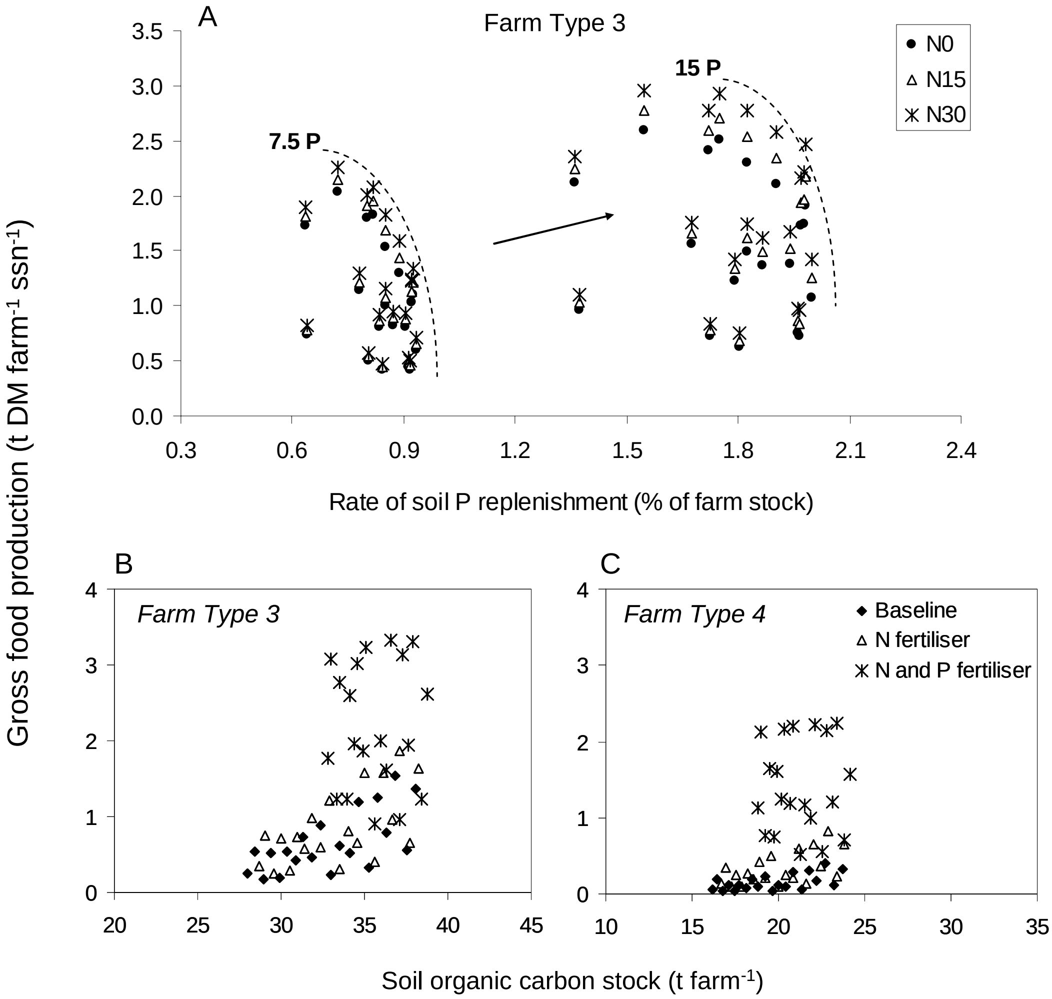

Figure 9: Simulation results from the 10-year scenario of N and P fertiliser use. (A) Gross food production vs. rate of farm-scale soil P replenishment with mineral fertiliser when 7.5 and 15 kg P farm^{-1} season^{-1} are used in case study Farm Type 3 as indicated in Table 3 B, without or with application of N at 0, 15 and 30 kg farm season^{-1} (N0, N15, N30, respectively), with 'hand-drawn' lines illustrating P-limitation to farm productivity. (B and C) Gross food production in Farm Types 3 and 4, respectively, without fertilisers (baseline), with 60 kg N farm^{-1} season^{-1} (N fertiliser) and with 60 kg N + 15 kg P farm^{-1} season^{-1} (N and P fertiliser) plotted against farm-scale soil C stocks (note the differences in the scale of the *x*-axes).

These results indicate that fields on these farms are within the range of 'non-responsive poor fertility' for N and 'responsiveness' for P (cf. Chapters 5 and 7). In principle, greater crop productivity could be expected with even higher rates of N and particularly P application (e.g., simulation results indicated positive responses to N and

P applied at rates of up to 120 and 60 kg farm^{-1}, respectively, in Farm Type 3 – not shown). However, C inputs to the soil via crop residues and manure remained too small to allow considerable build up of soil organic C and soil fertility (Table 5). The annual rate of CO_2 emission at farm scale also increases with fertiliser use as a consequence of greater crop and livestock productivity.

3.2.2 Qualitative changes in the cropping and livestock sub-systems

Increasing the area under Napier grass and reducing the area of maize, beans and sweet potato in farms of Type 3 and 4 had a positive impact on farm primary productivity, but decreased the production of edible energy and protein, leading to less food self-sufficient farms (Table 6; cf. Table 4). Napier grass production was more than doubled on both farms and their secondary productivity increased, particularly on Farm Type 3 where an extra cow could be kept with the extra fodder production (although the amount of Napier grass bought also increased). Less crop residue was fed to livestock on Farm Type 3 and barely the same amounts of concentrates were sporadically used as in the baseline runs. Milk production increased up to household self-sufficiency levels and more C and nutrients circulated through the livestock-manure sub-system, with a consequent increase in the amount of C returned to the soil as manure. In this scenario, 25% of the crop residue was fed to livestock or used as bedding and the remaining 75% incorporated in the soil, representing about half a tonne of C per ha incorporated every season.

By bringing in a more productive cow the average primary productivity of the entire system over the 10 year simulation increased even further in Farm Type 3, producing more food than necessary to cover household requirements and boosting milk production (Table 6). Livestock productivity was more than doubled; average milk yields increased to 4.6 L ha^{-1} day^{-1} (greater than in baseline Farm Type 1) due to the presence of a more productive cow that was better fed, reducing the calving interval to 18 months. Crop productivity increased due to more manure available for application in smaller fields as compared with the baseline (current) situation (cf. Table 4), with extra nutrients brought into the system in concentrates and fodder that were also cycled more efficiently by better manure handling, and with more C fixed and recycled within the farm system (Table 6). The total animal live weight on the farm and the amount of DM excreted per season are comparable with those of Farm Type 1 under the baseline (current) situation (cf. Table 4 and Figure 7 C). The average stock of soil organic C was 4.6 t ha^{-1} larger than in the baseline situation, while the amounts of N and P excreted by cattle (and potentially available to crops via manure) were c. 30 and 10 kg farm^{-1} season^{-1} larger with respect to the baseline. Note that similar amounts of N and P brought into the system as mineral fertilisers (e.g. 30 N and 7.5 P) produced substantial changes in farm productivity (cf. Table 5). In brief, bringing in a more productive cow lifted the system up to a higher overall productivity level.

Table 6: Indicators of productivity and efficiency for Farm Types (FT) 3 and 4 under the 'Napier grass' and 'Dairy cow' scenarios. Averages over a 10-year simulation presented per season (sn).

(A)

Scenario	Primary productivity ($t\ dm\ ha^{-1}\ sn^{-1}$)	Biomass yield ($t\ dm\ ha^{-1}\ sn^{-1}$)	Edible energy ($MJ\ ha^{-1}\ sn^{-1}$)	Edible protein ($kg\ ha^{-1}\ sn^{-1}$)	Energy requirement met (%)
Napier grass					
FT3	3.8	4.2	4558	45	52
FT4	2.7	2.5	1138	14	10
Dairy cow					
FT3	5.0	5.4	10632	100	123
FT4	2.9	2.7	2039	23	18

(B)

Scenario	Napier grass ($kg\ dm\ farm^{-1}\ sn^{-1}$)			Extra feeds* ($kg\ dm\ farm^{-1}\ sn^{-1}$)		Dry matter intake
	Produced	Bought	Fed	Crop residue	Concentrates	($kg\ dm\ farm^{-1} sn^{-1}$)
Napier grass						
FT3	3308	77	2724	208	3	2669
FT4	1996	5	1602	62	1	1279
Dairy cow						
FT3	3416	310	3043	405	104	2976
FT4	2027	296	1918	91	47	1690

(C)

Scenario	Secondary productivity ($t\ dm\ ha^{-1}\ sn^{-1}$)	No of animals ($TLU\ farm^{-1}$)	Live weight ($kg\ farm^{-1}$)	Weight gain ($kg\ farm^{-1} sn^{-1}$)	Milk production ($L\ farm^{-1} sn^{-1}$)
Napier grass					
FT3	0.31	2.4	662	23.9	356
FT4	0.20	1.2	308	11.7	165
Dairy cow					
FT3	0.86	2.2	909	35.4	1024
FT4	0.71	1.1	456	16.8	613

(D)

Scenario	Excreted DM	Excreted elements ($kg\ farm^{-1} sn^{-1}$)			C in manure heap ($kg\ sn^{-1}$)	
	($kg\ farm^{-1}\ sn^{-1}$)	N	P	K	Input	Output
Napier grass						
FT3	1079	16	12	48	345	219
FT4	511	7	6	23	180	108
Dairy cow						
FT3	1252	39	15	53	492	315
FT4	582	15	8	30	203	119

(E)

Scenario	Soil C stock ($t\ ha^{-1}$)	Manure C application ($t\ ha^{-1}\ ss^{-1}$)	C fixed by crops ($t\ ha^{-1}\ sn^{-1}$)	C incorporated ($t\ ha^{-1}\ sn^{-1}$)	Soil C losses ($t\ ha^{-1}\ sn^{-1}$)
Napier grass					
FT3	27.0	0.18	1.7	0.65	0.8
FT4	23.8	0.13	1.2	0.46	0.7
Dairy cow					
FT3	31.2	0.26	2.3	0.85	1.2
FT4	25.5	0.14	1.3	0.50	0.8

*Only feed items that changed with respect to previous scenarios are presented

In Farm Type 4, the impact on farm productivity of having introduced an improved cow was less in addition to the impact already brought about by increasing the area under Napier (Table 6). Milk production increased substantially, allowing surpluses for the market, but such production was sustained on extra fodder and concentrates. Less efficient handling and storage of manure (cf. Table 7) led to poorer C and nutrient cycling, and crop productivity did not improve any further. However, the main factor limiting productivity on this case study farm is not the efficiency of resource capture and cycling within the system but the total *amount* of resources cycled. Figure 10 depicts the amounts of N entering the manure storage heap in faeces, crop residue and other organic materials every season in the four farm types, and under the various scenarios simulated for farms of Type 3 and 4 (note the important differences in the scale of the *y*-axis for Farm Type 4). In all farms the amounts of N cycled through manure were not constant but varied between seasons following the variability in farm productivity. In terms of N losses, the scenario with an improved cow is less efficient in cycling N through manure in Farm Types 3 and 4. However, the amount of N coming out of the heap after storage in this case is almost equivalent to that entering storage under the other scenarios.

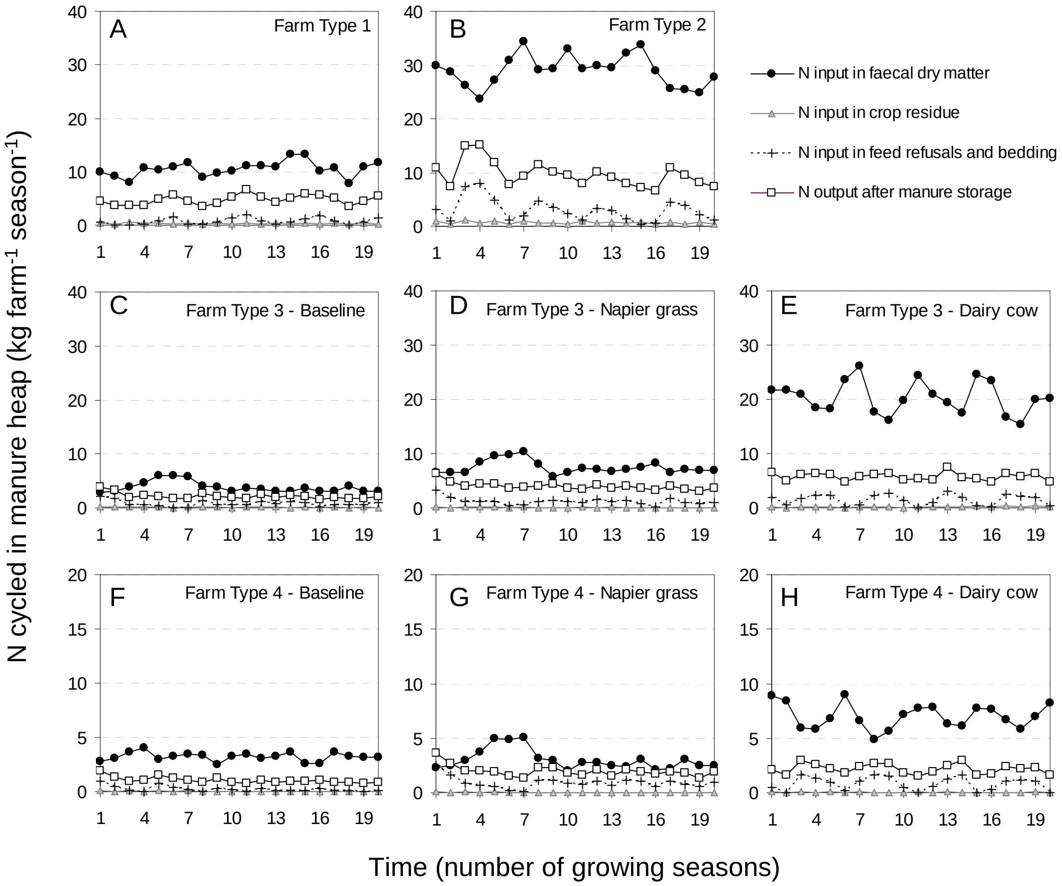

Figure 10: Seasonal amount of N cycled in the manure heap across farm types, indicating inputs of N in faecal dry matter, crop residue, feed refusals and bedding materials added to the heap and N coming out of the heap after storage. A, B, C and F: Farm Types 1 to 4 under the baseline scenario; D and E: Farm Types 3 and 4 under the Napier grass scenario; E and I: Farm Types 3 and 4 under the Dairy cow scenario.

Table 7: Indicators of productivity and efficiency for Farm Types (FT) 3 and 4 under the baseline, 'Napier grass' and 'Dairy cow' scenarios with application of N and P fertilisers. Averages over a 10-year simulation presented per season (sn).

(A)

Scenario	Farm Type	Primary productivity (t ha^{-1} sn^{-1})	Self-produced calories (%)	Live weight (kg $farm^{-1}$)	Weight gain (kg sn^{-1})	Milk production (L sn^{-1})	Excreted DM (kg sn^{-1})
15 kg P $farm^{-1}$ $season^{-1}$							
Baseline	FT3	4.7	190	366	14	207	613
	FT4	2.7	57	285	9	135	485
Napier grass	FT3	7.8	298	678	26	407	1122
	FT4	6.2	188	312	12	172	524
Dairy cow	FT3	7.8	300	899	33	1123	1279
	FT4	6.4	202	504	24	640	665
60 kg N and 15 kg P $farm^{-1}$ $season^{-1}$							
Baseline	FT3	5.8	269	368	15	208	619
	FT4	4.2	137	300	9	157	517
Napier grass	FT3	8.6	348	679	27	416	1129
	FT4	8.0	281	317	13	173	537
Dairy cow	FT3	8.6	349	906	34	1171	1299
	FT4	8.1	289	520	22	689	689

(B)

Scenario	Farm Type	Inputs to manure heap (kg sn^{-1})			Residue C incorporated	Average soil C stock	Soil C stock in best field	Farm CO_2 emission
		C	N	P	(kg sn^{-1})	(t ha^{-1})	(t ha^{-1})	(t sn^{-1})
15 kg P $farm^{-1}$ $season^{-1}$								
Baseline	FT3	248	5.4	1.0	0.2	28.3	39.0	1.2
	FT4	113	3.8	0.5	0.1	22.8	25.4	0.6
Napier grass	FT3	471	10.5	2.1	2.6	36.2	66.3	2.1
	FT4	227	4.5	0.9	2.1	31.4	54.4	1.3
Dairy cow	FT3	553	22.4	2.5	2.6	36.4	66.6	2.1
	FT4	230	8.7	1.0	2.2	31.7	54.4	1.3
60 kg N and 15 kg P $farm^{-1}$ $season^{-1}$								
Baseline	FT3	290	5.8	1.2	0.3	29.1	39.3	1.3
	FT4	145	4.2	0.7	0.2	23.9	28.6	0.7
Napier grass	FT3	494	10.8	2.2	2.9	37.5	66.4	2.2
	FT4	314	5.4	1.3	2.7	35.0	57.2	1.6
Dairy cow	FT3	584	22.7	2.6	2.9	37.6	66.7	2.3
	FT4	268	9.1	1.2	2.7	35.3	57.1	1.6

Under the new farm configurations, the 'Napier grass' and 'Dairy cow' scenarios, mineral fertilisers can be used more efficiently (Table 7). For instance, the use of 15 kg P in both farms under these scenarios induces greater primary productivity than 60 kg N $farm^{-1}$ + 15 kg P $farm^{-1}$ per season under the baseline situation. In Farm Type 4, food self sufficiency was surpassed with application of 15 kg P $season^{-1}$ under the Napier grass and dairy cow scenarios. Although changes in animal production by effect of fertiliser application were small, the amount of C and nutrients cycled within the system and the consequent stocks of soil C were larger. Due to the fixed spatial patterns of fertiliser and manure allocation set up in the simulations, the difference between the soil C content of the best yielding field and the farm average is wider when more nutrients are cycled in the system.

3.3 Towards the ideal farm

To analyse the capacity of rural households to adapt to increasing stresses such as increasing population density or climate change, Thornton et al. (2007) used a graphical Cartesian framework in which the *y*-axis represents some aspect of household well being and the *x*-axis livelihood options or alternative management/activities. These ideas are developed further in the scheme of Figure 11, which illustrates the pathway of intensification towards the 'ideal farm' as followed in this study. The improvement of household well-being takes place through discontinuous, alternating processes of input intensification within the current system state and qualitative 'jumps' to a new system state brought about by investment and/or diversification. In System state I, the various farm activities have a certain efficiency and responsiveness to input intensification. A low 'ceiling' of productivity of the activities A and B in response to input use is rapidly reached. In our examples, soil fertility builds up slowly under repeated nutrient additions if the crop residue is removed every season to feed livestock, and the responsiveness to mineral fertilisers remains poor (cf. Chapter 7).

In System state II qualitative changes induce substantial increase in the efficiency and responsiveness of activity A. In our example, more land is allocated to fodder production reducing the need of maize stover to feed livestock, crop production is intensified in smaller areas concentrating manure and external nutrient inputs, allowing for the fertility of the soil to build up in the long term (eventually requiring less external inputs). In System state III, activity A would need only half the amount of external inputs to achieve the same productivity level as in System state II. Resources are used and recycled more efficiently within the system due to a substantial increase in the efficiency of activity B and in the complementarities with activity A. Due to such complementarities, activity A becomes more productive even without external inputs, simply due to the increase in productivity of activity B. Back to our examples, this means that a more productive livestock subsystem may allow a more intensive cycling of nutrients within the farming system; of nutrients that may be either part of the farm soil stocks and/or brought-in as fertilisers or animal feeds.

As in the examples shown by Thornton et al. (2007), external system stresses may induce changes in livelihood options that can preserve levels of well-being. In our case study area, increasing population density and the consequent lack of communal grazing land has led to intensification of dairy production through zero grazing systems. A market niche was thus opened for fodder crops such as Napier grass, which is being grown in the area as a cash crop even by farmers without cattle (Tittonell, 2003). Acute permanent stresses and/or shocks, however, may displace the trajectory of intensification inducing lower levels of well being for a given livelihood option; i.e. the trajectory would be 'less steep'. The observations suggesting that rainfall patterns might be tending towards uni-modality in East Africa (cf. Chapter 3), discontinuing if not reducing the primary productivity of the system throughout the year, constitutes a type of stress to which rural households need to adapt by substantial changes in the system. In other words, alternative pathways must be followed. Different configurations of the final system state (i.e., a totally different 'ideal farm') through diversification of activities and processes would then be necessary.

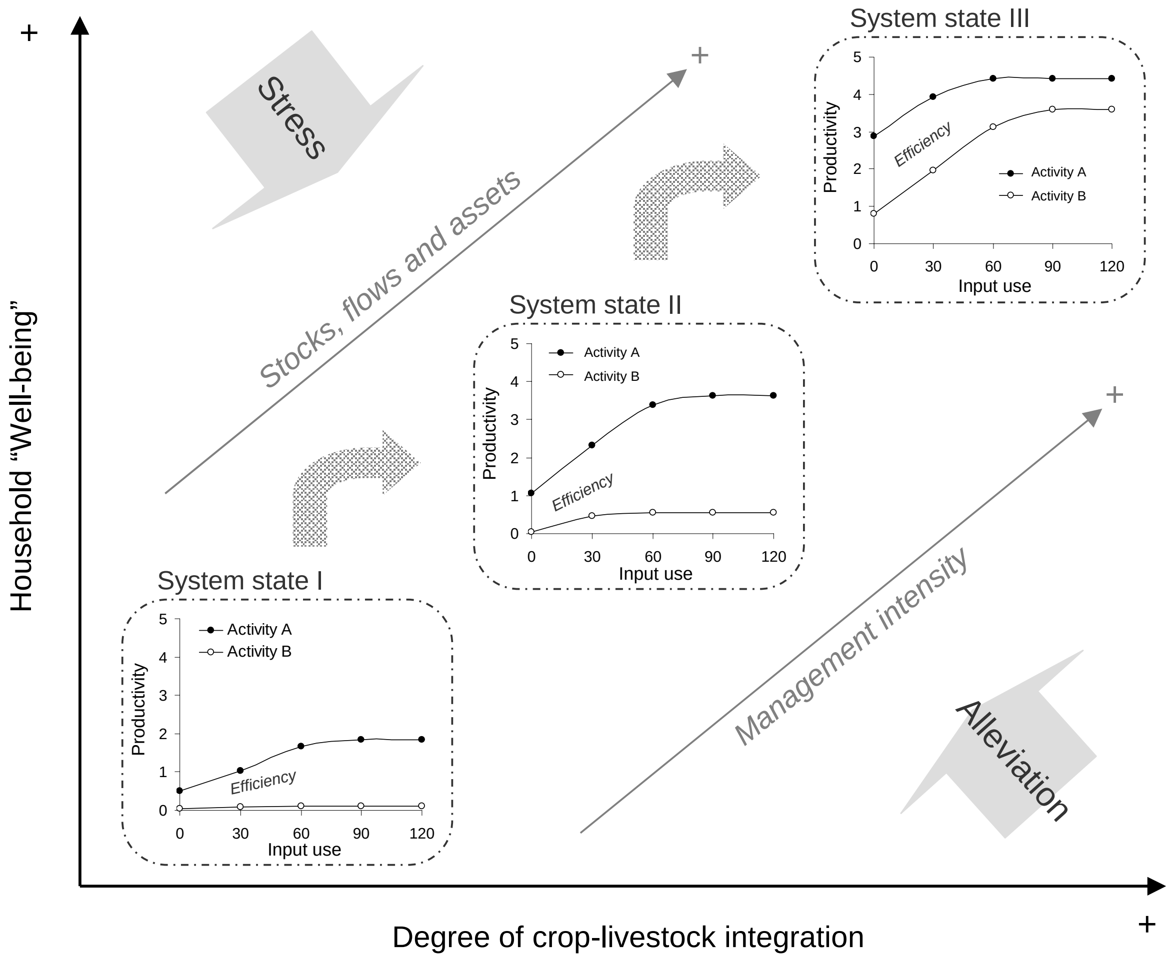

Figure 11: Schematic conceptualisation of pathways towards intensification and their potential impact on household well-being. In this case, the impact of intensifying crop-livestock interactions (x-axis) on different aspects of household well-being (y-axis) such as food security or cash income follows a discontinuous trajectory in which input-intensification (quantitative) must be followed by qualitative changes in the productive structure of the farm to induce 'jumps' of the system towards higher states. Resource use efficiencies, the degree of complementarities between production activities, resource endowment and management intensity increase from System states I to III. Stressing factors (e.g. population density) and alleviation interventions may modify the slope of the trajectory towards higher levels of well-being for a certain degree of intensification.

The 'steepness' in the trajectory towards the ideal farm as well as the total 'distance' to be covered is likely to differ between the various farm types (cf. Table 1), due to their capacity for innovation/adaptation and investment priorities, as observed also by Herrero et al. (2007) in their analysis of 'trajectories of change' in mixed crop-livestock systems. In some cases, households counteract stresses by substantial diversification, such as off-farm income-dependent livelihood strategies (e.g., the Farm Type 1). Alleviation policies, investments, marketing incentives or other forms of intervention should be designed to counteract the effect of such stresses, allowing a steep trajectory towards intensification. The scheme in Figure 11 also indicates that simply providing inputs to farmers will only serve (at most) to intensify activities within the current systems, without inducing qualitative changes that would eventually render the systems more sustainable (i.e. without inducing necessary jumps to higher system states). As farmers literally say in western Kenya: "give me one cow, and I'll improve my soil" – Misiko, 2007. But a more efficient management, necessary to capitalise positive crop-livestock interactions, requires substantial financial investment and more labour – two elements that were not explicitly considered in our analysis.

Towards intensification, the intensity of management and the resource endowment of the household should increase in parallel, thus gradually removing inefficiencies and resource constraints. But the potential feedbacks at higher scales should not be ignored. Bringing an improved cow to Farm Types 3 and 4 implies that part of the fodder to cover their requirements, to get through months of fodder scarcity or drier seasons, must be purchased on the market (Table 6, cf. Figure 5). In the hypothetical case in which most farmers would demand Napier grass from the market, it may happen that either: (1) the price of fodder increases, generating an attractive market for farmers without livestock; or (2) the demand cannot be covered by local production, which may compromise the sustainability of the system. Likewise, most of the milk produced by smallholder dairy farmers in western Kenya is sold locally (Chapter 3). If most farmers in the area produce milk for the market, local milk prices would most likely drop – which may benefit the poorer families – and substantial investments in infrastructure would be necessary to export milk surpluses to other regions.

Options for input-based biophysical intensification may have a high cost. For instance, according to the latest population surveys Vihiga district has 105,000 households, of which approximately 60% fall in the categories of Farm Types 3, 4 and 5 (Henry, 2006 – cf. Chapter 2). If one bag of 50 kg of DAP and one bag of CAN fertiliser was provided to each household, approximately 12,000 t fertiliser per year would be necessary. That amount is equivalent to 15.5% of the average annual fertiliser use of Kenya as a whole (www.earthtrends.org – see later: Chapter 9), which includes also the high-input export sectors of flowers, vegetables and coffee production, plus commercial farming in the 'White Highlands' of Kenya. Ideally, fertilisers should not be provided for free but rather *demanded* by farmers who recognise the need to recover or maintain the fertility of their soils. Nowadays, high transaction costs and limited availability at local markets deter their use/adoption by farmers; e.g., a bag of 1 kg of fertiliser is sold at 35 KSh in a village market, which is equivalent to 492 US$ t^{-1} (about 5 times the international market price). Yet, when mineral fertilisers induce responses of 30 kg maize kg^{-1} fertiliser, their use is still economically profitable, given the current fertiliser:grain price ratios in western Kenya (cf. Chapter 7). In addition, several other reasons may be put forward to explain the currently limited use of mineral fertilisers: lack of ‘cash in hand’ at the beginning of the planting season, competing expenditures such as school fees at that time of the year, lack of knowledge on their use, or simply that farmers do not see clear benefits from using them.

The results obtained from the simulations must be considered in the light of the assumptions that were made to simplify the farming systems, to make this exercise operational. In reality, systems are more complex and diverse. While there is little doubt that agriculture without external inputs is necessarily extractive, de Ridder et al. (2004) warned that the rates of resource degradation often reported for sub-Saharan Africa may overestimate the actual situation. Partial nutrient balances calculated in western Kenya farms indicate alarming rates of soil depletion; in most fields the outputs of N are more than double the inputs, irrespective of the amount of N inputs used by farmers of different wealth classes (Tittonell et al., 2005c – cf. Chapter 3). In spite of this, farming continues in the area, and although most fields exhibit C and nutrient stocks in equilibrium with poor input rates (Chapter 7), there must be some other elements of resilience that are not captured by these simple indicators. In complex, dynamic and spatially heterogeneous systems interactions take place across spatio-temporal scales that lead to emergent properties and self-regulatory mechanisms (Holling, 1973). For example, recent studies highlighted the contribution of ‘weeds’ and local vegetables to the dietary diversity and nutritional security of the households in Vihiga (Figueroa-Gomez, 2007). Often different ‘buffering’ mechanisms operating at village scale emerge from collective action as well (Meinzen-Dick et al., 2004). Next to regulatory feedbacks that may prevent smallholder systems from collapsing, farmers adaptive capacity and alternative strategies (e.g. through rural-urban connectivity) play a major role in systems resilience. In analogy to the concept of informal economies (de Soto, 2000), such alternatives represent ‘informal resource flows’ as they are often unaccounted for in farming systems analysis.

4. Concluding remarks

In addition to the conclusions of Waithaka et al. (2006), that the *ideal farms* would be hardly viable in economic terms, our results indicate that the trajectory of change towards their achievement is hardly feasible for a majority of farmers. On the other hand, it may be questioned how ‘ideal’ is the ideal farm. Further evidence to this was provided by simulation results indicating productivity declines even for the wealthier farms, if the current situation prevails. However, this model-based study illustrated the need for qualitative changes in the current farming systems that allow positive shifts in the magnitude of stocks and flows of resources within and through them. The impact of livestock on the recycling of nutrients and on the efficiency of nutrient use at farm scale can be large, provided that enough nutrients are present in (or enter) the system to be redistributed. When the absolute amounts of resources cycled within the system are small, improving cycling efficiencies is only part of the solution.

Promoting intensification through increased input use by e.g., providing one bag of fertiliser per household, is also a partial solution. Although in our study the use of mineral fertiliser led to achieving household food self-sufficiency on the poorer farms, the associated 'inefficiency' costs were substantial. The simulations showed that the response of the system to one bag of fertiliser depends to a large extent on its productive structure, chiefly on the presence of livestock, and on the intensity of management practices put in place to ensure efficient resource use. Some of the measures necessary to ensure efficient nutrient cycling are labour-intensive (e.g. improved manure handling) and/or require investments that farmers are not always able to afford. This calls for the need of approaches to systems research and design that consider system-scale processes and their (long-term) impact on livelihoods rather than effect of single inputs on a particular activity. In other words, to move from measuring the 'effect of input X on activity Y' towards assessing the 'impact of process X on system Y'.

The *ideal farms* designed by farmers in Vihiga district seem difficult to achieve for a majority of farmers. This may also imply that alternative prototypes are necessary. Although some of the scenarios of intensification explored here are hard – if not impossible – to accomplish, they do not differ much from what emanates from international recommendation panels or is seen in current policies (e.g., the '50 kg of nutrient per ha for sub-Saharan Africa' goal proposed in the Abuja Fertiliser summit in 2006, the 'one farmer one cow' policy in Rwanda, or the policy of 'fertiliser + improved seed packages' for agricultural intensification in Malawi). Such approaches, however, are rarely supported by studies conducted at the relevant scale of analysis or by a sound understanding of the dynamics of the farming systems.

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Chapter 9

General discussion[†]

[†] Parts of this chapter were presented as:
Tittonell, P., Vanlauwe, B., Misiko, M., Giller, K.E., 2007. Targeting resources within diverse, heterogeneous and dynamic farming systems: towards an 'uniquely African green revolution'. Oral presentation at the AfNet Symposium: Innovation as Key to the Green Revolution in Africa: Exploring the Scientific Facts, September 17-21, Arusha, Tanzania, proceedings book in press.

1. Introduction

The analysis performed in the various chapters of this thesis and the conclusions derived from them indicate that, in terms contributing to the design of sustainable farming systems that are capable to meet the basic requirements of rural households, this is still work in progress. Diverse methodologies were used to identify: (i) the drivers of farm diversity and heterogeneity affecting the implementation of integrated soil fertility management; (ii) the impact of farm heterogeneity on crop productivity, resource use efficiency and crop response to technological interventions; (iii) options and trade-offs that farmers face when making resource allocation decisions that reinforce the effects of such heterogeneity; and (iv) opportunities for restoration of current soil and system productivity through sustainable intensification. In tackling these issues, emphasis was placed on biophysical interactions taking place within dynamic socio-economic contexts and considering the effect of human agency. This provided insight in opportunities and limitations for the implementation of integrated soil fertility management (ISFM) as a means to restore soil productivity. The various approaches used proved useful either to understand the current systems, their constraints and trade-offs (Describe-Explain), or to represent the system reality and explore options for improvement of rural livelihoods (Explore-Design). These may be seen as lessons learnt in terms of approaches for farming systems analysis, and will be discussed in relation to the findings of this thesis.

The purpose of this chapter is to bring together the main findings and extract relevant conclusions placed in context. This will be articulated by first analysing opportunities and constraints facing farming systems, conditioning their future and the implementation of ISFM technologies, scaling down from region to households; to then analyse the physical feasibility of options for sustainable intensification within this context, moving from single plot to farm system scale, with emphasis on strategic targeting of limited resources.

2. From fallows to markets

In targeting interventions to improve livelihoods through agricultural policy, investment in infrastructure or technology promotion, two main dimensions that determine opportunities and constraints across locations are often considered: agroecological potential and market opportunities (e.g., IFPRI, 2007). To illustrate this, the six sites in Kenya and Uganda described in Chapter 2 were placed within a plane defined by these two dimensions (Figure 1 A). Market opportunities are defined by the size, development and accessibility of major markets (e.g. proximity to urban and export markets, infrastructure, market information, transaction costs). For example, Meru South and Mbeere vary widely in agricultural potential but both are located close to the city of Nairobi (with an international airport) and surrounded by the densely populated areas and mid-sized towns of central Kenya, well connected through major national roads (see Table 2 in Chapter 2). Soils are inherently more fertile in Meru South and Mbale, located on the foot slopes of Mt. Kenya and Mt. Meru, respectively, and receive ample rainfall. Soil organic C is a good proxy for the inherent soil fertility and agricultural potential of different sites in this case (see e.g., Figure 3 in Chapters 2, 4 and 5). Soils with proportionally more clay under cooler and wetter climates tend to accumulate more organic matter due to larger primary productivity (more water and nutrient availability for plant growth) and slower rates of organic matter decomposition (lower temperatures and physicochemical protection of C within the soil matrix) (cf. Chapter 1, Figure 3; see also Six et al., 2002).

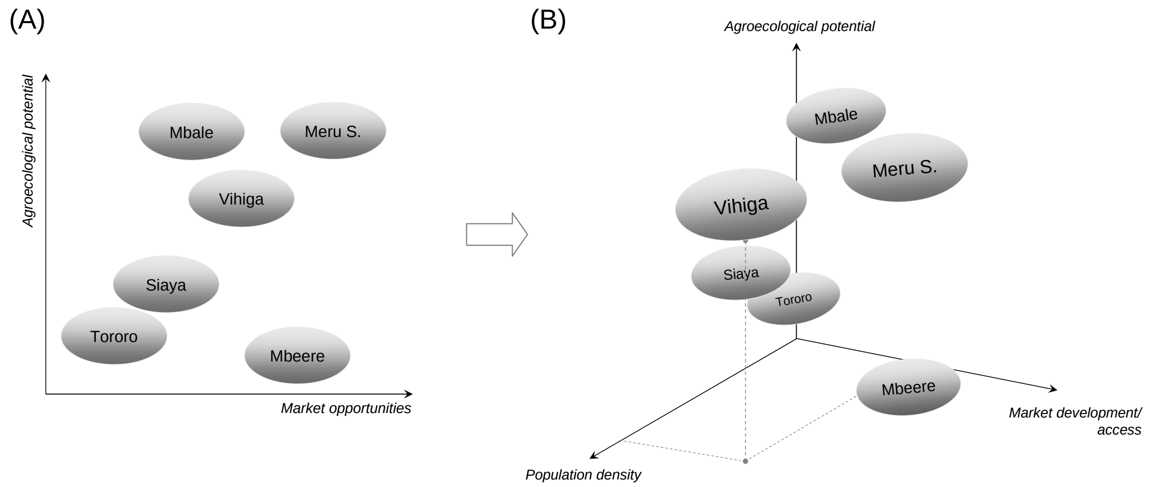

Figure 1: Different sites in Kenya and Uganda ordered by their agricultural potential and market opportunities (A), and by these two factors plus population density (B). Details on the six sites are presented in Chapter 2. For clarity, the intersections with the market and population axes are indicated for Vihiga.

However, agroecological potential and market opportunities – which are also frequently related to each other – are not enough to explain the observed diversity of livelihood strategies across and within locations. Historical, political and demographic processes, in combination with local variability among households, determine the space of opportunities and constraints within which households develop. In Figure 1 B, the same locations are placed within a space defined by agroecology and markets plus a third dimension representing population density. Intuitively, one may expect higher population densities in areas with the highest agroecological potential and best market opportunities. Vihiga, with more than 1000 inhabitants km^{-2} in much of the district, does not directly follow this rule due to its ethno-cultural and historical background (Crowley and Carter, 2000). Population densities beyond a certain (site-specific) threshold are often inversely proportional to the availability of resources per household, but a larger population may also create more local market and/or job opportunities in rural communities. If opportunities and constraints for the promotion of ISFM technologies across these sites were evaluated, yet a fourth dimension representing cattle densities (cf. Chapter 1) could be included in this analysis.

The diversity of livelihood strategies, which represents to a large extent production orientation and household objectives, has important implications for the targeting of agricultural technologies. Considering the two first dimensions discussed above, natural resources and local markets, Dorward et al. (2001) distinguish three main livelihood strategies of the poor in rural areas: (1) ‘Hanging in’, which takes place in situations of poor natural resource potential and market opportunities, and where households engage in activities to maintain their current livelihood (subsistence farming); (2) ‘Stepping up’, in situations of high agricultural potential and where investments in assets are made to expand current production activities (semi-commercial farming); (3) ‘Stepping out’, when activities are used to accumulate assets that may allow moving into different activities, not necessarily farming (i.e. migration to cities and/or local engagement in non-farm activities). At local scale, these strategies and their determinants are nuanced by differences between households in terms of resource endowment and social capital. A fourth group of households, those who are ‘Falling down’ may occur who fail to meet their basic household needs due to multiple constraints.

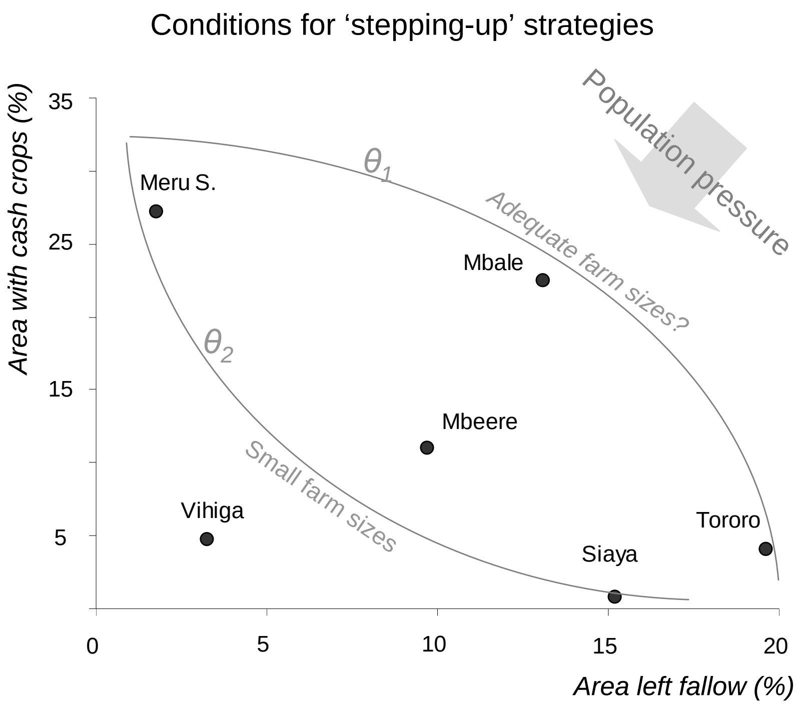

Figure 2: Market orientation against traditional soil fertility management systems. The six sites described in Chapter 2 were plotted according to the average area share of cash crops (a proxy to market orientation) and the percentage of the farm area left fallow (a proxy to traditional soil management) or fallow duration (cf. Table 7 in Chapter 2); i.e., an area 20% fallow is equivalent to 5 years of fallow duration (Ruthenberg, 1980). The hypothetical lines θ_1 and θ_2 indicate, respectively, the degree of complementarity and substitution between cash crops and fallow; i.e., a given area with cash crops may correspond with larger areas under fallow on θ_1 or with smaller areas left fallow on θ_2.

In areas of high resource potential and ample market opportunities such as Meru South (cf. Chapter 2), different households may hang in, step up or step out, or pursue mixed strategies, such as investing in lucrative cash crops and re-investing their income into higher education for their children (to eventually step out). By contrast, areas of poorer natural and market potential force most households to hang in. The conditions required to promote viable stepping-up strategies can be illustrated by looking at indicators of current land use and production orientation. In Figure 2, the six sites from East Africa have been plotted according to the area allocated to cash crops and left as fallow[‡] (cf. Table 7 in Chapter 2). While it may be assumed that market opportunities increase in parallel with the area allocated to cash crops, the effect of agroecological potential is not unidirectional. The lines θ_1 and θ_2 represent, respectively, the degree of complementarity and substitution between allocating land to cash crops (a proxy to market orientation) and leaving land fallow (a proxy for maintenance of soil fertility through traditional methods). Population growth exerts pressure by reducing the average farm sizes. Below a certain threshold, which differs across sites according to agroecology and market opportunities, most households are forced to step up. This is the case of Vihiga district, where a large number of families pursue off/non-farm income strategies (Chapters 2 and 3). Earlier studies in the Kenya highlands indicated minimum thresholds in farm sizes to ensure viability of smallholder farming to be around 0.4 ha – about one acre (Salasya, 2005; Waithaka et al., 2006), which is not far from the current average farm sizes of Vihiga in western Kenya (cf. Chapter 2).

Likewise, it may be hypothesised that there is an optimum farm size in relation to the particular characteristics of each locality that may allow complementarities between market orientation and sustainable land use, represented in Figure 2 by the line θ_1. Note that, the two least populated sites where most households achieve food self-sufficiency (Tororo and Mbale – cf. Chapter 2), lie close to the hypothetical 'complementarity' boundary described by θ_1. However, since such optimum farm sizes are larger than the current average farm sizes in many different regions of sub-Saharan Africa, farming systems need to intensify. Strategies for sustainable intensification of smallholder farming systems are urgently needed to replace traditional soil management systems by alternative means to maintain soil productivity, thereby displacing the minimum and optimum farm sizes to the left (i.e., requiring shorter or no fallow), as illustrated in Figure 3. With increasing population densities and decreasing farm sizes, the necessary increase in food production must be achieved through greater yields per unit area. Although it has been argued that integrated soil fertility management should be promoted to ensure food security (i.e., to promote annual growth rates in food production that are at least the same or larger than population growth – cf. Chapter 1), development should not stop there. Increasing market orientation implies stepping-up from viable farms for subsistence to viable enterprises. Analysing the optimum farm size across agroecological and market

[‡] Equivalent to fallow duration (see Ruthenberg, 1980).

development conditions is undoubtedly a research question to investigate further, to provide supportive evidence, for example, for land subdivision policies[§].

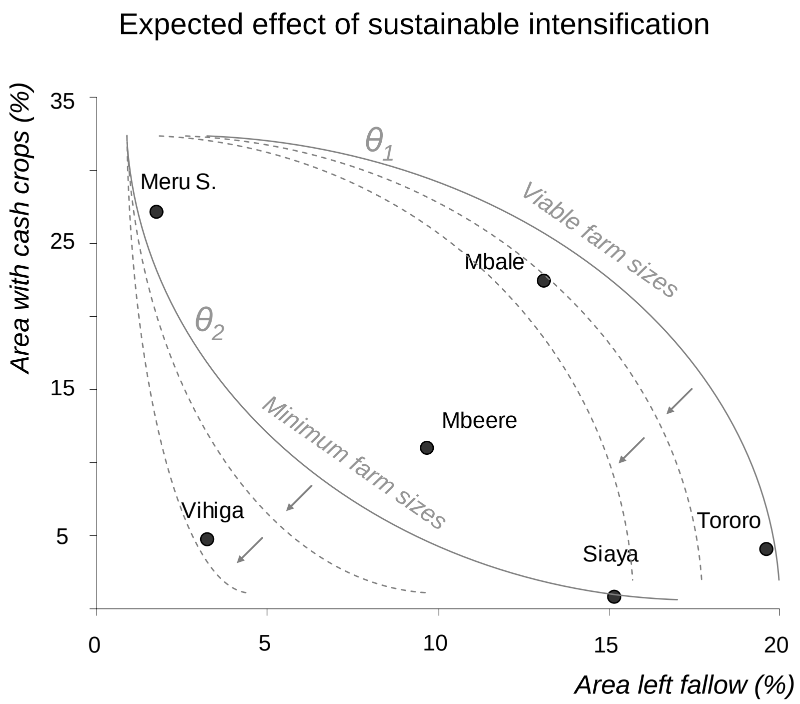

Figure 3: The expected effect of sustainable intensification. The implementation of ISFM technologies through use of mineral and organic fertilisers and efficient management of crops-livestock interactions may allow reducing the area of fallow needed to maintain soil fertility, reducing the viable and optimum farm sizes. The effect of intensification is represented by the arrows indicating the displacement of the hypothetical complementarity (θ_1) and substitution (θ_2) lines (cf. Figure 2).

3. Household diversity

Next to agroecology, markets and population density, other factors such as rural-urban connections and off-farm opportunities contribute to shaping livelihood strategies. Access to non-farm income through remittances or employment in urban areas, or to off-farm income from selling labour locally in rural areas have been used in combination with indicators of production orientation and resource endowment to categorise household types in East Africa (Tittonell et al., 2005b). This constitutes a functional typology of households in which the position of the household in the farm developmental cycle and production objectives are also considered (cf. Chapters 1, 2 and 3), going beyond the more common approach of structural farm typologies used to categorise households (e.g. wealth rankings through indicators of resource endowment – Mettrix, 1993). Although the range of variability and relative importance of major

[§] This is currently a hot debate in Kenya, where the government aims to pass a law by which land cannot be subdivided through inheritance below a certain threshold area (see e.g. The East African Standard, Nairobi, 22 September 2007, www.eastandard.net).

drivers of farm diversity change from site to site, similar *patterns* of livelihood strategies (i.e., Farm Types) could be recognised across sites.

The various Farm Types thus defined engage in different income-generating activities, exhibit contrasting patterns of resource allocation and prioritisation of investments, and pursue different long term livelihood strategies. For example, farms of Type 1 and 5, relying largely on off-/non-farm income have stepped out of agriculture on their own farms as a main income-generating activity. In promoting technologies, farms of Type 2 and 3 constitute the most promising target groups, since agricultural production represents their main source of income. In western Kenya, while Type 2 includes wealthier households headed by respected older farmers, Type 3 includes mostly households headed by younger, enterprising farmers that show a high degree of participation in extension activities such as farmer field schools (Misiko, 2007). Although Type 5 farmers live by working for other farmers, their income is often so restricted it seems unlikely that they will be able to invest sufficiently in their own farms to 'step up'.

The propensity or relative frequency of hanging-in, stepping-up or stepping out livelihood strategies differs from place to place across sub-Saharan Africa. Within a certain location, individual farms and decision-makers differ in resource endowments, objectives, individual attitudes, education and ability to innovate. Although this variability must be recognised and categorised for better targeting of technologies, the broader socioeconomic context cannot be disregarded. Most households in the study areas characterised in Chapter 2 are below the poverty line, as indicated by the poverty mapping (www.worldbank.org/research/povertymaps), and our categorisations basically distinguish between very poor, poor and less poor households. The potential beneficiaries of ISFM technologies in Africa are thus poor families, often lacking cash and assets, and farming small pieces of (frequently degraded) land.

2. ISFM technologies: opportunities and trade-offs

Technology interventions may target different entry points to the system, such as improving the efficiency of nutrient cycling between crop and livestock through better manure management (e.g. Rufino et al., 2007a), or introducing N_2-fixing grain legumes in rotation with maize (e.g. Chianu et al., 2006; Ojiem et al. 2006). In areas of high population density and generalised land degradation, the size of stocks and flows of nutrients to, within and from the system are too small (Chapter 8). Rather than nutrient-limited crops, we must speak of nutrient-limited farming systems. Thus, while the efficiency of nutrient cycling within the system can be doubled by improving manure handling and storage, the key limitation is the *amount* of nutrients being cycled (cf. Table 4 and Figures 6 to 9 in Chapter 8). This is particularly the case for P in western Kenya, which is deficient in most fields of smallholder farms (cf. Chapters

4 and 5) and generates large responses when applied to maize in mineral fertilisers (Chapters 7 and 8). Generalised P deficiencies reduce the ability of grain legumes and green manures to fix atmospheric N_2 in western Kenya (Ojiem et al., 2007; Misiko et al., 2007).

Mineral fertilisers are an option to bring nutrients into nutrient-limited farming systems. Mineral fertilisers often have a negative image in developed countries, which derives from their excessive use subsidised by other sectors of the economy, with consequent pollution of ground water, eutrophication of lakes, etc. For comparison, Figure 4 shows figures on fertiliser use intensity[**] at country level in selected developed and emerging economies. In Figure 4 A, fertiliser use intensity in The Netherlands and the average for Europe are included together with USA, Brazil, Argentina and three countries in sub-Saharan Africa where fertilisers are used: Zimbabwe, Kenya and Mali. In Figure 4 B, The Netherlands and Europe have been removed to expand the detail of the *y*-axis (note that the maximum value was changed from 1000 to 140 kg ha^{-1} $year^{-1}$). Although examining such data at country-level means that localised concentration of fertiliser use may be masked, it is clear that the negative effects caused by excessive fertiliser use – which shape public opinion – are a problem inherent to European agriculture. The negative perception on the promotion of fertilisers in Africa, born from experience in Europe, is a 'popular myth' without serious supporting evidence but difficult to eradicate (Vanlauwe and Giller, 2006).

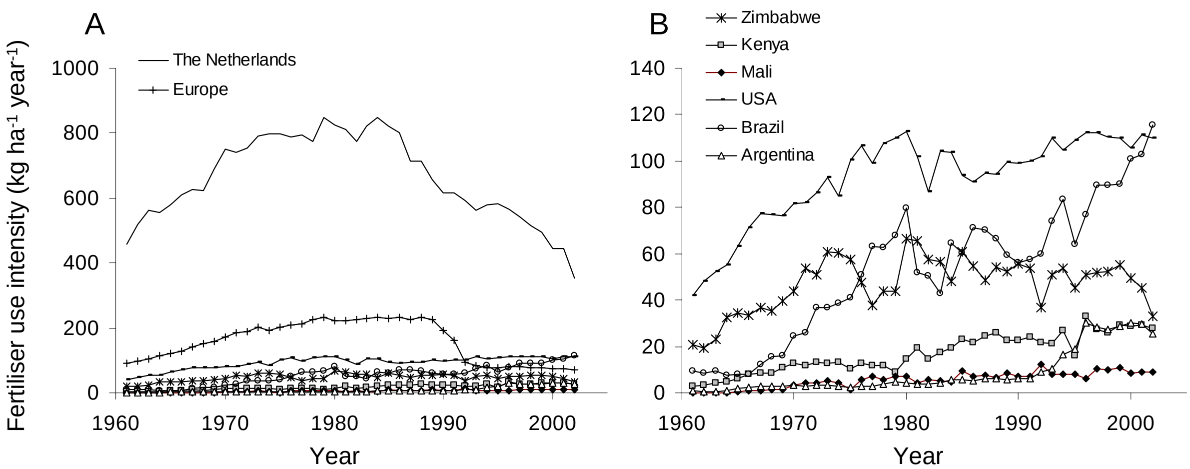

Figure 4: Fertiliser use intensity at national level in selected developed and emerging countries (www.earthtrends.org). In (A) the figures for The Netherlands and the average for Europe have been plotted together with the rest of the countries. In (B) The Netherlands and Europe have been removed to expand the scale of the y-axis. Fertiliser use intensity was calculated as the amount of fertiliser nitrogen (N), potash (K_2O), and phosphate (P_2O_5) consumed for agriculture per hectare of arable and permanent cropland, on an annual basis.

[**] Calculated as the amount of fertiliser nitrogen (N), potash (K_2O), and phosphate (P_2O_5) consumed for agriculture per hectare of arable and permanent cropland, on an annual basis.

But sometimes fertilisers also have a bad image among smallholder African farmers, since the continuous removal of crop residues (and the C and nutrients contained in them) from fields that receive N or P fertilizers may contribute to the perception among farmers in western Kenya that fertilizers 'spoil the soil' (Misiko, 2007) (cf. Chapter 7). Building soil fertility by means of fertiliser use can only be achieved when crop residues are kept in the field (Figure 6 in Chapter 7). Such a typical trade-off, between retaining crop residues in the field compared with using them to feed cattle, as fuel, sell them locally or add them to the compost, may prevent the widespread uptake of conservation agriculture in sub-Saharan Africa. By contrast, manure applications contribute to building more balanced C and nutrient stocks in the soil. When feasible manure application rates are small, and their C and nutrient contents too poor (as in most cases of smallholder systems), the combined application of manure with small amounts of mineral fertilisers may improve the attractiveness of the technology (immediate response) and the long term benefit to soil fertility (Chapter 7).

Degraded soils, and particularly those that are poor in P, exhibit poor *hysteresis* of restoration with applications manure alone (cf. Figures 8 and 9 in Chapter 7) – or low resilience, in the words of Lal (1997). On the other hand, mineral fertilisers alone may produce weak responses when applied to crops in the poorest fields of the farm due to multiple nutrient limitations, to other forms of soil degradation, to lack of water or to poor agronomic management in general (Chapters 5 and 7). When fertiliser N use was optimised at farm scale, the allocation of N favoured the more fertile fields of the farm located close to the homestead, where the efficiency of N capture was higher (Chapter 6). The influence of soil properties on the capacity of building up soil fertility using fertilisers can be seen by comparing the results of this thesis for western Kenya (Chapters 7 and 8) with those of Zingore et al. (2007b) and Tittonell et al. (2007b) on sandy soils in Zimbabwe. Due to the lack of substantial physical protection of soil organic matter in sandy soils, organic matter applications are a must to build soil C stocks (Chivenge et al., 2007).

The use of mineral fertilisers is strongly limited by financial liquidity at the time of planting, rather than by the return to investment in fertiliser (Chapter 6). Each kilogram of fertiliser invested in restoring soil productivity is better used when crop-livestock interactions are more intensively managed (Chapter 8). This implies that the sustainable intensification of farming systems should be designed by combining input intensification with qualitative changes in the configuration or productive structure of the systems (cf. diagrams in Chapter 1, Figure 5 and Chapter 8, Figure 11). In addition to the conclusions of Waithaka et al. (2006), that the *ideal farms* designed by farmers through participatory prototyping in western Kenya do not seem to be economically viable, the necessary shifts of current farming systems towards the ideal prototypes are also hardly feasible in practice. But what that exercise using the farm-scale model NUANCES-FARMSIM illustrated was the need for approaches to systems research and design that consider system-scale processes and their (long-term) impact on livelihoods rather than the effect of single inputs on a particular activity. This requires a move from measuring the 'effect of input X on activity Y' towards assessing the 'impact of process X on system Y'. Continuing to do research on the performance of different technologies without considering their implications and feasibility at the scale, and within the context, of the farming system, is equivalent to being trapped inside the lowest box of Figure 11 in Chapter 8.

Market development and accessibility, as affected by infrastructure and policies represent key incentives for technology adoption (Moll, 2005). However, market policies as single instruments are unlikely to promote development. Ehui and Pender (2003) argued that the downward spiral of declining soil fertility in western Kenya will not be broken by technology promotion, but by improved maize prices relative to input costs. This assumes that the extra income that farmers may get from selling maize at better prices will be reinvested in buying (presumably less expensive) inputs. When dealing with rural families that have a food deficit for most of the year (Chapter 2), or who may aspire to step-out of agriculture, such a market-led hypothesis falls short. Salasya (2005) concluded that maize production is limited by cash liquidity rather than labour, with the implication that the excess labour should be withdrawn and more fertiliser applied – but are these two factors so easily interchangeable?

While many technologies often show discouragingly limited adoption among smallholder farmers in sub-Saharan Africa (Giller et al., 2006), other technologies have found a specific niche within certain farm types and locations, as represented by the widespread adoption of the legume tree *Calliandra* for feeding of dairy cattle by farmers in Central Kenya (e.g. Mutegi, 2004). Examples such as this indicate that interventions to promote the sustainable intensification of smallholder farms need to target specific niches in the systems, which result from the interaction between agroecological conditions, markets and livelihood strategies.

4. Promoting technologies or designing new systems?

Promoting ISFM technologies under the same paradigm by which 'green revolution' technologies have been promoted in the past would most likely lead to failure. A green revolution for Africa must be 'uniquely African', as called for by Kofi Annan, due to the following characteristics of smallholder systems in SSA:

1. Farms are heterogeneous and complex - variability within and between farms may lead to failure of promising technologies in terms of boosting productivity and long-term sustainability. Truly integrated soil fertility management must consider the various components of complex systems; for example, recommendations for use of manure together with fertiliser must be based on realistic rates of application (in line with manure availability at farm scale), nutrient contents (which are often very poor) and labour availability on the farm.

2. Smallholder farms are not all commercially-oriented; rural livelihood strategies are diverse, conditioned by agroecology and markets, and determined by household objectives, resource endowment, and individual preferences of the decision-maker. While some families 'make a living' out of agriculture, many others keep the family land for a number of other reasons (e.g. a 'place to stay', social insurance) and regard agriculture as a secondary (or complementary) activity.
3. Land tenure and demographic processes are closely linked to culture, and vary broadly across sites. The lack of smallholder property rights on their land has led economists to argue[††] that farmers: (i) may lack motivation to invest in improving their soils; and (ii) are not able to access credits to purchase agricultural inputs or reproduce their assets.
4. Many rural families in Africa are below the poverty line and often farm land that is already degraded. To assume that promoting the use of agricultural inputs through price policies or subsidies will automatically boost productivity and improve livelihoods is too simplistic. This is particularly the case when rural families have diverse sources of income and/or the (short- or long-term) aspiration to step out of agriculture.

Effective targeting of ISFM technologies requires recognition of the diversity, heterogeneity and dynamics of the farming systems. Having specific recommendations for each plot of each farm is impractical, and thus it is necessary to categorise patterns of variability and identify possible entry points (cf. Chapters 4, 5 and 7). Ideally, such patterns and opportunities should be recognisable easily by farmers, whose capacity for decision-making is built on their knowledge of the systems they manage and their context. Input-based intensification may not lead to increasing productivity and sustainability of smallholder farming systems, unless qualitative changes in the system are implemented to allow a gradual stepping-up through sustainable intensification (cf. Figure 11 in Chapter 8). Moreover, increasing productivity based on input use, without substantial changes in the system, may lead to abrupt increases in inefficiencies or resource degradation beyond a certain threshold (cf. Figures 6 and 9 in Chapter 6). Far from simply promoting the use of agricultural inputs, an uniquely African 'green *evolution*' should contribute to the design of new systems, promoting improved resource use efficiencies, organisational skills and innovation systems that involve farmers (shared knowledge and learning), and the development of rural markets.

The paradox of African agriculture, however, is that "agricultural development is inhibited at once by overexploitation of the land because of overpopulation, and by poor market development because of underpopulation" – Breman and Debrah (2003). In highly populated areas such as Vihiga, which operate as semi-urban settings where food production on-farm is barely enough to cover three months of the annual household requirement, a sensible alternative to improve rural livelihoods is certainly

[††] This is a highly contentious issue – see Andersson (2007) for a discussion of this issue in relation to smallholder farming in Zimbabwe

to ensure low prices for staple food (e.g. maize) in local markets – note that a large number of farmers bought maize during nine months a year (cf. Figure 5 and Table 6 in Chapter 2). Not far from Vihiga, in Trans-Nzoia district of western Kenya, agricultural schemes started after independence in which families with a vocation for farming were allocated plots of land, ranging from 5 of 100 ha (Kenya Ministry of Agriculture and Rural Development[‡‡], Kitale Office, 2007). A medium-scale, commercial maize production system developed. Today, most of the maize consumed in Kenya (particularly in western Kenya) is produced in such systems. The effective performance of such farming systems depends on their scale, which allows mechanisation and input use while generating employment locally (Okumu, 2000). Thus, 'going commercial' may imply radical changes in the system. Under the current market and policy situation, smallholder farming is just subsistence farming, with only a few households in the community achieving a scale large enough to allow some degree of market orientation.

5. Are there rules on how a system should be represented?

(de Wit, 1968)

Agricultural systems are largely biological systems, complex to understand as a whole. Because of that, subsystems and sub-processes are distinguished and studied (System analysis) with the ultimate objective of interconnecting the resulting knowledge when returning to the farm scale (System synthesis) (Leffelaar, 1999). The system boundaries should be chosen so that the outside world may affect the system, but that the system hardly affects the environment. To minimise the omission of important feedbacks between the system and the outside world it may be necessary to choose boundaries that yield systems 'larger than necessary' with relation to the objectives (de Wit, 1982). An example of the difficulty in defining system boundaries, is the decision as to whether off-farm income should be included as part of the farming (livelihood) system or regarded as an external factor (cf. Figure 1 in Chapters 7 and 8). In either case, it is clear that off-farm income must be considered when trying to understand opportunities for households and for targeting of technologies to different farm types. In terms of the degree of detail to include in the representation of the system, this must be judged in terms of whether increasing complexity in model formulation would sufficiently increase causal insight, and/or whether increasing parameterisation errors would lead to more uncertainty (cf. Figure 5 in Chapter 1).

The simple approach to simulating crop and soil processes in the model FIELD (Chapter 7) proved sufficiently sensitive to capture the effects of soil heterogeneity, response to fertilisers and manures of different quality, and long-term changes in soil

[‡‡] I wish to thank Michael Ochieng' Okumu, from the Kenya Ministry of Agriculture and Rural Development based in Kitale, for his valuable discussion on production systems in Trans-Nzoia district.

fertility. However, by using a seasonal time-step for simulation some important aspects are overlooked with this model. For example, intra-seasonal rainfall variability may lead to dry spells during critical periods that may induce strong negative interactions with crop response to nutrients inputs, for example, during maize flowering, affecting grain set and/or early grain filling, or during crop emergence (particularly under point-placed fertiliser application). In such cases a brief shortage of rainfall will have a strong impact, irrespective of the total seasonal amount of rainfall received by the crop. Simulations of N use by maize in western Kenya using a daily time-step model indicated that when crops are planted late, early rainfall events on bare fields lead to substantial N losses by leaching, and/or soil losses by erosion on the sloping outfields (Tittonell et al., 2006). Such losses account for poor N capture efficiencies, and although soil texture and field slope are key determinants, these losses are caused by management decisions or labour constraints.

The farm-scale model, FARMSIM, used in Chapter 8 of this thesis is currently still being developed. In building up the model, we decided that the integration of modules that represent the different sub-systems of the farm should be done stepwise, first concentrating on biophysical feedbacks within the farm system. What was not achieved in this thesis – but is being developed while writing these lines – was the functional integration of the effect of labour within the system dynamics, and of the financial consequences of different management strategies and farmers' decisions on resource allocation as conditioned by economic performance. Such processes are highly relevant at farm scale, as they may override the effects of biophysical processes. However, their implementation in combination with models of biophysical processes is a great challenge.

The effect of labour constraints was included in Chapter 6 using inverse modelling techniques and correction coefficients in a dynamic crop model as a function of labour availability (cf. Figure 3 in Chapter 6). The functions used were derived from labour calendars and allocation rules discussed with farmers, with a great deal of 'common sense' – or subjectivity – and are not generalisable to other systems, crops or regions. The risk of including such an uncertain variable as labour is that the performance of the entire model at farm scale will depend on the performance of the process that is least understood. We may even risk losing insight in the system. A sensitivity analysis run with FARMSIM (van Wijk et al., 2007) indicates an overriding effect of labour, which may be partly due to the real effect of labour and partly to the choice of correction factors to represent labour in the model.

To analyse the performance of a system or of a certain technology we use several indicators relevant to the system properties under study. Indicators are also approximations, and their value or relevance differs between stakeholders. For formal comparisons across systems, indicators that are often less obvious may yield important information. For instance, a system–level indicator of efficiency could be derived expressing soil fertility as kg of soil nutrients available per family member (e.g., for N, it could be calculated as: Soil N content × Soil depth × Bulk density × Area cropped / Number of family members) (cf. Chapter 8). For instance in Tororo (Chapter 2), soil P availability is often low (2 - 3 mg kg^{-1}) but average farm sizes are large (up to 8 ha). The amount of nutrients available per family member is a pre-requisite to achieving food self sufficiency in low-input systems. Thus a key question is: 'How efficient is the production system (or what is the contribution of a certain technology) to capture and convert those nutrients into food?' Another interesting, emerging indicator is the degree of spread in the 'cloud' of management alternatives when labour and nutrient allocation strategies were analysed at farm scale using inverse modelling (Chapter 6). Under situations less conducive for farming, the spread of feasible strategies was more diffuse and sparser than under more favourable conditions.

Different analysis and explorations were performed by assuming little change in the current structure of the systems analysed, such as assuming a constant degree of some assets (e.g. farm size) or unchanging livelihood strategies over simulation periods of a decade (Chapter 8). However, smallholder farming systems are highly dynamic[§§]. Farming systems were simplified with respect to reality for their analysis (Chapters 6, 7 and 8), in part to reduce uncertainty of less-known processes or poorly-estimated parameters.

6. The 'state of the art'

Although this PhD thesis project started together with the launching of the AfricaNUANCES project in December 2004, I started developing the methodological approach while working on my MSc thesis (Tittonell, 2003). The MSc thesis project was conducted in the framework of a project led by TSBF-CIAT[***], analysing the causes and consequences of farmer-induced soil fertility gradients within smallholder farms, and building on the 'seeds' of the NUANCES approach (Giller and van Keulen, 2001). That work provided early evidence (cf. Chapter 3) relating to the general objective of this thesis, which was to reveal inefficiencies in resource allocation, their origin and consequences (Chapters 4, 5 and 6). The work conducted under the AfricaNUANCES project from 2004 deals with the other part of the main objective: to identify routes towards optimal use of scarce resources, with emphasis on soil fertility improvement (cf. Chapters 7 and 8). The value of the approaches used in this thesis should also be judged in the light of their contribution to methodology development within the NUANCES framework. At the various study sites of the project in Africa,

[§§]To illustrate this, I refer to an anecdote that involves Antonio Castellanos-Navarrete, who conducted his MSc thesis on cattle management strategies in western Kenya. In his weekly visits to the same farms over a season, farmers often gave totally different answers to the same questions and in several cases sold the livestock that was being monitored in his study between one visit and the next.

[***] Tropical Soil Biology and Fertility Institute of the International Centre for Tropical Agriculture

including those that formed part of our analysis (cf. Chapter 2), data are still being collected, analysis performed and systems modelled. This prevented the application of the framework in a comparative analysis across systems of East Africa, as was originally intended in this thesis.

7. ‘Scaling out’: the system, its context and the broader context

A decade ago, Campbell et al. (1997) questioned the feasibility of defining ‘sustainable development’ of peasant farming systems in operational terms, using approaches based on indicators. Sustainability assessments must consider issues related to selecting indicators or diagnostic criteria, setting systems boundaries and spatial-temporal scales. But, even if technical problems associated with the definition and/or estimation of indicators can be solved, accurate biophysical or socioeconomic data will not necessarily advance our knowledge of sustainability. Peasant systems are politically-guided management systems, whose boundaries are the state, not the field or the farm. In most cases, both internal and external interconnections must be considered as integral parts of the farming system – as in the case, for example, of strong rural-urban connectivity (Andersson, 2001).

In the same study referred to above, Campbell et al. (1997) reinforced their argument by stating that “attempts at sustainability assessment 100 years ago or even 20–30 years ago would have been completely superseded by events”. In our case, although the contribution of integrated soil fertility management to increasing food production can be substantial, the context in which farming systems operate should not be overlooked. While it is certain that poor soil fertility is the single main factor explaining the decline in per capita food production in sub-Saharan Africa (Breman and Debrah, 2003), a diversity of other problems affect rural households severely. Contextual processes taking place in Africa include political instability, dysfunctional institutions, volatility of international markets and changes in demand (e.g., the current ‘hunger’ for raw natural resources by fast-developing economies in Asia), increasing human population and risks to human health (malaria, HIV-AIDS), violation of human rights, climate change, and degradation of the natural resource base. Poor soil fertility is not only a major cause of poor crop production, but it can also be seen as a symptom of how these contextual processes constrain farming systems and their ability to nourish rural families in the short and long terms.

But this does not mean that soil fertility research should stop – it must be placed in context. Although the example of adoption of *Calliandra* in Central Kenya referred to earlier indicates that convenient and useful technologies are disseminated among farmers by themselves, more research is needed in identifying mechanisms to ‘scale-out’ ISFM technologies. This is particularly true given that agricultural extension networks have been dismantled in many African countries (Lynam and Omamo, 2005). Scaling-out has been defined as "to efficiently increase the socioeconomic impact from a small to a large scale of coverage" (World Bank, 2003). In the view of Tripp (2006), the lack of precision in the definition of the term is symptomatic of the lack of clarity on how this concept can be implemented. The scaling-out of technologies should be designed considering the key characteristics of farming systems – heterogeneity, diversity and dynamics – seeking ways to categorise such complexity. This thesis attempted to contribute to this goal. While it is certain that contextual processes confine farming systems, that poor market development and infrastructure are a burden to technology adoption, and that issues such as labour availability are key constraints to farm productivity, agriculture still depends centrally on light, water and nutrients.

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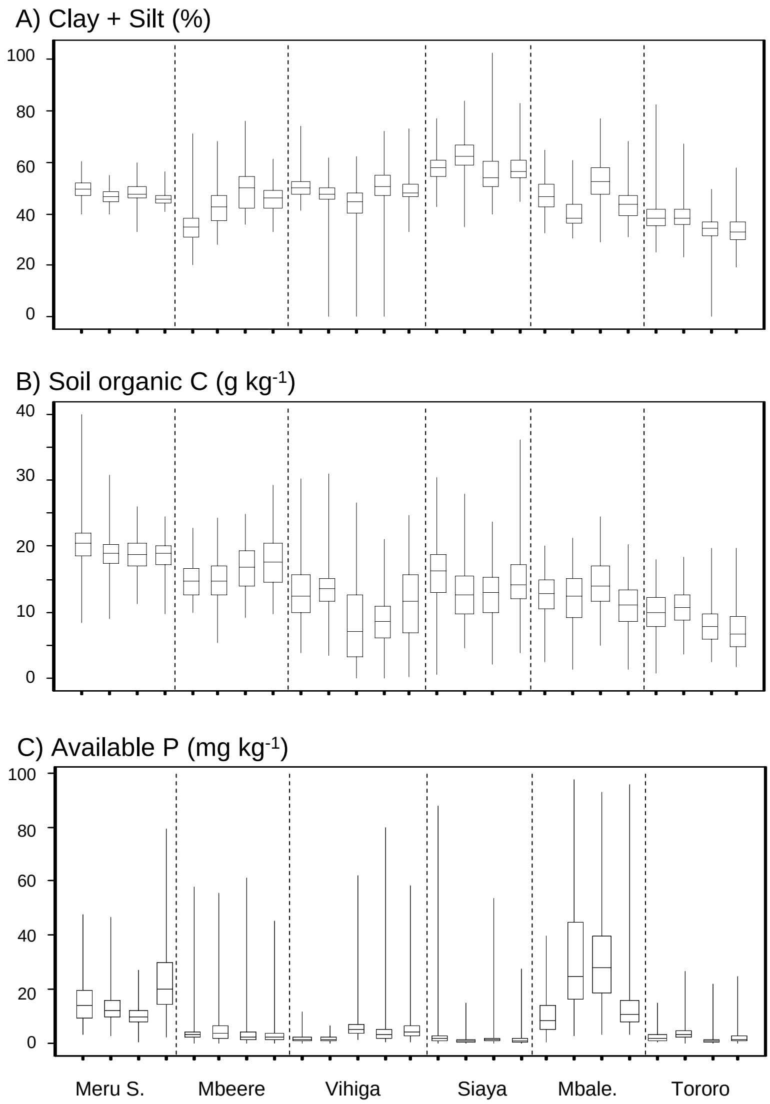
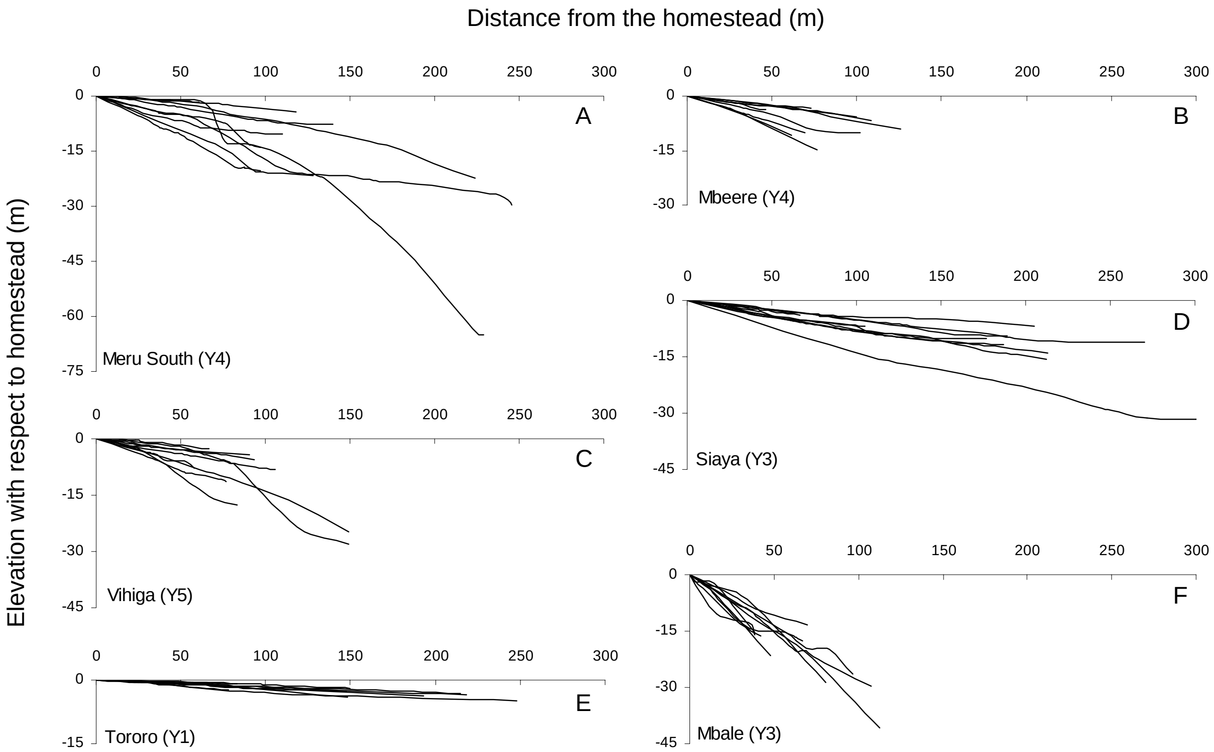
Appendices

Appendix 2.1 – Variability in soil properties across localities for the six sites of the East African highlands characterised in Chapter 2



Part of the overall variability observed in soil texture, organic C and available P could be ascribed to differences between locations (Y-frames) within each site (cf. Chapter 2, Section 3.2.1). Both the inter-quartile range and the differences across locations for clay+silt were the narrowest in Meru South, and the widest in Mbeere and Mbale. In Vihiga, the five locations were rather uniform in terms of soil texture and its variability, with the exception of scattered coarser soils in three of them. The largest variation in soil C between and within locations was observed in Vihiga. Available P was highly variable across and within locations in Meru South and Mbeere, at different locations with respect to Mt. Kenya and Mt. Elgon, respectively. In some cases, differences between locations may result from farms being sampled from slightly different agroecological zones (e.g. 6 different agro-ecozones had been distinguished within Mbale district). Finally, the randomly allocated sampling frames may also comprise variable relative proportions of different landscape units.

Appendix 2.2 – Topographic profiles of farms across East Africa (Chapter 2)



Topographic profiles of 10 farms (a Y-frame) per study site (cf. Chapter 2, Section 3.2.2); the homestead was located in the uppermost position within the farms, and all distances (vertical and horizontal) were plotted with respect to the homestead. The Y-frame shown for Mbale (F) corresponds to the higher parts of the district, with steeper slopes than the rest.

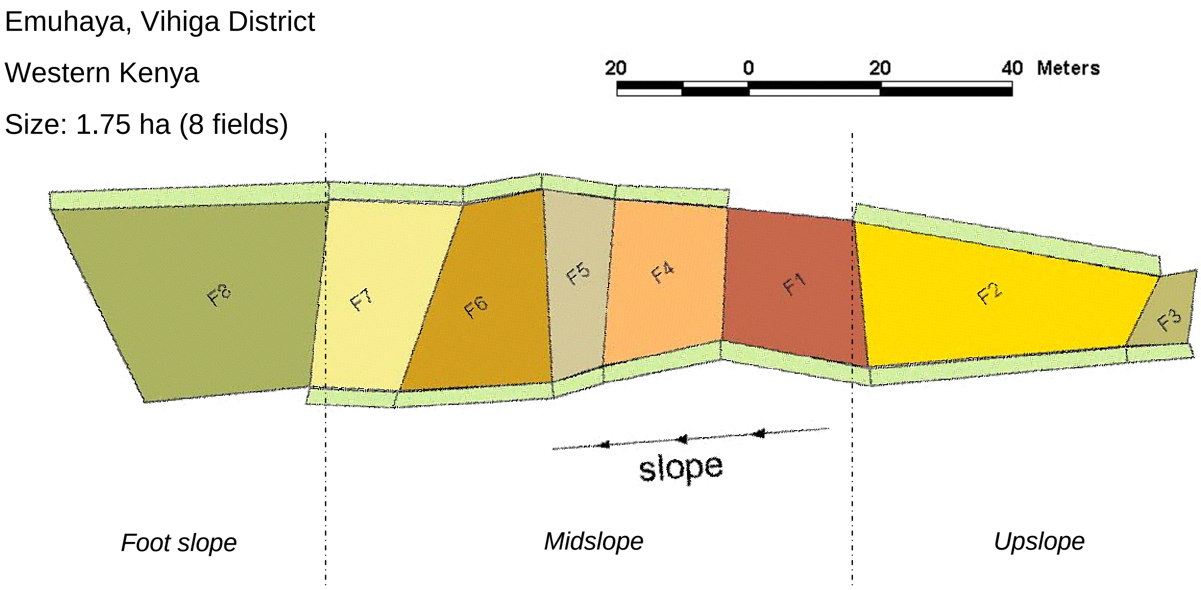
Appendix 2.3 – Variability in soil C, P and K across farm types (Chapter 2)

Weighed average, coefficient of variation and index of amplitude at farm scale for selected indicators of soil fertility status across districts and farm types (the back-transformed data are presented)

District	Farm type	*n*	Soil organic C (g kg^{-1})			Available P (mg kg^{-1})			Extractable K (cmol$_c$ kg^{-1})		
			W.Av.	CV	I_{SOC}	W.Av.	CV	$I_{Av.P}$	W.Av.	CV	$I_{Ex.K}$
Meru S.	1	9	19.5	0.10	0.3	18.6	0.38	1.0	0.58	0.25	0.7
	2	5	18.3	0.11	0.4	13.7	0.47	1.7	0.46	0.29	1.0
	3	8	20.1	0.12	0.4	17.3	0.41	1.5	0.62	0.28	0.8
	4	8	19.3	0.14	0.4	11.8	0.39	1.2	0.51	0.29	0.8
	5	10	18.8	0.14	0.3	18.5	0.40	1.2	0.54	0.39	0.8
	SED		*0.8*	*0.02*	*0.1*	*3.7*	*0.06*	*0.4*	*0.06*	*0.07*	*0.2*
Mbeere	1	11	6.3	0.40	0.6	5.8	0.77	1.1	0.41	0.42	0.6
	2	4	9.3	0.31	0.7	4.9	1.06	1.2	0.49	0.54	0.9
	3	10	7.3	0.41	0.6	4.7	0.71	1.4	0.44	0.45	0.8
	4	10	6.6	0.47	0.7	4.8	0.77	1.1	0.43	0.63	0.8
	5	5	6.3	0.46	0.8	3.4	0.58	0.9	0.54	0.35	0.5
	SED		*1.6*	*0.11*	*0.2*	*2.3*	*0.18*	*0.2*	*0.08*	*0.12*	*0.2*
Vihiga	1	12	13.8	0.27	0.5	4.8	0.98	1.8	0.26	0.58	1.4
	2	5	12.9	0.30	0.7	4.5	0.85	2.9	0.22	0.57	2.0
	3	11	13.9	0.29	0.5	5.2	0.70	1.6	0.27	0.63	1.3
	4	12	12.6	0.33	0.6	3.1	0.59	1.3	0.22	0.56	1.2
	5	10	15.5	0.25	0.5	2.7	0.72	1.4	0.21	0.55	1.2
	SED		*1.2*	*0.05*	*0.1*	*1.3*	*0.17*	*0.5*	*0.03*	*0.12*	*0.4*
Siaya	1	4	15.6	0.27	0.5	1.8	0.87	2.1	0.27	0.75	2.1
	2	5	13.5	0.22	0.7	3.2	0.87	3.4	0.35	0.73	2.2
	3	11	14.8	0.21	0.5	2.2	1.07	1.9	0.34	0.58	1.3
	4	12	14.2	0.25	0.4	4.3	1.16	2.8	0.35	0.64	1.5
	5	8	14.9	0.25	0.5	1.7	0.88	1.4	0.34	0.60	1.1
	SED		*1.2*	*0.05*	*0.2*	*2.4*	*0.39*	*1.1*	*0.09*	*0.21*	*0.6*
Tororo	1	9	9.3	0.27	0.5	3.1	0.62	1.4	0.32	0.40	0.8
	2	8	8.8	0.27	0.6	2.6	0.99	2.7	0.30	0.44	1.2
	3	11	9.7	0.29	0.6	2.6	0.79	1.9	0.31	0.47	1.0
	4	7	9.6	0.29	0.6	2.6	0.71	1.6	0.28	0.39	0.7
	5	5	7.4	0.35	0.5	1.9	0.65	1.2	0.25	0.47	0.7
	SED		*1.3*	*0.05*	*0.2*	*0.9*	*0.18*	*0.5*	*0.06*	*0.06*	*0.2*
Mbale	1	5	15.4	0.20	0.4	31.4	0.59	1.3	0.80	0.53	1.1
	2	6	13.1	0.22	0.3	15.7	0.57	1.3	0.58	0.49	1.0
	3	15	10.8	0.30	0.5	20.9	0.59	1.3	0.53	0.56	1.1
	4	8	12.5	0.20	0.2	32.0	0.51	0.6	0.62	0.56	0.8
	5	6	13.5	0.22	0.3	25.8	0.62	1.0	0.56	0.45	0.7
	SED		*1.3*	*0.05*	*0.1*	*9.3*	*0.15*	*0.3*	*0.12*	*0.13*	*0.3*

W.Av.: weighed average, CV: coefficient of variation, I_X: index of amplitude in the range of the soil indicator X (cf. Section 2.5); SED: Standard error of the difference.

Appendix 2.4 – Variability in soil fertility within a case study farm from Vihiga district, western Kenya



Field code	Land use	Area (ha)	Slope (%)	Clay + Silt (%)	SOC (g kg^{-1})	Total N (g kg^{-1})	Av. P (mg kg^{-1})	Ex. K (cm_+ kg^{-1})	Ex. Ca (cm_+ kg^{-1})	Ex. Mg (cm_+ kg^{-1})	pH water (1:2.5)
F1	MZ/VG/BN/FT	0.056	11	50	14.3	1.1	1.9	0.27	3.6	1.3	5.8
F2	MZ/BS/CP	0.075	4	48	16.0	1.3	3.4	0.34	5.1	1.1	5.8
F3	WDT	0.008	1	49	15.2	1.3	2.6	0.29	4.3	1.6	5.6
F4	MZ/BN/VG	0.036	10	55	11.6	0.9	1.1	0.25	2.7	1.2	5.5
F5	MZ/CV/SP/NG	0.026	12	58	12.6	1.0	0.9	0.27	3.0	1.5	5.4
F6	NG	0.028	22	56	6.9	0.4	0.5	0.22	1.8	1.0	5.2
F7	FLW	0.043	7	54	8.8	0.7	2.9	0.14	0.2	0.2	4.9
F8	WDT	0.112	10	50	8.6	0.7	0.9	0.13	1.9	0.5	4.9

Digital map of a case study farm in Vihiga district, indicating the various fields (F1-F8) and living fences, and land use and soil properties measured at each field. The homestead was located on F1. MZ; maize, VG: vegetable gardens, BN: banana, FT: fruit trees, BS: beans, CP: cowpea, WDT: woodlot, CV: cassava, SP: sweet potato, NG: Napier grass; FLW: fallow

Appendix 2.5 – Farmers' indicators of soil quality across the six sites of the East African highlands characterised in Chapter 2

Visual indicators of soil quality and degradation and their frequency of occurrence in fields classified by farmers according to their perceived fertility (Poor, Medium, Good); distribution of these field types in the landscape

Indicator	Category/ type	Fields per category *n*	Fields per category (%)	Occurrence within SF classes (%) Poor	Medium	Good
Soil erosion	Sheet	340	17	19	18	13
	Rill	431	22	29	20	13
	Mass	16	1	1	1	1
Hard settings	Temporary	227	92	13	11	9
	Permanent	19	8	1	1	2
Stoniness	0 – 5%	1855	93	93	94	94
	5 – 25%	72	4	3	4	4
	25 – 50%	39	2	2	2	2
	50 – 75%	12	1	1	1	0
	> 75%	10	1	1	0	0
Slope class	0 – 5%	919	46	37	49	55
	5 – 10%	442	22	22	22	22
	10 – 20%	317	16	16	16	15
	20 – 40%	247	12	18	11	7
	> 40%	63	3	6	2	1
Landscape	Upslope	371	19	12	17	33
	Midslope	1423	72	77	74	58
	Footslope	158	8	10	8	5
	Bottomland	36	2	1	1	3
Flooding (occasional/regular)		60	3	3	2	5
Total number of fields per farmers' soil fertility class:				646	934	408

Appendix 7.1 – Brief description of basic soil and crop processes as simulated in FIELD†

Soil organic matter dynamics

Three organic C pools are considered in the model: (1) a pool of added C in crop residues and other organic amendments (e.g. manure), (2) a pool of active soil organic C, or decomposing organic matter pool (N.B. not synonymous with the microbial biomass), and (3) a pool of humified soil organic C (Figure 1). The active pool represents the 'unprotected' organic matter; on seasonal time steps it can be assumed that the microbial biomass is in a steady-state, so we considered it as an implicit part of the active pool. The humified soil C pool represents the older physically and chemically stabilised organic matter. We assumed that all pools decompose following first-order kinetics. For each pool, there is a specific decomposition rate (k_R, k_A and k_S) and a stabilisation fraction (e_A, e_H and e_S, for the residue, active and humified C pools, respectively) or partitioning coefficient (1 – CO_2-C release). The coefficient e_A represents the growth efficiency of the microbial biomass, i.e. the fraction of the residue C pool that is incorporated into the active pool; e_H is the humification coefficient, i.e. the fraction of the decomposed C from the active pool that enters the humified pool; and e_S represents the physical stabilisation of C in the soil (the turnover rate k_S is affected by soil texture). Thus our approach follows the conceptual model of soil organic matter stabilisation of Six et al. (2002). A fraction of soil C is considered inert, and a certain amount is seasonally lost by soil erosion (calculated in a soil erosion module). The C:N ratios of the different pools are introduced as model parameters. Other quality aspects of the soil amendments such as lignin and polyphenol contents (Palm et al., 2001) are considered to calculate specific potential decomposition rates.

Without considering erosion losses, and assuming that the value of the fraction inert is zero, the amount of C in the humified soil C pool (C_S, in kg ha^{-1}) is calculated as:

$$C_S = C_{S(0)} + dC_S/dt \times t \qquad \text{Eqn. 1}$$

Where, $C_{S(0)}$ is the initial amount of humified soil C, and t is the time in years. The rate of change of soil C (dC_S/dt, in kg ha^{-1} year^{-1}) is defined as:

$$dC_S/dt = C_A \times k_A \times e_A - C_S \times k_S + C_S \times k_S \times e_S \qquad \text{Eqn. 2}$$

C_A (kg ha^{-1}) is the amount of C in the active pool; the rates k_R, k_A and k_S expressed in year^{-1}. Both k_S and e_S may be integrated in one single rate as:

$$dC_S/dt = C_A \times k_A \times e_H - k'_S \times C_S \qquad \text{Eqn. 3}$$

† Extracted from: Tittonell et al., 2007b.

Where k'_S represents: $(1 - e_S) \times k_S$. This parameter was fitted to experimental data on long-term changes in soil C, as explained later. The loss of C by water erosion (E_i, kg C ha^{-1}) is estimated in relation to soil loss (As, kg soil ha^{-1}):

$$E_i = [C_i] \times As \times Er_i \qquad \text{Eqn. 4}$$

where $[C_i]$ is the concentration of organic C in the soil pool i and Er_i is enrichment ratio of eroded soil (Van Keulen, 1995). Soil loss is calculated according to the Universal Soil Loss Equation (USLE), adapted to tropical conditions (Roose, 1983).

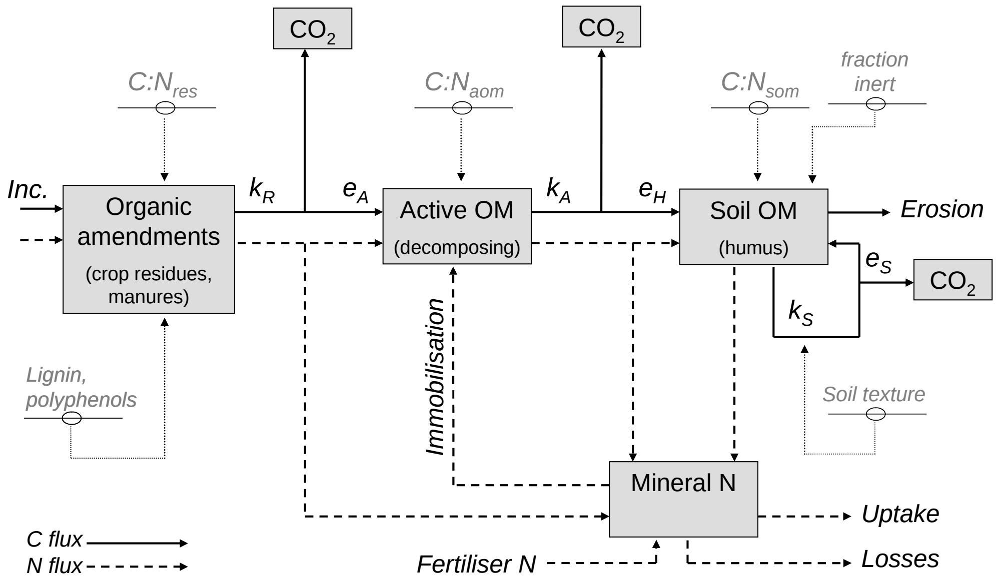


Figure 1: Schematic representation of the soil C and N module of FIELD

Soil N and P supply

Nitrogen mineralisation follows C decomposition, considering the C:N ratios of the different C pools. The C/N ratio of the active OM ($C{:}N_{AOM}$ ~ 8) determines the magnitude of the immobilisation flow from mineral soil N. The net rate of change of mineral nitrogen in the soil is calculated from the differences between the following influxes and effluxes:

$$dN_{min}/dt = NetN_{min} + N_{fert} - N_{upt} - N_{lost} \qquad \text{Eqn. 5}$$

Where, $NetN_{min}$ [kg ha^{-1} $season^{-1}$] is the rate of net N mineralization from decomposing organic matter, i.e. the difference between gross N mineralisation and mineral N immobilisation. N_{fert} is the rate of added N in mineral fertilisers, N_{upt} the rate of N uptake by crops and N_{lost} is the fraction of total soil mineral N lost by denitrification, volatilisation and leaching. The amount of mineral N available in the soil is partitioned between crop uptake, N immobilisation by microbes and N losses by different processes. This partitioning determines the priority for N allocation to the different processes. In models for high-input farming situations, losses and immobilisation are first discounted, and then the remaining N is assumed to be taken up by the crop (e.g. Wolf et al., 1989). Under low-input conditions, plant N uptake or immobilisation may have priority over leaching (Chikowo et al., 2004).

The potential availability of P from organic sources is treated in a similar way to N, using C:P ratios, particularly for P released from organic amendments and from the decomposing organic material or active OM ($C:P_{AOM} \sim 40$). For inorganic P a simplistic approach is used, in view of the limited knowledge on the transfer rates between stable and labile P pools in the soil, the occurrence of P sorption in tropical soils and the mismatch between labile P and extractable P observed in several studies (Keating et al., 2003). Total soil P is the sum of the organic and inorganic P pools in the soil, and in the model it constitutes a state variable used to keep track of soil P balances in the long-term. A fraction of the total soil P becomes potentially available, and this corresponds to the amount of available P measured using Olsen extractions (a method widely used for tropical soils – Anderson and Ingram, 1993). The ratio total-to-extractable P (i.e. a proxy to the ratio total-to-available P) has been derived from experimental data for a number of case studies encompassing tropical soils with clay contents ranging between 12 and 44%; this empirical relationship varies for soils of different texture and predicts Olsen-P values satisfactorily ($r^2 > 0.6$) for Acrisols and Nitisols of western Kenya with organic C > 8 g kg^{-1} in the topsoil (Tittonell et al., 2006). Similar approaches proved satisfactory for modelling maize response to P in Zimbabwean soils (A. Whitbread, pers. comm.). However, when not enough data is available or when soils out of the tested range are studied, and particularly when the model is used to simulate crop responses to nutrient applications without considering long-term dynamics, the empirical equation developed by Janssen et al. (1990) can be used, which estimates potential soil P supply as a function of (measured) average soil C, extractable P and pH.

Crop dry matter production and grain yield

Resource-limited total dry matter and grain production are calculated in FIELD on the basis of seasonal resource (light, water, nutrients) availabilities through application of crop-specific resource use efficiencies, which are derived from literature, experimental data and/or process-based modelling work. For each resource, use efficiencies are disaggregated into resource capture and conversion efficiencies. From the total amount of incident photosynthetically active radiation (PAR) during the season only a fraction is captured (intercepted) by the crop, and this is converted into biomass through a light conversion efficiency coefficient. Actual crop production in FIELD is calculated as the minimum of water-limited production and production determined by the availability of nitrogen or phosphorus. Seasonal crop available water is simply derived by considering seasonal rainfall and potential evapotranspiration corrected by soil type and surface conditions, and the crop water-limited production is calculated using a water use efficiency coefficient. Nutrient-use efficiencies determine nutrient-limited crop production. For a given resource A (representing N or P in this case), the A-limited yield (ALY, in kg DM ha^{-1}) is calculated as:

$$ALY = A_{availability} \times A_{capture\ efficiency} \times A_{conversion\ efficiency} \qquad \text{Eqn. 5}$$

Where, $A_{availability}$ (kg A ha^{-1}) represents the potential soil supply of A (from the soil plus that becoming available from applied organic and mineral fertilisers). Nutrient captures are represented by the recovery efficiencies (kg A available kg^{-1} A taken-up), which depend strongly on the nutrient considered, soil properties, crop type and management decisions (e.g. type of nutrient resource used, application rate, method, timing, etc.). Nutrient conversion efficiencies (kg DM kg^{-1} A taken-up) are the inverse of the weighted-average nutrient concentrations in grain, straw and roots, and range between crop-specific minimum and maximum values. When a second resource B is simultaneously considered, its conversion efficiency is affected by availability of resource A through a correction factor. The correction factor for $B_{conversion\ efficiency}$ is calculated by relating $A_{availability}$ to a target value for resource A, which is derived from the water-limited production level times the weighted-average nutrient concentrations in the crop:

$$BLY = B_{availability} \times B_{capture\ efficiency} \times B_{conversion\ efficiency} \times CF_{B/A} \qquad \text{Eqn. 6}$$

Where, $CF_{B/A}$ (with values between 0 and 1) is the correction factor for conversion of resource B when resource A is sub-optimally available, calculated as:

$$CF_{B/A} = A_{availability} / (WLY / A_{conversion\ efficiency}) \qquad \text{Eqn. 7}$$

Where, WLY stands for water-limited yield (see Appendix 7.2 for more details). Since the use efficiency of a certain resource (e.g. N) is affected by correction factors calculated on the basis of the availabilities of complementary resources (P, water), the approach to the simulation of resource interactions follows Liebscher's 'Law of the Optimum'; i.e. as availability of resource A becomes restricted and sub-optimal, the slope of the response to resource B may become less steep before resource A becomes completely limiting for plant growth. Total crop biomass is partitioned between grain, stover and root production through application of crop-specific harvest indexes and shoot to root ratios. The concentration of N and P in the crop products is derived from the yield and the uptake of both elements. The nutrient that is limiting is diluted to its minimum value, while the concentrations of other nutrients are derived from uptake and total dry matter yield.

Appendix 7.2 – Resource interactions as implemented in FIELD

Resource use efficiency

The utilization of biophysical resources by crops in FIELD is simulated using the general expression: *Crop production = resource availability × resource capture × resource conversion.* The product resource capture × resource conversion is the overall resource use efficiency, as defined by Trenbath (1986). Resource availabilities and efficiencies are calculated for (integrated over) a seasonal time step. This approach is used for the calculation of light-determined and water- or nutrient-limited yields (NLY, PLY and KLY for nitrogen-, phosphorus- and potassium-limited yields, respectively). However, resources interact in determining crop production and thus, particularly for nutrients, such interactions must be considered. In FIELD, light-determined and water-limited yields (LDY and WLY, respectively) are first calculated. The minimum of these is used as reference, 'ceiling' yield for calculation of nutrient-limited yields that are interdependent among each other, as explained in the following sub-sections. In all cases, yields refer to total aboveground biomass production, in kg DM ha^{-1}, and partitioning coefficients are later applied in FIELD to calculate production of different crop parts.

The term 'potential' yield or crop production level is often used as a synonym of light-determined yields (de Wit, 1992). Maximum crop production is achieved when water and nutrient limitations are not present, and when the product of radiation use efficiency times length of growing period is maximized. The latter depends on temperature and on genotypic characteristics of the crop cultivar considered (e.g. thermal sum from emergence to flowering in maize). Thus, even when water and nutrients are amply available, potential yields are only achieved when the proper cultivar for the location considered is planted on its optimum planting date and using optimum plant population densities. Since in smallholder farming systems these conditions are likely to be affected by management decisions and labour availability, light-determined yields are not necessarily always potential; e.g. an irrigated and well fertilised crop growing on a deep, fertile soil with good drainage would not reach its potential production level if it was planted late.

Light determined yield

Crop production determined by the amount of incident photosynthetically active radiation (PAR) captured by a crop canopy over a season is calculated as:

$$LDY = PAR \times FRINT \times LCvE_t \qquad \text{Eqn. 1}$$

Where, LDY is the light-determined yield level (kg DM ha-1), FRINT is the fraction of PAR that is intercepted or captured by the crop, and $LCvE_t$ is the light conversion efficiency (the sub-index 't' stands for theoretical), the amount of biomass produced per MJ of PAR intercepted by the crop integrated over a season. The product FRINT ×

$LCvE_t$ represents the overall use efficiency of the incident PAR over a season. It must be noticed that the value of the coefficient for light conversion into biomass (often appearing in literature as the radiation or light use efficiency, LUE) may also be affected by environmental crop growing conditions. LUE values from experiments are often reported as affected by other crop growth factors (e.g. LUE as a function of vapour pressure deficit - Kiniry et al., 1998), and a less number of studies gives LUE estimates for potential growing conditions. For African crops in particular, LUE values are often reported as measured in field experiments, where they are affected by environmental conditions and/or experimental treatments. In the exploratory simulations presented later in this paper the value of PAR use efficiency varying for different growing conditions was calculated as FRINT × PAR conversion; the conversion coefficient of PAR differs from the theoretical value of $LCvE_t$ in Equation 1, as it was affected in this case by planting dates, water and N availability.

Water-limited yield (WLY)

When enough soil physical data are available to perform a water balance, a 'seasonal' value of potential water availability (mm season-1) may be calculated and thus WLY would be equal to the product of seasonal water available times some coefficient representing water use efficiency integrated over the season (in kg DM ha-1 mm-1). However, for a seasonal time step the gain in accuracy by calculating water balances is not expected to be high, as the water status in the soil depends on the presence of a crop. For the degree of detail we pursue in developing farm-scale models, the following expression can be used:

$$WLY = Rainfall \times FRCAP \times TCvE \qquad \text{Eqn. 2}$$

Where, FRCAP is the fraction of rainfall captured, i.e. the amount of water transpired by the crop over the rainfall during the period from planting to harvest (thus, a late emerging crop will have a smaller FRCAP value); TCvE is the transpiration conversion efficiency ((kg DM ha-1 mm-1), the amount of biomass produced per mm of water transpired by the crop canopy integrated over the period considered. The product FRCAP × TCvE represents the overall, seasonal rainfall use efficiency by the crop.

Nutrient-limited yields

The calculation of nutrient-limited yields in FIELD is illustrated for N, since the same approach is taken for P and K, starting from the general expression:

$$NLY = N\ availability \times NCtE \times NCvE \qquad \text{Eqn. 3}$$

Where, NCtE is the capture efficiency of the mineral N available to the crop during the entire growing season, calculated as N uptake / N availability (soil + fertiliser), and

NCvE (kg DM kg-1 N) is the conversion of N taken up by the crop into crop biomass, or the inverse of the average N concentration in the plant.

N uptake is taken as the minimum between N supply and a target N uptake, so that when N limits crop production N uptake approaches N supply and the value of NCtE approaches 1. N supply is calculated as the sum of net N mineralization (= gross mineralization - immobilization) from the soil pools and organic materials applied to the soil (crop residues, manure), minus N leaching and gaseous losses. The target N uptake is calculated using the following expression:

$$NUPT_{target} = Min\ (LDY, WLY) / [(NCVE_{max} + NCVE_{min}) \times \alpha] \qquad \text{Eqn. 4}$$

Thus the minimum between LDY and WLY is divided by a value in between the maximum and the minimum N conversion efficiencies (i.e. the average NCvE when $\alpha = 0.5$, as it is often the case for most crops) to calculate the target crop N demand. Crops growing under non limited conditions dilute N to its physiological minimum in the plant tissues (i.e. the production of biomass per unit N taken up is maximized), while the opposite happens under grow limitation (i.e. N will be concentrated in plant tissues when light, water, P or K are limiting). Thus, $NCvE_{max}$ corresponds to the physiological minimum N concentration in the plant and vice versa.
The coefficient of conversion of N taken up into crop biomass, NCvE in Equation 3, is calculated as the maximum value between $NCVE_{min}$, the minimum conversion efficiency physiologically sensible, and the value of $NCVE_{max}$ corrected by the availability of water, P and K, as follows:

$$NCvE = Max\ (NCVE_{min},\ NCVE_{max} \times WRF \times PRF \times KRF) \qquad \text{Eqn. 4}$$

Where, WRF, PRF and KRF are the reduction factors accounting for the availability of water, P and K, calculated as:

$$WRF = (\text{Water availability} / WTRA_{target}) \times \beta_W \qquad \text{Eqn. 5}$$
$$PRF = (\text{P availability} / PUPT_{target}) \times \beta_P \qquad \text{Eqn. 6}$$
$$KRF = (\text{K availability} / KUPT_{target}) \times \beta_K \qquad \text{Eqn. 7}$$

Where, $WTRA_{target}$, $PUPT_{target}$ and $KUPT_{target}$ are the target seasonal water transpiration, target crop P and K uptakes, respectively, and β_W, β_P and β_K are weighing coefficients to control the interactions. WRF, PRF and KRF take values between 0 and 1. When enough data is available to parameterize the nutrient capacity and intensity soil pools of FIELD, the seasonal availability of P and K is calculated by the model; otherwise, empirical functions estimating soil P and K supply from soil analytical data (Soil organic C, Extactable P, Exchangeable K, pH) as implemented in the model QUEFTS (Janssen et al., 1990) are used. Target crop P and K demands are calculated in the same way as explained earlier for target crop N demand. Target water transpiration is calculated from light-determined yields and water use (capture × conversion) efficiency. An N reduction factor (NRF) is also calculated taking the same approach, and used in the calculations of P and K conversion efficiencies (PCvE and KCvE, respectively).

Finally, the Resource-limited yield is taken as the minimum between NLY, PLY and KLY, and crop- (and cultivar-) specific biomass partitioning coefficients are used to calculate the yield of different plant organs. Note that at this stage the interaction between crop resources has already taken place at different stages. For example, if a crop is planted late or with a sparse population density - below its compensation capacity, the light determined yield will be low and therefore the target water, N, P and K uptakes will also be lowered, reducing the severity of the reduction factors and the actual resource uptake rates. However, although this way of modeling resource interactions may make mathematical sense, it does not necessarily make sense in terms of crop physiology. Different crops produce and store different proportions of constituents of different nature (e.g. different types of amino acids are stored by legumes and cereals), show preferential uptake of certain nutrients (e.g. crops producing turgescent fruits take up larger amounts of K) or have different mechanisms to cope with draught or competition involving changes in their nutrient concentrations. Therefore, the coefficients β_W, β_N, β_P and β_K, taking values between 0 and 1, may be used to 'tune' the intensity of the interactions between resources; i.e., for a certain crop, the magnitude of the effect of K limitation on N conversion efficiency is not necessarily as strong as that of P limitation. Nevertheless, in most of the examples for which FIELD was parameterized and tested to date, satisfactory predictions of crop production were obtained keeping the value of these coefficients = 1.

Appendix 7.3 - Estimating soil K supply in FIELD for depleted soils from the Kenya highlands

Problems simulating K supply in depleted soils

K supply to crops in FIELD is estimated using the functions derived by Janssen et al. (1990) for the model QUEFTS:

$SK = (fK * 400 * \text{exch. K}) / (2 + 0.9 * SOC)$(Eq. 1)

Where, SK is the seasonal amount of K (kg ha^{-1}) potentially available for the crop, exch. K is the content of exchangeable K measured in the soil (in $mmol_{(+)}$ kg^{-1}) and SOC is the content of soil organic C (in g kg^{-1}). *f*K is a correction factor for pH, calculated as:

$fK = 0.625 * (3.4 – 0.4 * pH)$(Eq. 2)

K supply is positively related of the degree of K saturation of the cation exchange capacity of the soil, and therefore negatively related to the latter. Consequently, *f*K is a negative function of pH. Since SOC contributes to increasing the cation exchange capacity, K supply is inversely proportional to SOC (Eq. 1).

Such and inverse relationship between SOC and K supply poses a problem for simulating long term changes in soil fertility and K availability to crops in FIELD. When soils are cropped for long periods of time without C and nutrient inputs and with continuous removal of crop residues from the field, their content of organic C tends to decrease. As a consequence, when K supply is calculated using Eq. 1 its value tends to increase over time, because it is inversely related to SOC. However, symptoms of K deficiency in maize crops and/or responses to fertilizer K applications are often – although not generally – seen in depleted outfields of western Kenya (Vanlauwe et al., 2006), particularly in soils that are also poor in SOC. When crop production is mostly limited by K, as often is the case for tuber crops or bananas, the model simulates increasing crop yields over time due to this ‘artificially’ increased supply of K. For these reasons, a modification of the procedure to estimate K supply for highly depleted soils (such as those of western Kenya) that allows also simulation of long term effects was introduced in FIELD as derived from empirical data.

While the concept behind Eq. 1 remains valid for a wide range of soil types in the tropics, its predictive validity might probably be less for highly depleted soils. Figure 1 A shows iso-lines for the relationship between K supply and SOC for soils with different level of exchangeable K, as calculated with Eq. 1, as presented in Janssen (1995). The dotted arrow in Figure 1 A schematically indicates the range of SOC for 160 soil samples from home- and outfields in western Kenya; the average content of exchangeable K for these samples was 3.48 +/-3.46 (0.5 – 21.7) mmol kg^{-1}. Clearly, most soil samples fall around the lower end of the range of model validity, according to the data from which Eq. 1 was developed. Figure 1 B shows the relationship between values of K saturation calculated from measured values of exchangeable K and the effective cation exchange capacity corresponding to the 160 samples, and K supply estimated for these samples with Eq. 1.

For most samples, the saturation of the cation exchange capacity with K was below 10% (Figure 1 B). K saturation decreased only slightly with increasing SOC, being poorly described by the following relationship: *K saturation = 0.0768 - 0.0018*SOC* ($r^2 = 0.038$), contrasting with the model of Figure 1 A. Additionally, in Eq. 1 K supply is proportional to soil pH, and the analysis of the empirical data show a trend towards lower pH values for soils with lower SOC (Figure 2 A), counterbalancing the net effect of the latter on SK.

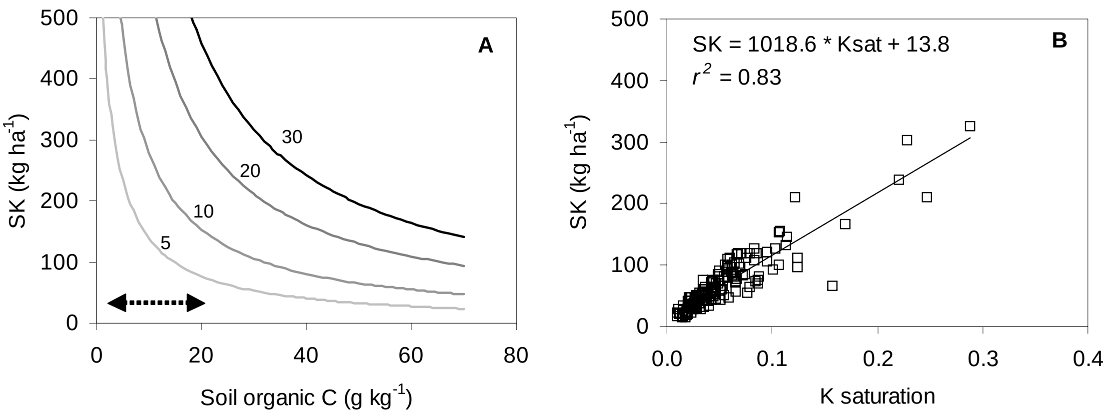


Figure 1: (**A**) Calculation of soil K supply (SK) as a function of soil organic C for different levels of exchangeable K in the soil (5, 10, 20 and 30 $mmol_{(+)}$ kg^{-1}) using Eq. 1, assuming an average soil pH of 6.44 (*f*K = 0.6875). (B) Calculation of soil K supply (SK) with the exchangeable K, soil C and pH data from 160 soils in western Kenya plotted as a function of K saturation (%) calculated for the same samples. The dotted arrow in A indicates the range of soil organic C in the 160 samples. The average value of exchangeable K for this sample set was 3.5 +/-3.5 $mmol_{(+)}$ kg^{-1}.

The modification introduced

In the modified procedure to estimate K supply implemented in the model FIELD, the observed relationship between K saturation and K supply was derived from the empirical data in Figure 1 B:

SK' = 1018.6 * *Ksat* + 13.8 (Eq. 3)

Where *SK'* is the new estimate for soil K supply (in kg ha^{-1}), and *Ksat* is the fraction of the effective cation exchange capacity saturated with K (= exchangeable K / ECEC). This formulation implies that in long term simulations FIELD must keep track of exchangeable K and ECEC over time to be able to calculate K saturation and estimate

K supply. An empirical relationship was derived from this dataset to estimate ECEC as a function of soil C (Figure 2 B). Although, the value of ECEC does not depend only on SOC but also on the soil clay fraction and the type of clay, within the range of soils sampled (dominated by kaolinite clays of poor exchange capacity) SOC contents were closely associated to soil texture (Figure 2 C) and the addition of clay content as an extra term in a regression model resulted non-significant (Table 1).

Table 1: Estimation of the effective cation exchange capacity of the soil using SOC and clay content as explanatory variables

Parameter	Estimate	Square error	$T_{(n = 154)}$	Significance
Constant	-1.022	0.504	-2.03	0.044
SOC (g kg^{-1})	0.5451	0.0409	13.32	<.001
Clay (%)	0.0160	0.0200	0.80	0.426

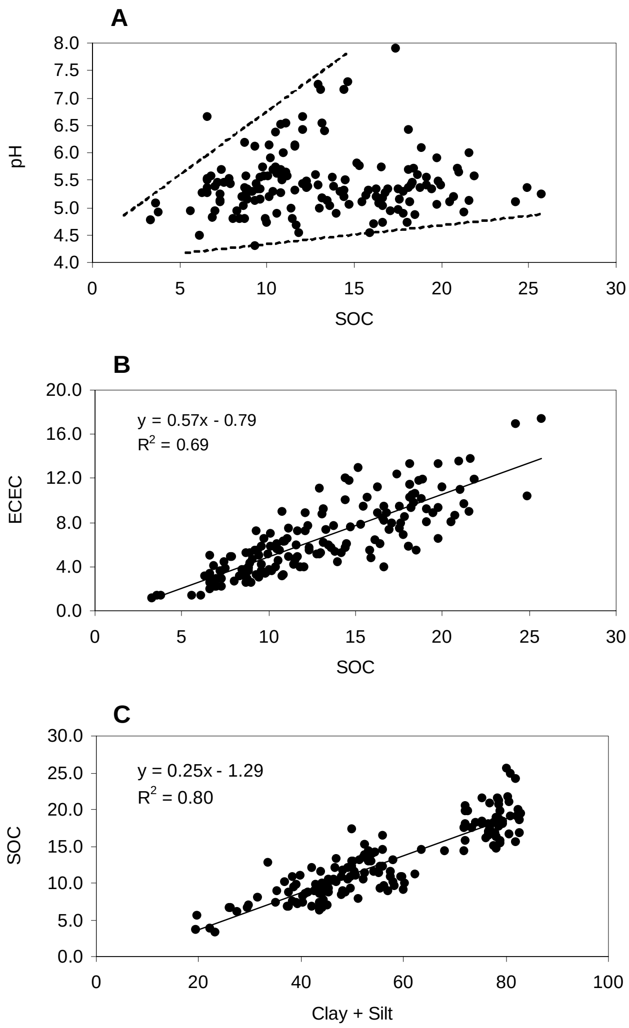


Figure 2: Relationships between measured soil fertility indicators for 160 soils in western Kenya: (A) topsoil pH (water 1:2.5) vs. soil organic C (SOC, in g kg^{-1}); (B) effective cation exchange capacity (ECEC, in cmol(+)kg^{-1}) vs. soil organic C (SOC, in g kg^{-1}); (C) soil organic C (SOC, in g kg^{-1}) vs. Clay plus silt content (%).

FIELD was able to satisfactorily simulate long term changes in SOC for Zimbabwean soils with clay contents ranging between 3 and 35%, and thus having the value of ECEC linked to SOC allows also the estimation of long term changes in ECEC.

To keep track of long term changes in exchangeable K contents, the model assumes a state variable representing a potential amount of exchangeable K available to the crop ($EXCK_{available}$, in kg ha^{-1}), which value changes in time according to the seasonal rate of change $dEXCK_{available}$ (in kg ha^{-1} $season^{-1}$), calculated as:

$dEXCK_{available} = - K_{uptake} + K_{applied} + K_{weathering}$ (Eq. 4)

Where, $K_{applied}$ represents the total amount of K applied seasonally in mineral and organic fertilizers (including ashes), while $K_{weathering}$ is calculated assuming an annual amount of K becoming available from the mineral soil pools, which may range between e.g. 7 and 13 kg ha^{-1} $year^{-1}$ for tropical Ferralsols of Brazil (Cardoso, 2001). This rate can be calibrated against long term data when available, considering also that plant roots can promote K release from mineral soil pools when K levels approach deficiency (B. Janssen, pers. comm.). The state variable $EXCK_{available}$ is initialized in the model from measured soil data on exchangeable K, converting the usual unit $cmol_{(+)}$ kg^{-1} into kg ha^{-1} (1 mol = 39 g), and assuming that a fraction of it remains unavailable to the crop. For their model on K cycling in tropical forests, Noij et al. (1993) assumed that fraction to represent 0.07 $mmol_{(+)}$ of exchangeable K per kg of soil, remaining adsorbed to the soil surfaces and not available to plants.

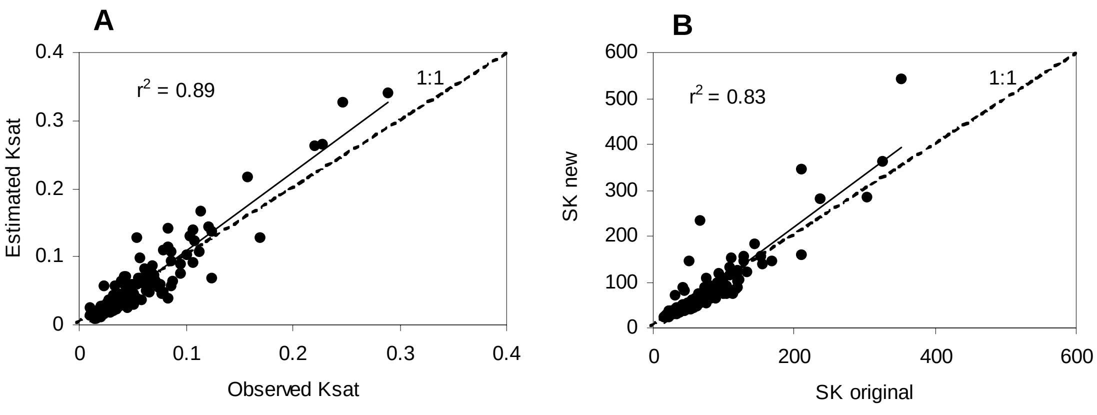


Figure 3: (A) Observed vs. estimated K saturation for 160 soil samples from western Kenya, and (B) agreement between both ways of calculating soil K supply (original: as in Eq. 1; new: as in Eq. 3) for the same sample set.

Finally, Figure 3 shows the agreement between estimated and observed K saturation and between the both ways of calculation soil K supply. Thus, with this new procedure the positive relationship between K saturation and K availability to crops – the basic concept of QUEFTS – is maintained, but no ‘artificial’ increase in K supply occurs when long term simulations indicate C losses from the soil, as is often the case in smallholder systems.

Appendix 8.1 – Brief description of the farm-scale model NUANCES-FARMSIM[‡]

General approach

The basic approach used in the NUANCES-FARMSIM model follows the Wageningen school of agro-ecological modelling in its use of the hierarchy in growth and production factors and its use of the determination of efficiencies to define production levels (Van Ittersum et al. 2003). The concepts of potential, attainable and actual production situations for cropping and livestock systems are illustrated in Figure 1, showing the various yield defining, yield limiting and yield reducing factors affecting both crop and animal production. The limiting and reducing factors are the entry point of interactions between socio-economic factors like labour availability and allocation and their effects on crop and livestock productivity. This will be explained later in the section 'Interactions between modules'.

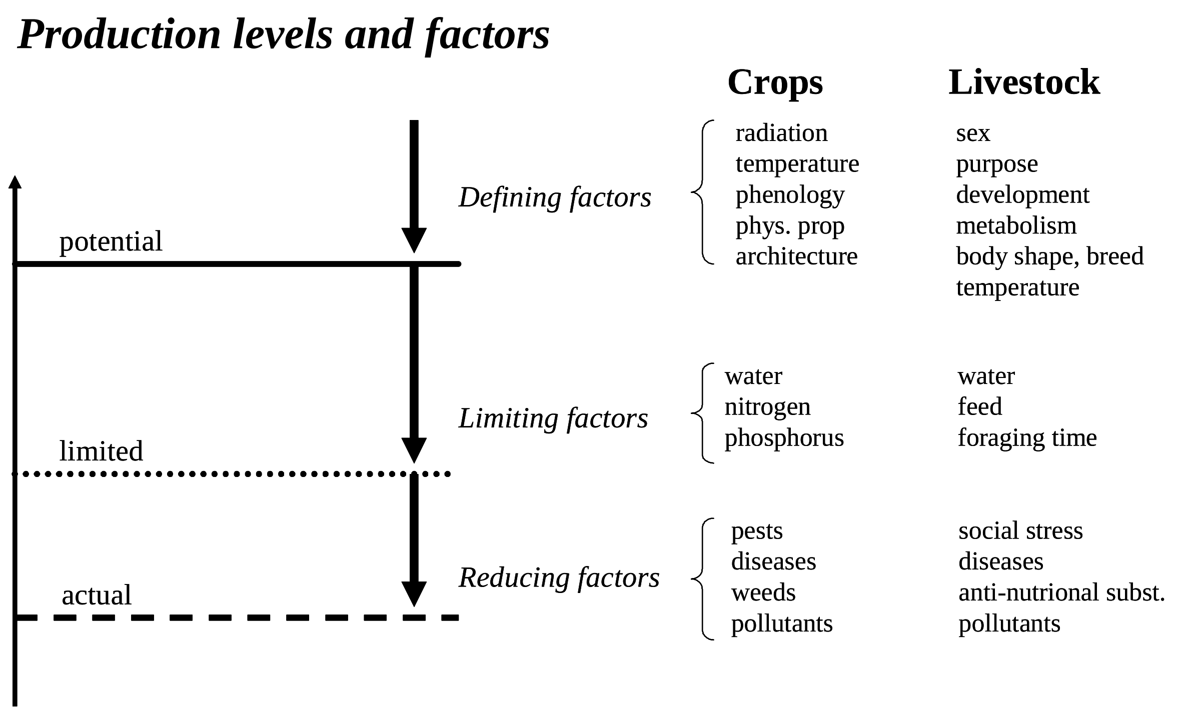


Figure 1: Concepts in production ecology for analysis and design of animal and plant-animal production system (Van Ittersum et al, 2003)

Overview of the modules

The following components of the farm (see Figure 2A and B) are or will be dynamically simulated in a separate sub-module (between parentheses the name of the model):

Crop and Soil (included in 'NUANCES-FIELD'; Field-scale resource Interactions, use Efficiencies and Long-term soil fertility Development; Titttonell et al. 2007b)

‡ Extracted from: Van Wijk, et al., 2007

Livestock ('NUANCES-LIVSIM'; LIVestock SIMulator)
Manure handling and storage ('NUANCES-HEAPSIM'; Heap SIMulator)
Labour availability ('NUANCES-LABOURSIM'; Labour Simulator)

FIELD, LIVSIM and HEAPSIM have been described in previous studies (Tittonell et al. 2007b; Rufino et al. 2007a,b) and will only be characterized briefly. The coupling between the modules, the flow of organic matter and nutrients between the modules, LABOURSIM and the way decision making is dealt with in the model will be described in detail in this manuscript.

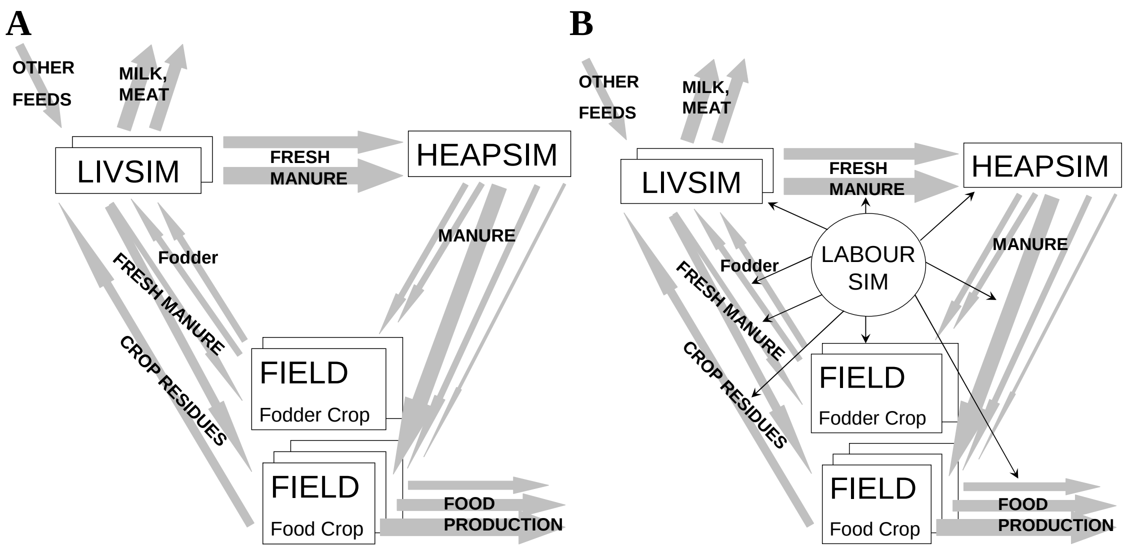


Figure 2: FARMSIM modules together with their interactions, with A) only showing the most important biophysical interactions and B) also showing the interactions with LABOURSIM when labour is a limiting resource

NUANCES-FIELD

FIELD uses a simple, seasonal approach to simulate i) water and macronutrient dynamics in the soil and supply to crops, ii) to calculate crop yields and iii) to monitor indicators of resource degradation, such as soil organic matter dynamics and soil erosion. The FIELD module can be parameterised easily for a variety of crops and soil types. Different combinations of crops and soils can be simulated to explore the interactions occurring within the farm for different field types (e.g. infields and outfields, annual and perennial crops, etc.). The most important state variables that are followed in time are linked to soil fertility: organic carbon, nitrogen, phosphorus and potassium. Per season crop yield is calculated depending on soil fertility and external inputs like manure and mineral fertilizer. With the module more than one field in the farm can be simulated: the user can determine the number of fields and the size, the soil characteristics and the crop that is grown on each field. For fodder crops (in this study Napier grass) a field model is developed which uses a two-monthly time step in order to simulate regular cuttings. By dividing the Napier grass field in different sections, ranges of cutting intervals can be simulated and every month Napier grass can be fed to the animals, if needed according to the system characterization.

NUANCES-LIVSIM

LIVSIM is an individual based livestock production model that simulates animal production (meat, milk, calves and manure) and maintenance requirements. Different livestock units can be taken into account, each characterised by production objectives (dairy, meat, manure, traction), animal species and breeds. The model runs on a monthly basis, and can be used in either a deterministic or a stochastic version. The state variables of the module are the age, weight and reproductive status of the animal. Per month the production by the animals is calculated. More detailed information can be found in Rufino et al. (2007a).

NUANCES-HEAPSIM

The dynamics of nutrients via manure collection, storage and use as well as changes in quality due to management are simulated by the module HEAPSIM, which considers the transfer efficiencies for the different processes under different livestock production systems, types of storage and handling facilities. Also this module runs on a monthly basis. More detailed information can be found in Rufino et al. (2007b).

NUANCES-LABOURSIM

Labour is in many regions an important limiting resource in Sub-Saharan African smallholder farming systems. In the model labour is not treated as a dynamic variable but as a resource that is internally available (as a consequence of members of the family working on the farm) and as an external resource that can be bought. The model keeps track of a monthly balance of labour availability, so that the variability of demand and availability of this resource within the year is captured.

The monthly total amount of labour available (the sum of internally available and externally bought labour) is allocated to different activities. The labour allocated to an activity will affect the outcomes simulated by the models of the different subsystems (i.e. livestock, crop and soil and manure management). For each of the modules a set of key activities is defined, and the amount of labour that is needed for performing each of these activities is quantified. As several of these activities take place at certain moments in the year, for example weeding the maize fields only takes place in the second and third month after planting the maize, this leads to a temporal variability in the demand for labour to be able to perform the activities as best practices (i.e. without loss of productivity). These monthly values for the demand of labour are compared to the monthly values of labour availability. If in each month labour availability is larger or equal to labour demand, no reduction takes place in the biophysically determined values of production (e.g. crop production, livestock production and manure production in HEAPSIM). If in certain months not enough labour is available to cover labour demand for best practices, a decision has to made how the limited resource labour is allocated, and to which activities a priority is given. For those activities in which demand is not covered by the amount of labour allocated to those activities, the biophysically determined levels of production are reduced by multiplying them by a labour reduction factor. This reduction factor is a function of the amount of labour allocated to the activity and depends further on the type of activity. For example, in LIVSIM the reduction factor will affect the amount of feed that can be collected for the cattle. In FIELD insufficient labour can have different effects as the consequences of investing not enough labour in either planting and ploughing, weeding, harvesting or erosion control measures will be different. The timing of these activities within FIELD is not fixed, but will depend on which crops are grown. The model is set up in such a way that if a certain crop is chosen, that then automatically certain activities need to take place at certain moments in the season. Depending on the size of the field a certain amount of labour should be invested to achieve the attainable crop yield (biophysically determined). A lack of labour for a certain activity at a certain moment will lead to a reduced crop yield (in the case of planting, weeding and harvesting), or to increased soil erosion (if the labour necessary for erosion control measures is not available).

At the moment we use simple relationships between the amount of labour available and its effect on productivity parameters. For example, we use a linear relationship between a yield reduction factor and the amount of labour available (expressed in man days per month per ha) for each field. Key parameters in this relationship are what the yield reduction is when no labour is invested during that specific weeding period (either month 2 or 3 after planting) and the amount of labour needed for optimal weeding management. Similar relationships are defined for the amount of labour invested into activities like planting and ploughing and the consequences in terms of delay in planting. This delay is an input variable for the FIELD module, which uses it to adjust the availability of nutrients in the soil for the crop and the potential light interception. The relationships between planting date and the availability of nutrients and light interception are based on simulations with detail process-based models like LINTUL and APSIM.

This setup of the labour module allows the user to simulate the effects of labour on the productivity of the subsystems in a dynamic way without increasing model complexity and model data demand too much. For example, FIELD operates on a seasonal time step, but thanks to the linkage of the cropping calendar to the timing of certain activities, the overall effects of labour shortages on certain moments in the year or season can be taken into account, and it is possible to identify the critical moments in the year in which labour availability is a major constraint. Therefore we can use a simple summary model like FIELD which has a low data demand and is easily parameterisable for different crop growing conditions but still capture key variability of labour availability.

Interactions between modules

All the flows of resources between the modules are determined by the decision-rules that are applied within the model. These decision rules are determined by the description of the smallholder system under study and by the type of analysis that the user wants to do with the model. For example, a rule could be that all aboveground crop residues are taken from the field, fed to a zero-grazing cow and the refusals of the cow are put on the heap. This then automatically determines how the modules interact and how much of each resource is flowing from module to module. All modules, except for FIELD, are working on a monthly basis. The interaction between FIELD and the other modules takes place at the beginning and end of each rainy season, except for FIELD-NAPIER, where the interactions take place on a monthly basis. Maize thinnings fed to the animals are kept track of, and maize yield at the end of the season is reduced by the amount fed to the animals. no other resources flow between these two compartments within the cropping season.

One of the most important flow going from module to module is the flow of organic matter. Starting from LivSim, manure is produced and refusals are calculated based on the difference between actual feed intake of the animals and the amount of fodder on offer. These monthly values of fresh manure and refusals are collected with certain efficiencies and go into HEAPSIM. HEAPSIM calculates on a monthly basis the losses of carbon, nitrogen, phosphorus and potassium. After 6 months the composted manure and refusals in the heap are applied to the fields, according to certain allocation rules. The manure can for example be spread out evenly over all the fields, or concentrated on the best fields. Based on the existing soil fertilities, the manure applied, possibly mineral fertilizers applied and the climate, the FIELD module calculates crop yield and the changes in the state variables (see Tittonell et al. 2007b). This yield can be reduced if labour is not available for all the best practices. Based on these yields (of both fodder and food crops) and the decisions made with regard to the management of the crop stover, crop residues stay in the field, are stored or are fed directly to the animals.

Decision making within FARMSIM

The core of FARMSIM is formed by the different modules described in the previous section. In FARMSIM the decision module is outside of this core, and only supplies the necessary input to make the modules run and communicate to each other. The decision module supplies the necessary inputs to determine how resources should be allocated on a monthly or seasonal basis over the different components of the farm and the different activities that should take place. The core of FARMSIM in which all the modules are linked then calculates the consequences of these decisions for that growing season using also all the other inputs necessary for running the model. The results of this model run are then reported back to the decision module.

Depending on the specific interests of the user, different types of analyses can be performed with the decision module:

A fixed scenario –analysis can be performed: the consequences of a fixed strategy in time are calculated. This means that from season to season and year to year the same decision parameters are generated by the decision module, and the farm is simply followed in time to see what will happen if the farmer would follow such and such strategy.
state-based decision making: depending on the state that is simulated (e.g. soil fertility or cash availability) the type of decision that is made can be changed: this can be from simple to complex, for example rule – based or a Linear Programming decision tool can be built in
optimization and inverse modelling techniques can be applied: certain outputs of the model when a strategy is chosen are evaluated, and on the basis of these outputs strategies can be optimized, or ‘acceptable’ farming strategies can be identified

Data needs for the model
The FARMSIM model as such needs a wide range of different types of data: data are needed for the parameterization of the biophysical processes incorporated in the different modules, the current state of farming system and decision making. Because of this data need we developed a detailed protocol with which it is possible to run the model. It is important to note here that NUANCES-FARMSIM is not suitable to represent a real African smallholder farm with all its different crops, its home garden, all its livestock components (cattle, goats, chicken, rabbits) in all its fascinating complexity. The tool can be used after the researcher has extracted the most important characteristics that he or she wants to analyse in more detail: NUANCES-FARMSIM can be used to analyse so-called virtual farms, which represent the most important components of the real farm and the most important flows and decision entry points.
Information needed for the settings of the farming system to be analysed with the model can be collected using standard questionnaires and detailed expert knowledge on the functioning of the farming systems under study. These questionnaires give the model user the settings for the labour, cash, family and decision making modules within NUANCES-FARMSIM. The settings of LIVSIM, HEAPSIM, and FIELD come from a combination of information available through the questionnaires and some basic soil sampling to get the current status of the fields within the farming system and a quantification of the current state of the animals. The processes incorporated into LIVSIM, HEAPSIM, and FIELD are parameterized either through results obtained in experimental research or analyses of more detailed process models.

Appendix 8.2 – Brief description of LIVSIM, the Livestock Simulator[§]

1. Overview

NUANCES-LIVSIM (Livestock Simulator) is a simple dynamic model based on principles of production ecology. There is a hierarchy of production ecological factors that determine whether potential, limited or reduced yields are attained (see Figure 1 in Appendix 8.1). In LIVSIM, individual animals are followed in time, performance being dependent on genetic potential and feed resources. Genetic potential is described in the model by mature weight, the potential growth rate and the maximum milk yield (Figure 3).

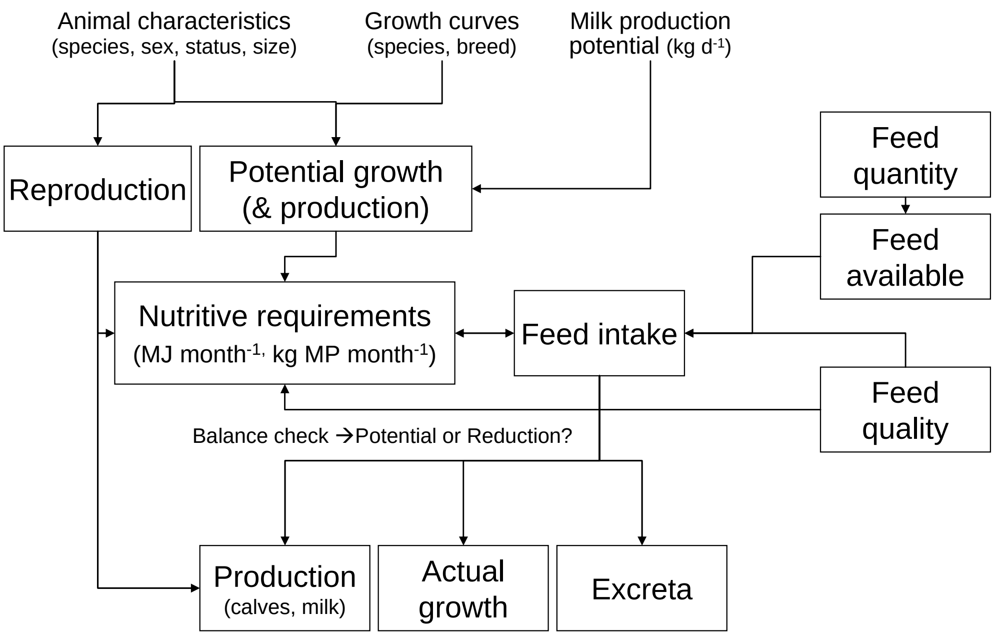


Figure 1: Simplified scheme of LIVSIM-cattle

The current version of LIVSIM is developed to simulate cattle production. Conception, sex of the calves and mortality (involuntary disposal) are triggered stochastically while changes in age, weight and mortality due to under-nutrition are described deterministically. Intake is driven by feed quality and animal characteristics. Decision variables represent different management strategies related to feeding (quantity and quality), reproduction policies. Reproductive performance can be evaluated through a number of indicators: age at first conception, days open, calving interval and length of the productive life (culling date minus first calving date). Productivity can be assessed with number of calves, milk production, weight gain and manure production. The model is written in MATLAB v.7.1 (The Math Works, 2005), the integration time-step can be set from 1 to 30 days. The basic structure of the model is based on the model developed by Konandreas and Anderson (1982). LIVSIM differs

[§] Extracted from: Rufino et al., 2007b from that model in the nutritive requirements calculations - which are based on metabolisable energy (ME) and protein systems of AFRC (1993), feed intake - based on the model of Conrad et al (1964), excreta production, and the decision making variables. Individual components of the model were tested against experimental data obtained from literature and are presented in the model evaluation section.

2. Model structure

The cattle system is described with 4 state variables: age, bodyweight, the reproductive status comprising a pregnancy index and a calving index (Figure 2). The pregnancy index is used to track the pregnancy and its nutritive demands and to trigger calving. The calving index is used to track the lactation (and its nutritive demands) and for triggering the next conception.

2.1 Growth and compensatory growth

Potential growth is a function of time, breed and sex. Potential growth and minimum bodyweight curves are built for cross-breed cattle fitting data on mature weight and growth rates found in the literature to a simplified Brody model (Brody, 1945). The potential growth curve used currently in the model for female cross-bred Holstein x Zebu is shown in Figure 3.

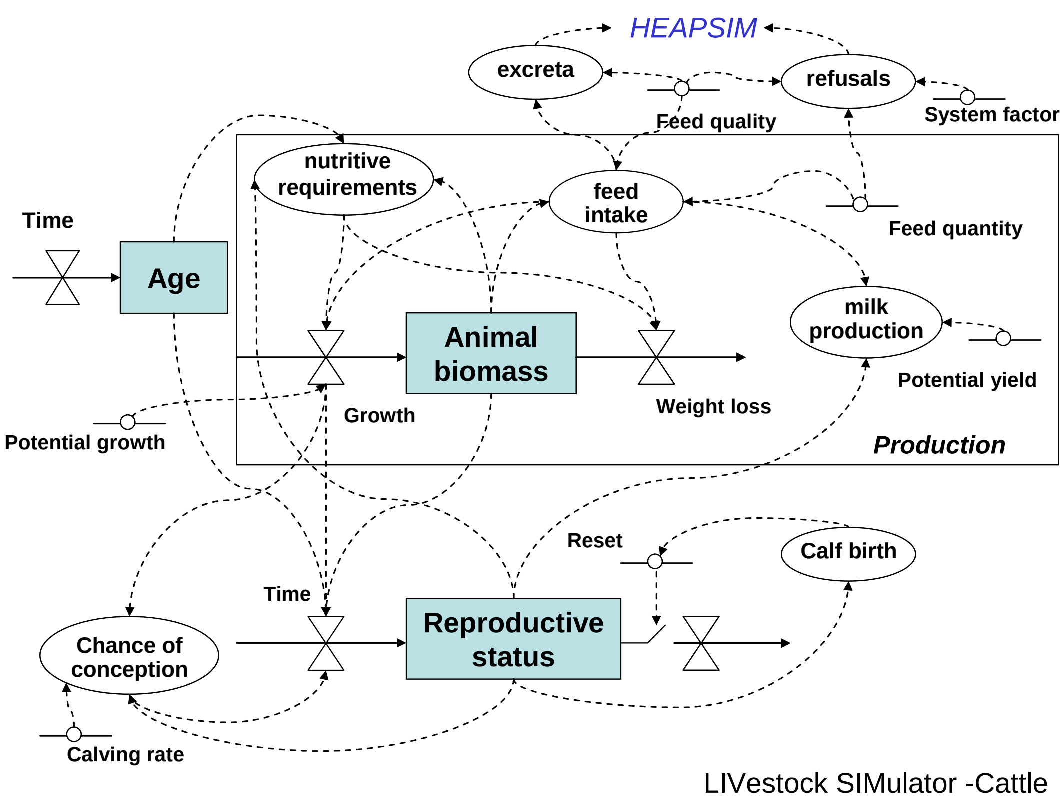


Figure 2: State and rate variable diagram of LIVSIM-cattle

Maximum and minimum bodyweights are calculated by interpolation from Figure 3. Compensatory growth is accounted for in the model by using different potential growth rates according to quality of the feed.

2.2 Reproduction

Reproduction is simulated stochastically by using probabilities associated to bodyweight and age combinations. We used the approach of Konandreas and Anderson (1982) and data from literature to determine a feasible age-bodyweight set when heifers achieve reproductive maturity (Figure 3). The minimum (1.5 y), average (2.2 y) and maximum (4 y) ages for conception were derived from the minimum age at first calving from 12 studies with grade and cross bred Holstein cattle in SSA (Figure 3). Probabilities for conception are derived from the annual calving rate (input to the model), this probability being further affected by age and nutrition. The feedback nutrition-reproduction is described through the effect of bodyweight changes on the conception rate. New calves are assumed to be born with a user-defined initial weight and gender is assigned randomly.

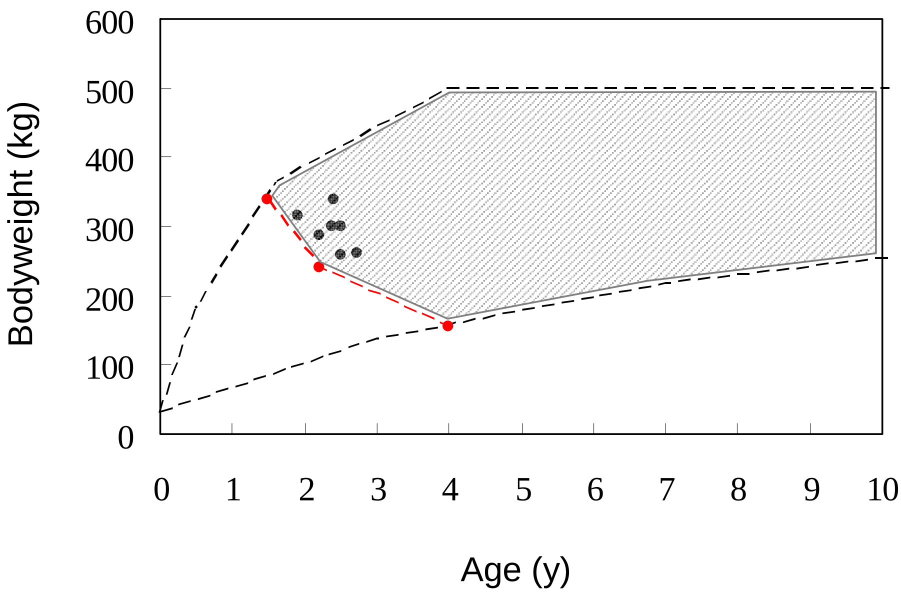


Figure 3: Feasible set of bodyweight-age combinations for conception of grade and cross-bred Holstein x Zebu in SSA. Dots are some of the minimal measured bodyweight - age combinations used for calibration of the feasible set. See Rufino et al (2007b).

2.3 Milk production

Milk yields are simulated by using a breed dependent potential milk yield function of lactation length, affected by of age and condition index of the cow. Lactation length and dry period are characteristic of the system under study and therefore inputs to the model. The dry period is assumed to be 2 months. Milk production is calculated by using interpolated potential milk yields from the potential lactation curve and accounting for the age and body condition effects. The condition index is calculated based on the current weight of the animals relative to the maximum weight possible at the age of the animal.The calculated milk yield implies a certain energy and protein demands that have to be met by the feed intake. When there is feed scarcity and under-nutrition, the actual milk yield is determined by iteration with all the processes demanding energy and protein and a set of priority rules as explained later in the text. Weaning age of calves is user-defined as well as the milk allowance. Mortality rates due to causes other than under-nutrition are input to the model. Mortality due to starvation is simulated by using the growth and reproduction routines.

2.4 Nutritive requirements

Nutritive requirements are calculated following the approach of AFRC (1993). Metabolisable energy (ME) and metabolisable protein (MP) needs for potential growth and production are calculated separately for maintenance, growth, pregnancy and lactation. This structure suits the purposes of the model because allows applying the concepts of production ecology (van de Ven et al, 2003).

2.5 Reduction of production under limiting conditions

When the available feed supply equals nutrient requirements, the potential production level is achieved provided that there are no other limiting and reducing factors. Water requirements and reducing factors (diseases, pollutants) are not (yet) included. When the nutrients provided by feed intake cannot meet the nutrient demands the nutrients are used to meet the demands of different process according to given priorities. First, it is determined whether metabolisable energy or metabolisable protein are limiting potential production, then the physiological and reproductive status of the animal are checked. When potential production cannot be achieved, the next check is whether maintenance nutritive requirements can be met. This decides which routine are executed by the model: either little growth or weight loss. Through several iterations growth and production that match the feed inputs are calculated. Mortality is simulated both as a probabilistic process qualified by the age of an animal and deterministically defined by nutritional status. There is a threshold to weight loss beyond which the animal dies. See further details in Rufino et al. (2007b).

2.6 Manure production

LivSim simulates faecal dry matter production, faecal N and urinary N. Faecal dry matter is simulated based on feed intake and the digestability of the feed. Faecal N and urinary-N are calculated by using the metabolisable protein (MP) system of AFRC (1993). Partitioning between organic N and ammonium is also important for recycling but it is not currently simulated.

2.7 Aggregation to represent herds

LIVSIM simulates individuals that have to be aggregated to represent different animal subsystems: dairy, animal traction, mixed herds for beef production or fattening subsystems. Management decisions related to feeding and breeding are incorporated into LIVSIM but marketing and culling decisions are derived from household strategies, goals and production orientation and are included in the core model FARMSIM.

3. Model runs, calibration and evaluation

For the simulations we use a monthly time step, acknowledging that the level of detail suffices the purposes of our study and will allow in the future easy coupling to a farm-scale model. Because the model simulates discrete event by using stochastic variables, replicated runs are needed to estimate the output variables. We performed experiments to evaluate the minimum number of replicates that capture the effect of the treatments. The experiments were performed using the common feeding practice of the dairy smallholders (Napier grass and two kg of concentrates offered only to lactating animals). In Figure 4 we present results of the preliminary test using the dataset of Ayantunde et al (2001) for steers feeding in a pasture in Niger. The model simulations show good agreement with the observed data for individual animals (Figure 4a,b and c) and for all the animals together (n=86) (Figure 4d). See for further details Rufino et al (2007b).

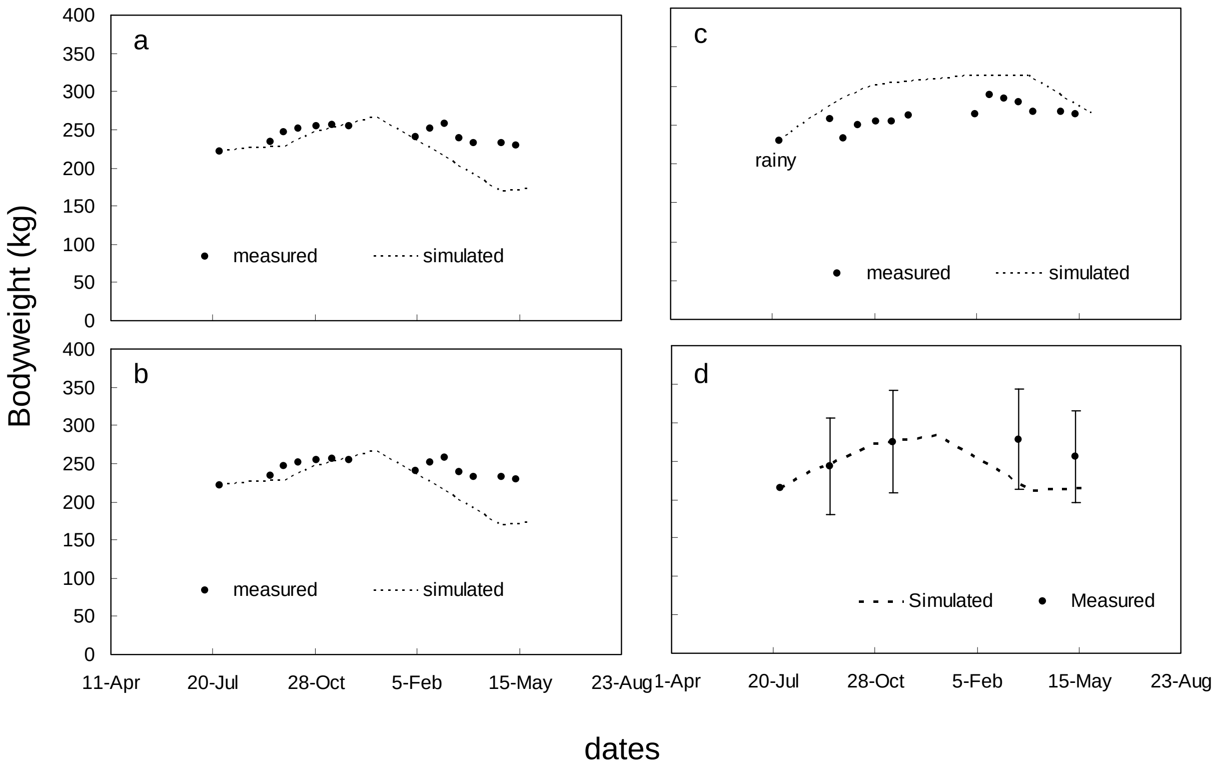


Figure 4: Model testing using a dataset for steers grazing in a pasture in Niger. Figures a, b and c show predictions for individual animals and figure c for all animals together (n = 86). Data source Ayantunde et al. 2001.

Appendix 8.3 – A first application of HEAPSIM, the manure simulation module**

HEAPSIM is a simple model designed to analyse the effect of manure management on the efficiency of mass and nutrient retention within smallholder complex system (Figure 1). In a first application (Rufino et al., 2007a), the calculations with the model use information on manure excreted and manure management collected from case-study smallholder farms in the Kenyan Highlands, results of experimental work on manure mass, C, and N losses during storage, complemented with data available from the literature to parameterise the model and a fuzzy logic system to model the effect of management on manure losses during storage. Fuzzy systems translate linguistic variables into real values based on sets of rules that can be derived from expert knowledge, and using on-farm analysis and results from simple experimentation. This approach was illustrated by applying it to the analysis of N cycling efficiencies within a smallholder case study farms from western Kenya.

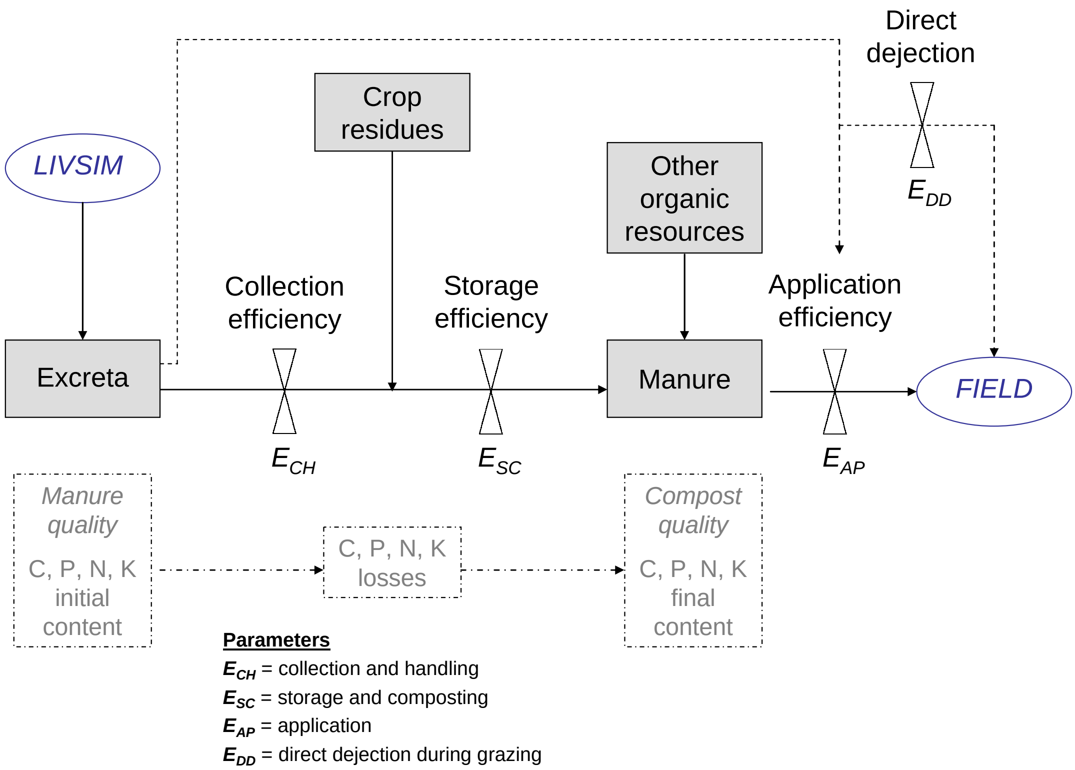


Figure 1: Overview of HEAPSIM and its connection with the livestock (LIVSIM) and crop/soil (FIELD) models

Simulations of the model showed that manure management during collection and storage has a large effect on the efficiency of C and nutrient retention within the smallholder farming system. The differences in NCE between farmers of different wealth classes are mainly caused by differences in resource availability. For the poorer

** Extracted from: Rufino et al., 2007a.

farmers large N losses occur at all stages of the recycling (before, during collection and during storage). Urinary-N losses were common to all farmers but they impact on NCE of the poor and medium class farmer is larger due to the relatively smaller total N amount available for recycling. Farmers hardly make use of the urine, although in some cases it may represent up to the 50% of the N contained in the excreta. The current management allows the poor farmer to apply less than 1 kg of composted manure from the almost 15 kg excreted by the cattle. Improving the manure storage does not help increasing the overall NCE significantly because of the large losses before the storage. For the wealthier farmer improvement of the manure storage results in noticeable increases in NCE and would allow recycling about 30% of the N excreted by the cattle (about 30 kg) with small investment in composting and about half of the excreted if urinary-N is utilised. Experimentation showed that the use of the polythene film reduces mass and N losses considerably. The application of our modelling approach to the analysis of a smallholder farm in the highlands of western Kenya exemplifies the effect of manure management for N, that together with P are largely responsible for poor crop productivity in this region. This study showed a narrower range of NCE for the collection (39-61%) and storage (34-51%) than that reported before by Rufino et al. (2006). Opportunities for the poor to increase the overall NCE require investment (e.g cattle housing) and knowledge (e.g. to recycle urinary-N). Improving the feeding of cattle and cattle number would have a larger effect on manure available to crops but feed scarcity at the larger scale and cash constraints at farm scale will impede that the poorest benefit from this technology. The absolute amounts of N recycled (between 1-6, 4-17 and 7-18 kg N y^{-1} for poor, medium and wealthier farmers) are small compared to the maize crop demands (50 kg N ha^{-1}), N rates that are hardly realised by poor farmers who usually purchased small bags of fertilisers. Thus, although the absolute amounts of N that farmers may recycle with improve management have little impact in crop productivity in the short term, this is often the only one input that farmers have available and can afford. Manure provides other important macro and micro nutrients to the crops and has a positive effect on maintaining (and sometimes increasing) soil organic matter, reasons that justify the search for interventions that will help farmers to make a better use of this resource.

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Summary

Soil fertility decline is the major single factor explaining the decrease in per capita food production in sub-Saharan Africa. With population growth rates larger than the rates of increase in food production, and less land becoming available for farming, yields per area of major food crops must increase. Traditional systems of soil fertility management – shifting cultivation, fallow, use of animal manure – are increasingly restrictive as population continues to grow, due to the consequent reduction in farm sizes and communal areas for grazing or biomass collection. The problem of declining productivity is more acute in areas of high agroecological potential, where originally fertile soils and ample rainfall attracted dense human settlement. Integrated soil fertility management (ISFM) is an approach to improving or restoring soil productivity based on capitalising synergies between combinations of organic and mineral fertilisers, improved germplasm and N_2-fixation. However, the adoption of ISFM technologies by farmers has been limited. This is due in part to particularities of the farming systems, which are not always considered in the development of ISFM interventions, to dissemination failures and/or to lack of contextualisation of ISFM technologies within smallholders' livelihoods by the scientific community.

Smallholder farms in sub-Saharan Africa are highly diverse, heterogeneous and dynamic, often operating in complex socio-ecological environments. Much of the heterogeneity within the farming systems is caused by spatial soil variability, which results in its turn from the interaction between inherent soil/landscape variability and human agency through the history of management of different fields. Technologies and resources designed to improve crop productivity often generate weak responses in the poorest fields of smallholder farms. Thus options for soil fertility improvement must be targeted strategically within heterogeneous farming systems to ensure their effectiveness and propensity to enhance the efficiency of resource (e.g. land, labour, nutrients) use at farm scale. Key issues in design of approaches for strategic targeting of resources include: 1. Inherent soil variability across agroecological gradients; 2. Social diversity, farmers' production orientations and livelihood strategies; 3. Farmer-induced gradients of soil fertility, their causes, and consequences for efficient allocation of scarce resources; 4. Competing objectives and trade-offs that farmers face between immediate production goals and long term sustainability; 5. The complexity of farmers own indicators of success. An analytical framework (NUANCES) in which systems analysis is aided by survey, experiments and simulation modeling is used in this study to analyse farming futures in the highlands of East Africa. Analysing case studies from moderate to high potential agricultural systems of East Africa, this work contributes to the design of more tailor-made ISFM technologies, using combinations of mineral fertilizers and organic matter management, and evaluating technology interventions that suit the diverse and heterogeneous smallholder farming systems of sub-Saharan Africa.

A study based on comparative quantitative and qualitative evidence from six districts in Kenya and Uganda (*n* = 250 farms), was designed to understand cross-scale interactions between the major drivers of household diversity and soil heterogeneity in farming systems in the region (Chapter 2). Wide diversity was observed in socioeconomic (e.g. 4 vs. 10 months year^{-1} of food self sufficiency) and management (e.g. fertiliser use by 0 vs. 95% of the farmers) factors across and within districts. Across districts, all the households with less than 3 months year^{-1} of food self-sufficiency had a land:labour ratio (LLR) < 1, and all those with LLR > 1 produced enough food to cover their diet for at least five months. Households with LLR < 1 were also those who generated more than 50% of their total income outside the farm. Dependence on off-/non-farm income was one of the main factors explaining socio-economic variability. Based on resource endowment, dependence on off-farm income and production objectives, households were grouped into five Farm Types: 1. Farms that rely mainly on permanent off-farm employment; 2. Larger, wealthier farms growing cash crops; 3. Medium resource endowment, food self-sufficient farms; 4. Medium to low resource endowment farms relying partly on non-farm activities; and 5. Poor households with family members employed locally as agricultural labourers by wealthier farmers. These farm types differed in land, labour and financial resources and potential nutrient availability (e.g. animal manure) which affect land use and soil fertility management. However, the five farm types differed more in the degree of soil heterogeneity than in their average soil fertility status at farm scale. Across the 250 farms (i.e. 2,607 fields) the variation in soil organic C and total N was mostly related to differences in the inherent properties of the soils across sites and the landscape, while available P, K and pH were associated with spatial soil heterogeneity within farms. Soil heterogeneity was greater in farms (and sites) with poorer soils and smaller in farms owning livestock. In allocating nutrient resources, farmers prioritised the fields they perceived as most fertile. Due to multiple interactions between site-specific factors, farm resources and objectives, landscape variability and history of land use and management, the variability in soil fertility indicators often observed within individual farms could not be summarised in consistent, generalisable patterns of spatial heterogeneity.

Western Kenya is one of the most densely populated areas of sub-Saharan Africa, and has favourable conditions for crop production (Chapter 3): a bimodal rainfall regime and relatively deep soils dominated by clay and loam textures, which were inherently fertile. Due to high population in the subsistence smallholder sector (up to 1000 inhabitants km^{-2} in the highland areas), average farm sizes tend to be very small (from 0.5 to 2.0 ha, on average). Being an area of high human population density and intense soil degradation, western Kenya may represent a future demographic scenario for other regions with comparable climate and soil types. For these reasons, most of the work in this thesis has focused on western Kenya and particularly in the highland sites, where farm sizes have dwindled and communal grazing and wood lands virtually disappeared. The current number of cattle per household is small and the resources to feed them are scarce, restricting their contribution to the maintenance of soil productivity with manure. However, farms in the highlands are closely integrated crop-livestock systems that can exploit synergies to improve nutrient cycling and minimise risks. Although current soil fertility is poor, high potential to fix atmospheric C into crop biomass (two cropping seasons a year) and predominantly fine-textured soils offer ample scope for restoring farm productivity in the region through ISFM.

Crop productivity is highly variable within smallholder farms, strongly influenced by variation in both current crop management (e.g. planting dates, fertilizer rates) and soil fertility (influenced by past soil and crop management). The aim of Chapter 4 was to investigate the relative importance of soil fertility and crop management factors in determining yield variability. Soil fertility status was assessed on 522 farmers' fields on 60 farms and paired with data on maize-yield and agronomic management for a sub-sample 159 fields. Because of the complexity of the data set, classification and regression trees (CART) were used to relate crop yields to soil and management factors. Maize grain yields for fields of different soil fertility status as classified by farmers were: poor, 0.5 – 1.1; medium, 1.0 – 1.8; and high, 1.4 – 2.5 t ha^{-1}. The CART analysis showed that resource use intensity, planting date, and time of planting were the principal variables determining yield, but at low resource intensity, total soil N and soil Olsen P became important yield-determining factors. Only a small group of plots with high average grain yields (2.5 t ha^{-1}; n = 8) was associated with use of nutrient inputs and good plant stands, whereas the largest group with low average yields (1.2 t ha^{-1}; n = 90) was associated with soil Olsen P values of less than 4 mg kg^{-1}. This classification could be useful as a basis for targeting agronomic advice and inputs to farmers. The results suggest that soil fertility variability patterns on smallholder farms are reinforced by farmers investing more resources on already fertile fields than on infertile fields.

Soil heterogeneity generates variable responses of crops to fertilisers due to large variability in resource use efficiency within single farms. In Chapter 5, databases on maize production under farmer (F-M) and researcher management (R-M) were used to analyse within-farm variability in the components of nutrient use efficiency by maize: nutrient availability, capture and conversion efficiencies. Subsequently, the simple model QUEFTS was used to calculate attainable yields with and without fertilisers based on measured soil properties across heterogeneous farms. The yield gap of maize between F-M and R-M varied from 0.5 to 3 t grain ha^{-1} $season^{-1}$ across field types and localities, and was not only caused by soil fertility. Even without fertilisers poor fields under R-M yielded up to 1.1 t ha^{-1} more than F-M, which is attributable to improved agronomic management and germplasm. The relative response of maize to N-P-K fertilisers tended to decrease with increasing soil quality (soil C and extractable P), from a maximum of 4.4-fold to –0.5-fold relative to the control. Soil organic C and soil P availability exhibited co-variability in the most and least fertile fields of the farms due to long-term organic matter management by farmers; P availabilities > 10

mg kg^{-1} were only measured in soils with > 10 g kg^{-1} organic C. Across sites and farms, P was the most limiting nutrient, although N is required in the largest amounts. Soil heterogeneity affected resource use efficiencies mainly through effects on the efficiency of resource capture (e.g., recovery efficiencies varied between 0 and 70% for N, 0 and 15% for P, and 0 to 52% for K), with less variation in the resource conversion efficiency (with average values of 97 kg DM kg^{-1} N, 558 kg DM kg^{-1} P and 111 kg DM kg^{-1} K taken up). Using measured soil chemical properties QUEFTS over-estimated observed yields under F-M, confirming that variable crop performance within and across farms cannot be solely ascribed to soil nutrient availability (cf. Chapter 4). QUEFTS predicted positive crop responses to fertilisers for a wide range of soil qualities, indicating that there is room to improve current crop productivity through fertiliser use.

Farmers' day-to-day decisions have implications for the sustainability of their farming system, implying multiple trade-offs between short- and long-term objectives that have biophysical and socio-economic dimensions. Chapter 6 shows that inverse modelling techniques can be used effectively for optimisation and trade-offs analysis of farming systems. A multi-objective optimisation algorithm (MOSCEM) and a crop/soil dynamic simulation model (DYNBAL) were combined and used to select farming strategies. Trade-offs between resource productivity, use efficiency and conservation in relation to different patterns of resource allocation (including labour) were analysed for a maize-based, simplified case study farm from western Kenya, under three scenarios of financial liquidity to invest in labour and inputs (2000, 5000 and 10000 KSh ha^{-1}; 75 KSh = 1 US$). Increasing maize yields above a certain threshold by applying mineral fertilisers was associated with larger N losses by leaching, runoff and soil erosion; this threshold was 2.7 t grain ha^{-1} for the scenario of no financial limitations (10000 KSh ha^{-1}). N losses at farm scale fluctuated between 36 to 54 kg N ha^{-1} season^{-1}, while the maximum maize yields achieved were around 3.4 t grain ha^{-1}. Soil losses by erosion increased abruptly beyond a certain maize yield (e.g., 1.8 t grain ha^{-1} for the 2000 KSh ha^{-1} scenario), while the minimum rate of soil loss was less under better financial scenarios. The set of strategies to achieve a certain goal was more numerous and variable when the conditions were less conducive for farming. Investments in hiring labour were prioritised over fertiliser use to obtain the greatest yields, and the allocation of fertiliser and labour favoured the fields around the homestead, where the efficiency of nutrient capture was the largest. Productivity could be increased up to a certain threshold beyond which N losses increased abruptly, when fertilisers were applied to the most degraded outfields of the farm.

The findings described above indicate that degraded outfields must be rehabilitated through organic matter additions, before crops growing on them can respond to nutrient applications. Studies on ISFM options indicate synergistic effects of combined applications of manure and mineral fertilisers. However, the evaluation of ISFM technologies should consider key features of smallholder farms: 1. Management-

induced soil heterogeneity; 2. Long term system dynamics; 2. Limited availability of manure of poorer qualities than often tested in controlled experiments; 4. Limited access to mineral fertilisers; and 5. Competing uses for crop residues on the farm. In Chapter 7, the simple dynamic simulation model FIELD was used to explore long-term management strategies for the allocation of realistic rates of mineral fertiliser and manure, using soil and manure quality parameters measured on case-study farms in western Kenya. The model was calibrated and tested against four datasets including long-term crop and soil dynamics, and capturing within-farm variability in crop responses to fertilisers. Patterns of responsiveness to increasing application rates of N fertiliser from 0 to 180 kg N ha^{-1} (+/- 30 kg P ha^{-1}) distinguished: poorly-responsive fertile fields (grain yields ranged from 4.1 to 5.3 t ha^{-1} without P and from 7.5 to 7.5 t ha^{-1} with P) from responsive fields (c. 1.0 to 4.3 t ha^{-1} and 2.2 to 6.6 t ha^{-1}) and poorly-responsive infertile fields (c. 0.2 – 1 t ha^{-1} and 0.5 – 3.1 t ha^{-1}). Soils receiving combined manure and fertiliser applications over 12 years stored between 1.1 to 1.5 t C ha^{-1} $year^{-1}$ when 70% of the crop residue was retained in the field, and between 0.4 to 0.7 t C ha^{-1} $year^{-1}$ when only 10% of residues were retained. Degraded outfields could not be rehabilitated with manures of average quality for farms in western Kenya (e.g., 23 – 35% C, 0.5 – 1.2% N, 0.1 – 0.3% P) applied for 12 years at a (realistic) rate of 1.8 t dm ha^{-1} $season^{-1}$, without mineral fertilisers. Application of the best quality manure found in the region (39% C, 2.1% N, 0.2% P) led to an increase in c. 1 t C ha^{-1} $year^{-1}$ in the poorest fields. Different qualities of manure, initial soil conditions and combinations of manure plus mineral fertilisers induce a different degree of *hysteresis* of soil restoration. Mineral fertilisers may contribute in the initial phases of soil rehabilitation to induce restoration of biomass productivity that will lead to higher potential C inputs to the soil.

During participatory prototyping activities conducted in Vihiga, western Kenya farmers designed what they considered to be the *ideal farm* (Waithaka et al., 2006): one in which high productivity would be achieved through optimising crop-livestock interactions. Three major observations were derived from such exercise: 1. Farmers had an optimistic view on the climatic and market conditions in which the ideal systems would operate; 2. They tended to overestimate the size of the flows that determine crop-livestock interactions; 3. The productive structure of the ideal farm resembled, to a large extent, the current configuration of the wealthier farms in the area. The objective in Chapter 8 was to analyse the physical feasibility of shifts in the productive structure of the majority of farms in the area necessary to move them closer to the ideal prototype, having the current wealthier farms as reference. A dynamic, farm-scale simulation model (NUANCES-FARMSIM) was parameterised with data from four case-study farms representative of Type 1 to 4 (cf. Chapter 2) to investigate: (i) the current differences in resource use efficiencies and degree of crop livestock interactions across farms types; and (ii) the impact of different interventions on producing the desired shifts in productivity towards the ideal farm. Simulations were run for 10 years, and changes in the system were introduced stepwise, as both

intensification of input use and qualitative changes in farm configuration. Results indicate that household food self-sufficiency (expressed in energy units) can be achieved in all farm types through input intensification. However, the feasibility of implementing such interventions on a large number of farms is disputable. The impact of livestock on the recycling of nutrients and on the efficiency of nutrient use at farm scale can be large, provided that enough nutrients are present in (or enter) the system to be redistributed. However, the trajectory of change towards the ideal farm is hardly feasible for a majority of farmers in the region.

Agroecological potential and market opportunities determine the propensity of a certain locality or site to stimulate hanging-in (subsistence), stepping-up (market orientation) or stepping-out (off/non-farm income) livelihood strategies. Population density operates as a stressor that may induce shifts in livelihood strategies. While rural families may adapt to such stresses through different coping strategies, there are thresholds in resource endowment (e.g., land size) below which most families are forced to step-out of agriculture as their main activity. The sustainable intensification of farming practices is urgently needed to lower such thresholds, particularly in areas where traditional means of maintaining soil fertility are no longer feasible. ISFM technologies must be tailor-made to fit the diversity of livelihood strategies, without ignoring the broader context in which farming systems operate. While certain technologies exhibit discouragingly limited adoption, others have found specific socio-ecological niches within certain farming systems, and disseminate spontaneously among farmers. The scaling-out of ISFM technologies should be designed considering the key characteristics of farming systems – heterogeneity, diversity and dynamics – seeking ways to categorise and harness such complexity.

Samenvatting

De afname in bodemvruchtbaarheid is de belangrijkste factor die de afnemende voedselproductie per hoofd van de bevolking in Afrika ten zuiden van de Sahara verklaart. Met groeisnelheden van de bevolking die groter zijn dan de snelheid waarmee de voedselproductie toeneemt, en met een afname in de hoeveelheid land die beschikbaar wordt voor landbouw, is het noodzakelijk dat de opbrengsten van de belangrijkste voedselgewassen per eenheid oppervlakte gaan toenemen. De mogelijkheden voor het toepassen van traditionele systemen van het beheer van bodemvruchtbaarheid – brandbouw, wisselrotaties, en dierlijke mest – verminderen omdat de bevolking blijft toenemen in aantal, omdat de grootte van de boerderijen en de gemeenschappelijke begrazingsgronden (belangrijk voor onder andere begrazing en het verzamelen van brandhout) consistent afneemt. Het probleem van afnemende productiviteit is meer nijpend in gebieden met hoge agro-ecologische potentie, waar de oorspronkelijk vruchtbare bodems in combinatie met voldoende regenval hoge bevolkingsdichtheden aantrokken. Integraal beheer van bodemvruchtbaarheid (Engelse acroniem: ISFM) is een aanpak om bodemproductiviteit te verbeteren of te herstellen en deze is gebaseerd op het gebruik van synergieën tussen combinaties van organische mest en kunstmest, verbeterde rassen en stikstof fixatie door leguminosen. De adoptie van ISFM technologieën is echter beperkt. Dit wordt onder meer veroorzaakt door de typische karakteristieken van de agrarische bedrijfssystemen welke niet altijd worden meegenomen tijdens de ontwikkeling van ISFM interventies, door fouten tijdens de voorlichting en/of door te weinig inbedding van ISFM technologieën door de wetenschappers binnen de gemeenschappen van kleine boeren.

Kleine boerderijen in Afrika ten zuiden van de Sahara zijn erg divers, heterogeen en dynamisch, vaak operationeel in complexe socio-economische omgevingen. Veel van de heterogeniteit binnen de agrarische bedrijfssystemen wordt veroorzaakt door ruimtelijke bodemvariabiliteit, die op zijn beurt veroorzaakt wordt door de interactie tussen de oorspronkelijke bodem c.q. landschapsvariabiliteit en menselijk handelen, door de historie van het beheer van de verschillende velden. Technologieën en bronnen die ontworpen zijn om gewasproductiviteit te verhogen, leiden veelal tot zwakke responsen in de slechtste velden van kleine boerderijen. Hierdoor moeten opties voor de verbetering van bodemvruchtbaarheid strategisch toegepast worden binnen de heterogene agrarische systemen, dit om hun effectiviteit in het verbeteren van de efficiënties in het gebruik van bronnen (bv. land, arbeid en nutriënten) op bedrijfsniveau toe te laten nemen. Belangrijke vraagstukken in het ontwerpen van aanpakken voor het strategisch toepassen van bronnen zijn: 1. De oorspronkelijke bodem variabiliteit over agro-ecologische gradiënten; 2. Sociale diversiteit, de productieoriëntaties van boeren en strategieën van huishoudens; 3. De door boeren veroorzaakte gradiënten in bodemvruchtbaarheid, en de gevolgen hiervan voor efficiënte allocatie van beperkt beschikbare bronnen; 4. De tegenstrijdige doelstellingen en trade-offs tussen productiedoelen op de korte termijn en

duurzaamheid op de langere termijn; 5. De complexiteit van de indicatoren voor succes van boeren zelf. Een analytisch gereedschap (NUANCES) waarin systeemanalyse wordt ondersteund door enquêtes, experimenten en simulatiemodellering is in deze studie gebruikt om de toekomstmogelijkheden van de agrarische sector in de hooglanden van Oost-Afrika te analyseren. Door middel van de analyse van agrarische systemen met gemiddelde tot hoge productie potenties in Oost-Afrika, draagt deze studie bij tot het ontwerpen van meer specifiek toepasbare ISFM technologieën. In deze technologieën wordt gebruik gemaakt van kunstmest in combinatie met het beheer van organisch materiaal, en worden technologische interventies geëvalueerd die passen bij de diverse en heterogene kleine bedrijfssystemen in Afrika ten zuiden van de Sahara.

Een studie gebaseerd op een kwantitatieve en kwalitatieve vergelijkingsanalyse in 6 districten in Kenia en Oeganda (n=250 bedrijven), was ontworpen om de interacties op verschillende schaalniveaus tussen de belangrijkste sturende variabelen van diversiteit in huishoudens en heterogeniteit in bodems in agrarische systemen in de regio beter te begrijpen (Hoofdstuk 2). Een grote diversiteit werd waargenomen in socio-economische factoren (bijvoorbeeld 4 versus 10 maanden van voedsel zelfvoorziening) en in typen van management (bijvoorbeeld gebruik van kunstmest door 0 tot 95% van de boeren) tussen en binnen districten. In alle districten hadden alle huishoudens met minder dan 3 maanden voedselzelfvoorziening een land - arbeid ratio (Engelse acroniem: LLR) die kleiner was dan 1, en alle bedrijven met een LLR groter dan 1 produceerden voldoende voedsel voor ten minste 5 maanden. Huishoudens op bedrijven met een LLR kleiner dan 1 genereerden meer dan 50% van hun inkomen buiten hun bedrijf. De afhankelijkheid van inkomen anders dan van het bedrijf was een van de belangrijkste factoren die de socio-economische variabiliteit verklaarde. De huishoudens werden, gebaseerd op de beschikbaarheid van bronnen en hun productiedoelen, geclassificeerd in 5 typen: 1. Boerderijen die vooral afhankelijk zijn van permanent werk buiten het bedrijf; 2. Grotere, rijkere boerderijen waar gewassen geproduceerd worden voor de verkoop; 3. Middel-rijke bedrijven die zelfvoorzienend zijn in voedselproductie; 4. Middel-rijke tot relatief arme bedrijven die gedeeltelijk afhankelijk zijn van activiteiten buiten het bedrijf; en 5. Arme huishoudens met familieleden die lokaal werken bij de rijkere boeren. Deze bedrijfstypen verschilden in de beschikbare hoeveelheden land, arbeid en financiën, en de potentiële beschikbaarheid van nutriënten (bijvoorbeeld dierlijke mest), welke hun landgebruik en beheer van bodemvruchtbaarheid sterk beïnvloed. Echter, de vijf bedrijfstypen verschilden meer in termen van bodemheterogeniteit dan in termen van de gemiddelde status van bodemvruchtbaarheid op bedrijfsniveau. Over alle 250 boerderijen (in 2607 velden) was de variatie in bodemorganisch koolstof (C) en totaal stikstof (N) vooral gerelateerd aan de verschillen in de oorspronkelijke karakteristieken van de bodems in de locaties en het landschap, terwijl beschikbaar fosfor (P), kalium (K) en de pH meer gerelateerd waren aan de ruimtelijke variabiliteit binnen bedrijven. Bodemheterogeniteit was groter in boerderijen (en locaties) met armere bodems en kleiner in boerderijen met vee. Boeren gaven prioriteit aan velden die zij als vruchtbaarheid beschouwden in de allocatie van nutriënten. Vanwege de meervoudige interacties tussen locatiespecifieke factoren, de beschikbaarheid van bronnen op bedrijfsniveau en de bedrijfsdoelstellingen, kon de variatie in bodemvruchtbaarheidsindicatoren die op bedrijfsniveau waargenomen werd, niet samengevat worden in consistente, algemeen geldende patronen van ruimtelijke heterogeniteit.

West-Kenia is een van de meest dichtbevolkte gebieden van Afrika ten zuiden van de Sahara, en heeft goede condities voor de productie van landbouwgewassen (Hoofdstuk 3): twee regenvalseizoenen per jaar en relatief diepe bodems die gedomineerd worden door kleiige textuur en die oorspronkelijk vruchtbaar waren. Door de hoge bevolkingsdichtheid (tot 1000 inwoners per vierkante kilometer in de hoogland gebieden) zijn de gemiddelde bedrijfsgroottes erg klein (tussen 0.5 en 2.0 hectare). Door deze hoge bevolkingsdruk en door de intense bodemdegradatie kan West-Kenia beschouwd worden als een mogelijke uitkomst van toekomstige demografische scenario’s van andere regio’s met vergelijkbare klimaat en vergelijkbare bodemtypes. Het meeste werk in deze thesis heeft zich daarom op West-Kenia gericht, en dan vooral in de hoogland locaties, waar de boerderijgroottes sterk afgenomen zijn en waar gemeenschappelijke begrazingsgronden en bossen nagenoeg verdwenen zijn. Het huidige aantal eenheden vee per huishouden is laag en de bronnen om het te voeden zijn beperkt, waarmee de bijdrage die het vee kan leveren aan het onderhouden van de bodemvruchtbaarheid met behulp van dierlijke mest beperkt is. De boerderijen in de hooglanden zijn echter nauw geïntegreerde gewas-vee systemen die gebruik kunnen maken van synergieën binnen het bedrijf om de nutriëntstromen te verbeteren en om gevaren te minimaliseren. Hoewel de huidige bodemvruchtbaarheid laag is, geven de grote potentie om atmosferische koolstof vast te leggen in de vorm van gewasbiomassa (2 productieseizoenen per jaar) en de fijn-textuur gronden voldoende kansen om de productiviteit van bedrijven in de regio te herstellen met behulp van ISFM.

Gewasproductie is zeer variabel binnen kleine boerenbedrijven, voornamelijk veroorzaakt door variatie in het huidige beheer van gewassen (bijvoorbeeld datum van planten en mestgift) en in bodemvruchtbaarheid (beïnvloed door de historie van bodem en gewasbeheer). Het doel van Hoofdstuk 4 was om de relatieve importantie van factoren in het beheer van bodemvruchtbaarheid en gewasgroei op de uiteindelijke gewasproductie vast te stellen. De status van bodemvruchtbaarheid werd bepaald op 522 boerenvelden binnen 60 boerderijen, en deze data werden gecombineerd met meer gedetailleerde gegevens van maïsopbrengsten en agrarisch beheer van 159 velden binnen dezelfde steekproef. Vanwege de complexiteit van de dataset werd een classificatie en regressie analyse (CART) toegepast om gewasopbrengsten en bodem en beheersmaatregelen aan elkaar te relateren. De maïsopbrengsten van velden met verschillende bodemvruchtbaarheidstatus zoals deze door boeren werden geclassificeerd waren: laag, 0.5 tot 1.1, middel, 1.0 tot 1.8, en hoog, 1.4 tot 2.5 ton per hectare. De CART analyse liet zien dat de intensiteit waarmee beschikbare bronnen gebruikt worden, samen met de datum en planning van planten de belangrijkste variabelen waren die de gewasproductie bepaalden. Bij lage intensiteit van gebruik van beschikbare bronnen werden totale bodem stikstof en bodem fosfor belangrijke factoren die de gewasopbrengst bepaalden. Alleen een kleine groep van velden met een gemiddeld hoge maïsopbrengst (2.5 t ha^{-1}; n=8) kreeg nutriënt giften en had goede plant-dichtheden, terwijl de grootste groep velden met gemiddeld lage opbrengsten (1.2 t ha^{-1}; n = 90) bodem Olsen P waarden had van minder dan 4 mg kg^{-1}. Deze classificatie kan nuttig zijn om specifiek agronomisch advies en inputs aan farmers te geven. De resultaten suggereren dat patronen in bodemvruchtbaarheidsvariabilititeit versterkt worden door boeren die hun beschikbare bronnen meer toepassen op vruchtbare velden dan op onvruchtbare velden.

Heterogeniteit in bodems veroorzaakt variabele responsen van gewassen op kunstmest, voornamelijk door de grote variabiliteit in de efficiency van brongebruik binnen een bedrijf. In Hoofdstuk 5 werden grote datasets over maïs productie, behaald onder beheer van boeren (Engelse acroniem: F-M) en behaald onder beheer door wetenschappelijke onderzoekers (Engelse acroniem: R-M), gebruikt om de variabiliteit binnen een bedrijf van de verschillende componenten van de nutriënt gebruiksefficiëntie van maïs te analyseren: nutriënt beschikbaarheid, opname en conversie. Vervolgens werd het eenvoudige model QUEFTS gebruikt om de mogelijke opbrengsten met en zonder het gebruik van kunstmest te berekenen, gebruikmakend van gemeten bodemkarakteristieken in heterogene boerderijen. Het verschil in maïsopbrengsten tussen F-M en R-M velden varieerde van 0.5 tot 3 ton per hectare per seizoen over veldtypes en locaties, en werd niet alleen veroorzaakt door de bodemvruchtbaarheid. Zelfs bij geen toepassing van kunstmest gaven de minst vruchtbare velden onder R-M tot zo'n 1.1 ton per hectare per seizoen meer gewasopbrengst dan velden onder F-M, waarschijnlijk veroorzaakt door de toepassing van betere rassen en beter agronomisch beheer. De relatieve response van maïs op N-P-K meststoffen nam toe met toenemende bodemkwaliteit (bodem C en extraheerbaar P), van een maximum van 4.4 keer tot 0.5 keer de opbrengst behaald bij controle metingen. Bodem organisch C en bodem P beschikbaarheid lieten covariatie zien in in de meest en de in minst vruchtbare velden van de boerderijen, veroorzaakt door het lange termijn beheer van organisch materiaal door boeren: P beschikbaarheden groter dan 10 mg kg^{-1} werden alleen gemeten in bodems met meer dan 10 g kg^{-1} organisch C. Over de locaties en boerderijen was P het meest limiterende nutriënt, alhoewel N nodig is in de grootste hoeveelheden. Bodemheterogeniteit beïnvloedde de nutriënt gebruiksefficiëntie vooral door effecten op de opname van nutriënten (bijvoorbeeld de opname efficiënties varieerden tussen 0 en 70% voor N, 0 en 15% voor P en 0 en 52% voor K), en veroorzaakte minder variatie in de conversie efficiëntie (met gemiddelde waardes van 97 kg drogestof kg^{-1} N, 558 kg drogestof kg^{-1} P and 111 kg drogestof kg^{-1} K opgenomen). Alleen gebruikmakend van de bodemchemische karakteristieken overschatte QUEFTS de gemeten opbrengsten onder F-M, daarmee bevestigend dat de variabele gewasprestaties binnen en tussen boerderijen niet alleen toegeschreven kunnen worden aan nutriënt beschikbaarheden (zie ook Hoofdstuk 4). QUEFTS voorspelde positieve responsen op kunstmest over een breed interval van bodemkwaliteiten, een indicatie dat er ruimte is om de huidige gewasproductiviteit te verbeteren door het gebruik van kunstmest.

De beslissingen die boeren van dag tot dag maken hebben consequenties voor de duurzaamheid van hun bedrijfssysteem, daarmee implicerend dat er meerdere trade-offs plaatsvinden tussen korte en lange termijn doelstellingen met zowel biofysische als socio-economische dimensies. Hoofdstuk 6 laat zien dat technieken op het gebied van invers modelleren effectief gebruikt kunnen worden voor optimalisatie en trade-off-analyses van agrarische bedrijfssystemen. Een algoritme voor de optimalisatie van multipele doelstellingen (MOSCEM) en een gewas/bodem simulatie model werden gecombineerd en gebruikt om bedrijfsstrategieën te selecteren. De trade-offs tussen productiviteit, efficiëntie en duurzaamheid, veroorzaakt door verschillende allocatiepatronen van de beschikbare bronnen (inclusief arbeid), werden geanalyseerd voor een gesimplificeerde boerderij met vooral maïs uit West-Kenia, gebruikmakend van 3 scenario's van geldbeschikbaarheid: 2000, 5000 and 10000 KSh ha^{-1} waarbij 75 KSh = 1 US$. Toenemende maïsopbrengsten door het toepassen van kunstmest werden boven een bepaalde drempel gevolgd door toenemende verliezen van N door uitspoeling en bodem erosie; deze drempel was 2.7 t graan ha^{-1} bij het scenario van afwezigheid van financiële limitaties (10000 KSh ha^{-1}). Verliezen aan N op bedrijfsniveau fluctueerden tussen 36 tot 54 kg N ha^{-1} seizoen^{-1}, terwijl de maximum maïs opbrengsten zo'n 3.4 t graan ha^{-1} bedroegen. Bodem verlies door erosie nam drastisch toe boven een bepaalde maïs opbrengst (bijvoorbeeld 1.8 t graan ha^{-1} voor de 2000 KSh ha^{-1} scenario), terwijl de minimum snelheid van bodemverlies door erosie verbeterde onder de scenario's met meer financiële mogelijkheden. De set van strategieën om een bepaald doel te bereiken was groter en meer divers wanneer de condities slechter waren voor agrarische activiteiten. Investeringen in het huren van arbeid waren belangrijker dan het kopen van kunstmest om hogere opbrengsten te verkrijgen. Allocatie van kunstmest en arbeid vond preferentieel plaats op de velden dicht bij de locatie van de boerderij zelf, waar de efficiëntie van nutriënt opname het hoogst was. De productie kon opgevoerd worden tot een bepaald niveau waarboven N verlies drastisch toenam, wat vooral veroorzaakt werd doordat op dat moment kunstmest ook op de meest gedegradeerde velden werd toegepast.

De bevindingen die hierboven beschreven zijn laten zien dat de gedegradeerde buitenvelden (dit is: relatief ver van het huis) gerehabiliteerd moeten worden door toepassing van organisch materiaal, voordat de gewassen op deze bodems reageren op nutriënt applicaties. Studies over ISFM opties laten synergistische effecten zien van de gecombineerde applicatie van dierlijke mest en kunstmest. Echter, de evaluatie van ISFM opties moet ook de volgende kernkarakteristieken van kleine boerenbedrijven meenemen: 1. Bodem heterogeniteit die veroorzaakt is door beheer; 2. Lange termijn dynamiek; 3. De gelimiteerde beschikbaarheid van dierlijke mest die bovendien veelal van slechtere kwaliteit is dan die welke die getest wordt in gecontroleerde experimenten; 4. De gelimiteerde toegang to kunstmest; en 5. De competatitieve toepassingen van crop residuen op de boerderij. In Hoofdstuk 7 werd het eenvoudige dynamische simulatiemodel FIELD gebruikt om lange termijn beheersstrategieën in de allocatie van realistische hoeveelheden kunstmest en dierlijke mest te onderzoeken, gebruikmakend van bodem en mest kwaliteitswaarden gemeten op studieboerderijen in West-Kenia. Het model was gekalibreerd en getest met behulp van 4 datasets met daarbij data van de lange termijn gewas en bodem dynamiek. Het model beschreef de variabiliteit in gewas reacties op kunstmest binnen een bedrijf. Verschillende klassen in de mate van respons op toenemende hoeveelheden toegepaste N kunstmest (van 0 tot 180 kg N ha^{-1} (+/- 30 kg P ha^{-1}) konden worden onderscheiden: velden met een hoge bodemvruchtbaarheid met weinig respons (graan opbrengsten tussen 4.1 en 5.3 t ha^{-1} zonder P en tussen 7.5 en 7.9 t ha^{-1} met P), velden met een hoge respons (1.0 tot 4.3 t ha^{-1} en 2.2 tot 6.6 t ha^{-1}) en velden met een lage bodemvruchtbaarheid met weinig respons (0.2 tot 1 t ha^{-1} en 0.5 tot 3.1 t ha^{-1}). Bodems die gedurende 12 jaar een gecombineerde toepassing kregen van dierlijke mest en kunstmest sloegen tussen 1.1 en 1.5 t C ha^{-1} $jaar^{-1}$ op wanneer 70% van de gewasresiduen opnieuw werd gebruikt in het veld, en tussen 0.4 en 0.7 t C ha^{-1} $jaar^{-1}$ wanneer slechts 10% van de residuen opnieuw werd gebruikt. Gedegradeerde buitenvelden konden niet hersteld worden met dierlijke mest met de gemiddelde kwaliteit zoals die beschikbaar is in boerderijen in West-Kenia (23 – 35% C, 0.5 – 1.2% N, 0.1 – 0.3% P) na een applicatieperiode van 12 jaar met een hoeveelheid van 1.8 t droge stof ha^{-1} $seizoen^{-1}$, zonder kunstmest. Toepassing van de beste kwaliteit dierlijke mest van de regio (39% C, 2.1% N, 0.2% P) leidde tot een toename van ongeveer 1 t C ha^{-1} $jaar^{-1}$ in de meest arme velden. Verschillen in de kwaliteit van de dierlijke mest, de initiële bodemcondities en combinaties van dierlijke mest en kunstmest hebben een verschillende mate van *hysterese* van bodemherstel tot gevolg. Kunstmest kan bijdragen in de initiële fase van bodemherstel om daarmee de biomassa productie te verhogen die weer kan leiden tot een hogere potentiële C instroom naar de bodem.

Gedurende participatieve prototyperingsactiviteiten in Vihiga, West-Kenia, ontwierpen boeren wat zij beschouwden als de ideale boerderij (Waithaka et al., 2006): dit bleek een boerderij te zijn waarin hoge productiviteit bereikt kan door de interacties tussen de gewas en vee componenten te optimaliseren. Drie belangrijke observaties werden gedaan tijdens deze oefening: 1. Boeren hebben een optimistische blik op de klimatologische en markt omstandigheden onder welke deze ideale systemen zouden werken; 2. Boeren hebben de neiging de grootte van de stromen tussen het gewas en vee componenten te overschatten; 3. The productiestructuur van de ideale boerderij lijkt erg op hoe de rijkere boerderijen er op dit moment uitzien in de regio. Het doel van Hoofdstuk 8 was om de fysische mogelijkheden te analyseren om de productiestructuur van de huidige boerderijen te veranderen zodat deze meer op de ideale boerderij zouden lijken, waarbij de rijke boerderijen van dit moment als referentiepunt dienden. Een dynamisch simulatiemodel op boerderijniveau (NUANCES-FARMSIM) was geparameteriseerd met data van vier casestudy boerderijen van Type 1 tot 4 (zie Hoofdstuk 2) om daarmee te onderzoeken: (i) wat de huidige verschillen in efficiëntie en mate van gewas en vee interacties tussen de verschillende boerderij typen zijn; en (ii) wat de impact van verschillende interventies is om de gewenste verschuivingen in de richting van de ideale boerderij te verkrijgen. Simulaties werden uitgevoerd voor 10 jaar, en veranderingen in de systemen werden stapsgewijs geïntroduceerd in de vorm van intensivering van gebruik van inputs en kwalitatieve veranderingen in de boerderij configuratie. De resultaten laten zien dat voedselzelfvoorziening van huishoudens (uitgedrukt in energie eenheden) kan worden bereikt in alle typen boerderijen door intensivering van de inputs. Echter, de mogelijkheden om interventies te implementeren op een groot aantal boerderijen is twijfelachtig. De impact van vee op het hergebruik van nutriënten en op de efficiëntie van het gebruik van nutriënten op boerderijniveau kan groot zijn, onder de voorwaarde dat genoeg nutriënten beschikbaar zijn, of genoeg nutriënten het systeem binnen komen om herverdeeld te worden. Echter, het traject van verandering in de richting van de ideale boerderij is nauwelijks mogelijk voor de meerderheid van de huidige boerderijen in de regio.

Agroecologische potentie en markt mogelijkheden bepalen de manier waarop een regio of locatie boeren kan stimuleren in hun strategie om te blijven doorgaan (‘hanging-in’), te ontwikkelen (‘stepping-up’) of te stoppen (‘stepping-out’). Bevolkingsdichtheid opereert als een stressfactor die kan leiden tot veranderingen in leefstrategieën. Terwijl landelijke families zich kunnen aanpassen aan deze stress door middel van verschillende strategieën, zijn er drempelwaarden in het bezit van goederen (bijvoorbeeld land) waaronder families gedwongen zijn om te stoppen met landbouw als hun belangrijkste activiteit. De duurzame intensivering van landbouw praktijken is noodzakelijk om deze drempelwaardes te verlagen, vooral in gebieden waar de traditionele methoden om de bodemvruchtbaarheid te waarborgen niet meer mogelijk zijn. ISFM technologieën moeten specifiek ontworpen worden om aan te sluiten bij de diversiteit aan levensstrategieën, zonder daarbij de bredere context waarin boerderijen opereren uit het oog te verliezen. Terwijl sommige technologieën een ontmoedigend laag niveau van adoptie hebben, hebben andere technologieën specifieke socio-economische niches gevonden, en verspreiden zich spontaan over boeren. Het proces om ISFM technologieën breder toepasbaar te laten zijn, zou de belangrijkste karakteristieken van boerderijen mee moeten nemen – heterogeniteit, diversiteit en dynamiek – op een manier waarin deze complexiteit gecategoriseerd en verstevigd wordt.

Resumen

Msimu wa Kupanda[†]

Asignando recursos para un manejo integrado del suelo en sistemas agrícolas diversos, heterogéneos y dinámicos del África oriental

El agotamiento de la fertilidad del suelo es el factor más importante responsable de la caída en la producción *per capita* de alimentos en el África sub-sahariana (ASS). Con un ritmo de crecimiento poblacional mayor que la tasa de incremento de la producción agrícola, y con una reducción del área de nuevas tierras disponibles para la agricultura, el rendimiento unitario de los principales cultivos alimenticios debe necesariamente aumentar. La implementación de sistemas tradicionales de manejo del suelo – basados en desmontes transitorios, barbechos, uso de estiércol – se ve cada vez más restringida por el continuo aumento poblacional, lo que trae aparejado la disminución del tamaño promedio de las explotaciones y de las áreas comunales para el pastoreo del ganado o la recolección de biomasa. La pérdida de productividad de las tierras es aún más aguda en zonas de mayor potencial agro-ecológico, las cuales han recibido una mayor afluencia de población atraída por suelos originalmente fértiles y lluvias abundantes.

El manejo integrado de la fertilidad del suelo (MIFS) es un enfoque integral para el mejoramiento o la restitución de la productividad del suelo. El MIFS se basa en las sinergias positivas entre el efecto de fertilizantes minerales y orgánicos utilizados en forma conjunta, el uso de germoplasma mejorado y la fijación simbiótica de nitrógeno atmosférico. Sin embargo, hasta el presente, la adopción de técnicas de MIFS por parte de los agricultores de pequeña escala en ASS ha sido muy limitada. Esto se debe en parte a que las particularidades de los sistemas agrícolas en ASS no son siempre tenidas en cuenta en el diseño de intervenciones para promover el MIFS, en parte a problemas en la difusión de las tecnologías, y/o a la falta de contextualización de las mismas en el marco de los modos de vida rurales en los sistemas de producción familiar, predominantemente de autoconsumo o subsistencia.

Los sistemas agropecuarios mixtos de pequeña escala (SAMPE) en el ASS son sumamente diversos, espacialmente heterogéneos y dinámicos, operando a menudo en ambientes socio-ecológicos complejos. Gran parte de la heterogeneidad de estos sistemas radica en la variabilidad espacial del suelo, que resulta a su vez de la interacción entre la variabilidad edáfica inherente al paisaje y la variabilidad inducida por la historia de uso y manejo de las tierras. Con frecuencia, las intervenciones tecnológicas orientadas a mejorar la productividad de los cultivos generan respuestas variables sobre estos suelos y muy baja eficiencia en las peores parcelas de la explotación. Las tecnologías necesarias para mejorar la productividad del suelo deben ser orientadas estratégicamente para asegurar su efectividad y su propensión a mejorar

[†] Del Swahili: 'Tiempo de plantar'

la eficiencia en el uso de los recursos (por ej. tierra, mano de obra, nutrientes) a escala de la explotación.

Los aspectos clave a tener en cuenta en el diseño de tales estrategias para los SAMPE incluyen: 1. La variabilidad inherente al clima y la geología a lo largo de gradientes agro-ecológicos y edáficos; 2. La diversidad social, orientación productiva y estrategias de sustento de las familias rurales; 3. Los gradientes de fertilidad edáfica inducidos por el manejo dentro de las explotaciones de pequeña escala, sus causas, y su consecuencias para el uso eficiente de recursos productivos escasos; 4. El conflicto entre objetivos de producción inmediatos y de sustentabilidad en el largo plazo; 5. La complejidad de los indicadores de referencia utilizados por los agricultores en su evaluación de estrategias. Este estudio utiliza un marco analítico (NUANCES – Uso de Nutrientes en Sistemas de Producción Agropecuaria - Eficiencias y Escalas) en el cual técnicas de análisis de sistemas son apoyadas por encuestas, experimentos y modelación en el análisis de escenarios futuros de uso y manejo de las tierras. Utilizando estudios de caso de las regiones altas del África oriental, de moderado a elevado potencial agro-ecológico, este trabajo es una contribución al diseño de tecnologías para el MIFS hechas 'a medida' de los sistemas locales, combinando el uso de fertilizantes minerales y orgánicos, y evaluando intervenciones de largo plazo estratégicamente orientadas a los sistemas de explotación familiar diversos y heterogéneos que pueblan las zonas rurales del ASS.

En un análisis comparativo, seis distritos en las regiones centro y oeste de Kenya y este de Uganda con diferente potencial agoecológico y grado de acceso a mercados fueron relevados en términos biofísicos y socioeconómicos, mediante encuestas y muestreo sistemático de suelos (Capítulo 2). Las densidades de población en zonas rurales variaron entre 250 y más de 1000 habitantes km^{-2}, las que se correspondieron con 11 y 4 meses por año de autosuficiencia alimentaria, respectivamente. En base a su dotación de recursos productivos, su dependencia de ingresos por actividades extra-prediales y sus objetivos de producción, los hogares rurales encuestados (n = 250) fueron categorizados en cinco tipos de explotación (TE): 1. Las subsidiadas por empleo y/o ingresos extra-prediales permanentes; 2. Las orientadas al mercado produciendo cultivos comerciales a pequeña o mediana escala; 3. Las correspondientes a familias en expansión (jóvenes) de clase 'media' con estrategias de sustento diversas; 4. Las de subsistencia, en parte realizando actividades no agrícolas (por ej. alfarería); y 5. Las dependientes del empleo rural local, normalmente empleados por los TE 1 y 2. Más allá de sus diferencias en términos de acceso a recursos productivos, estos TE difirieron más en el grado de heterogeneidad espacial que en el nivel de fertilidad promedio de sus suelos, con un menor grado de heterogeneidad en las explotaciones que poseían ganado.

La productividad del maíz, el principal cultivo alimenticio en la región, se mostró ampliamente variable dentro de explotaciones individuales, fuertemente influenciada tanto por la heterogeneidad edáfica como por las prácticas de manejo del cultivo (Capítulo 3). De hecho, en un análisis clasificatorio utilizando árboles de regresión (CART) las variables: intensidad de insumos utilizados, época y densidad de siembra fueron las de mayor jerarquía en la determinación del rendimiento de maíz en parcelas de agricultores en la región oeste de Kenya; sólo en aquellas parcelas que no recibieron insumos los nivel de N total y P disponible adquirieron mayor importancia en la determinación del rendimiento (Capítulo 4). La heterogeneidad del suelo afectó la respuesta del maíz a la aplicación de N y P en forma de fertilizantes minerales; la misma osciló ente – 0.5 y +4.4 veces más que los testigos sin fertilizar en suelos con contenidos de C orgánico y P disponible variables (Capítulo 5). En diferentes sitios del oeste de Kenya P fue el nutriente más limitante del rendimiento, en tanto que disponibilidades de P > 10 mg kg^{-1} sólo fueron observadas en suelos con > 10 g kg^{-1} de C orgánico. Esta co-variación es inducida por decisiones de manejo cotidianas en la asignación de recursos nutritivos (por ej. abonado con estiércol), los que son normalmente concentrados en las parcelas de la explotación más cercanas a la vivienda.

Un estudio basado en técnicas de modelación inversa permitió analizar y cuantificar el efecto de este tipo de estrategias, acoplando el modelo de simulación dinámico de suelo/cultivo DYNBAL con un algoritmo de optimización del tipo Metrópolis (MOSCEM), vinculando la simulación de prácticas de manejo a la disponibilidad de mano de obra en la explotación (Capítulo 6). En una explotación tipo, espacialmente heterogénea, la asignación de fertilizantes y mano de obra favoreció a las parcelas con mayor calidad de suelo, cercanas la vivienda, donde la eficiencia de captura y utilización de los nutrientes aplicados por parte del cultivo fue mayor. A escala de la explotación, la productividad del suelo pudo ser mejorada mediante el uso de fertilizante nitrogenado hasta un umbral máximo, mas allá del cual las pérdidas de N por lixiviación y de suelo por erosión aumentaron en forma abrupta, especialmente en escenarios en que las parcelas más degradadas fueron cultivadas con maíz y fertilizadas con N para aumentar la producción total del establecimiento. Éstas parcelas, sumamente degradadas por años de cultivo sin insumos ni medidas de conservación, requieren de su rehabilitación mediante tecnologías de MIFS que aseguren adiciones continuas de materia orgánica al suelo como pre-requisito para obtener una respuesta del cultivo a los fertilizantes minerales. Sin embargo, la calidad de los abonos de origen animal comunes en la región (por ej., 23 – 35% C, 0.5 – 1.2% N, 0.1 – 0.3% P) y su disponibilidad a nivel de la explotación son demasiado limitadas como para permitir suficiente histéresis el la rehabilitación de estos suelos (Capítulo 7).

Por otra parte, los residuos de cosecha, que son fundamentales para inducir acumulación de materia orgánica en el suelo mediante uso de fertilizante, tienen diversas formas de aprovechamiento en los SAMPE. Su uso como alimento para el ganado o como combustible para la cocina implican su remoción casi completa de la parcela al final de cada ciclo de cultivo. Simulaciones con el modelo para dinámicas de suelo-cultivo de largo plazo FIELD, que fue calibrado y testeado para la región utilizando 4 bases de datos independientes, indicaron un incremento en la cantidad de C orgánico almacenado en el suelo, luego de 12 años de aplicaciones anuales de fertilizantes y abonos orgánicos, de entre 1.1 y 1.5 t C ha^{-1} $año^{-1}$ cuando 70% del residuo de cosecha fue incorporado en el suelo, y de 0.4 a 0.7 t C ha^{-1} $año^{-1}$ cuando sólo el 10% fue incorporado. Sin embargo, el uso de residuos de cosecha como forraje permitiría mantener más animales y obtener más estiércol para el abonado de los campos. Cuando grupos de campesinos en el oeste de Kenya diseñaron, en forma participativa, prototipos de lo que ellos consideraban la *explotación agrícola ideal,* su énfasis residió en la importancia de capitalizar estas interacciones entre los subsistemas animal y vegetal dentro del predio, con una tendencia a la sobreestimación de los posibles flujos de nutrientes entre subsistemas. La factibilidad biofísica para la intensificación de estas interacciones fue analizada utilizando el modelo a escala de explotación FARMSIM, que vincula al modelo FIELD con modelos de simulación del subsistema ganadero y del reciclaje de nutrientes a nivel predial (Capítulo 8). Las interacciones ganado-cultivo manejadas en forma intensiva permitieron una mayor eficiencia en el ciclado de los nutrientes incorporados al sistema mediante fertilizantes. Sin embargo, la trayectoria a cubrir para transformar a las explotaciones actuales en algo cercano a la explotación ideal es muy extensa, y la factibilidad de los cambios necesarios difícilmente factible para la mayoría de las familias rurales de la región.

El potencial agro-ecológico junto con las oportunidades de mercado en una región determinada estimulan y condicionan la adopción de diferentes estrategias de sustento entre las familias rurales, ya sea de subsistencia, comerciales o extra-prediales (por ej. trabajo asalariado). El crecimiento poblacional es un factor de estrés sobre los SAMPE que es capaz de inducir desplazamientos entre tales estrategias de sustento. Si bien diferentes familias rurales muestran distinto grado de adaptación a estos factores de estrés, existen asimismo umbrales mínimos de dotación de recursos productivos (por ej. tamaño de la explotación) por debajo de los cuales la mayor parte de la población rural se ve forzada a abandonar la agricultura como medio de sustento (Capítulo 9). Por ello, se requiere con urgencia una intensificación sustentable del manejo de los recursos productivos que permita reducir tales umbrales, especialmente en zonas del ASS donde los sistemas tradicionales de manejo del suelo resultan ya impracticables. Este estudio demuestra que las tecnologías de MIFS sólo podrán contribuir a tal efecto en la medida en que sean diseñadas a medida y en el contexto de la realidad que enfrenta a los SAMPE. Mientras ciertas tecnologías muestran un desalentador nivel de adopción entre los agricultores, aquellas que han encontrado su nicho ‘socio-ecológico’ dentro de los SAMPE se diseminan espontáneamente – boca a boca – entre campesinos. Estos nichos deben ser identificados mediante el análisis y la categorización de la diversidad, heterogeneidad y dinámica de los complejos sistemas rurales, como paso previo al diseño y promoción de cualquier intervención tecnológica.

Acknowledgements

I have counted a total of 19 co-authors in the various chapters of this thesis, plus some other 33 names mentioned in the acknowledgement paragraphs at the end of each chapter. This says something: I would not have been able to do all this work alone. There is thus a large number people I want to thank, but there is also a certain limit to the final length of this book. Since I don't want to omit anybody (although, involuntarily, I might anyway) I just decided to reduce the font size in the following paragraphs. I hope this is not too annoying.

Let me start by saying a few words about some people who have been very special in my career during the last years. Prof. Dr. Ken E. Giller, my main supervisor. His ideas are challenging and his enthusiasm contagious. He walked me into African farming systems analysis when I started doing my MSc thesis with him in 2002. Now I can't walk away from it anymore. I want to emphasise his continuous support (in the widest possible sense of the word) throughout the completion of this work and to acknowledge with gratitude all the doors he opened for me during these years. Thanks Ken for teaching me a critical view on research, for keeping me motivated about my work and for all the space and freedom you created for me during these years.

Bernard Vanlauwe, my supervisor in Kenya, is a person I highly admire as a scientist and deeply esteem as a friend. His input to my work has been enormous, strongly influencing my way of doing science. We have many things in common with Bernard, both personally and professionally, but the most conspicuous is probably this: we both feel we are somehow frustrated musicians (and there is hardly any musician that feels a frustrated scientist!). It's never too late to start…

Mark van Wijk has always been there to solve what (to me) looked like the most difficult problem ever: "*Tsj, aaah, that's easy…*" has always been his answer. The few times we had the chance to spend (quality) time working together, either at Wageningen or in Kenya, had been very fruitful and plenty of ideas and progress came out of those interactions (as testified by Chapters 6 and 8 of this thesis). Mark, I enjoyed the tough discussion we often got into!

I had two other 'unofficial' supervisors, advisors or collaborators – whatever you may call them, Nico de Ridder and Marc Corbeels have been always around for help and discussion. In discussion meetings within the team I often feel identified with Nico's point of view, and that's not pure chance. His experience in Africa, his flexibility to work within a wide range of topics, and his often pragmatic approach to science are qualities I'd like to build in my own career. Marc's inputs and ideas have been crucial to my work, and with nobody else as with him I have discussed concepts in so much detail.

Other people have also been very influential in my work, and their names can be found mentioned here and there in my thesis. But most importantly, these people became my friends during these years. Mariana Rufino, with whom I bounce ideas all the time (sometimes too many!); Michael Misiko, with his challenging view on research and development; and Mario Herrero, whose creativity has always been inspiring. I hope, and will do anything possible, to continue working with all of you in the future.

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Although intermittently, I spent a sufficient number of months in Wageningen to share time and space with different people. I was lucky to have shared office with Shibu and Senthilkumar, two wonderful people. I am happy to have had Rik, Tom, Jessica, Pytrik (thanks for the tips on formatting!), Shamie, Marjolein, Barbara, Dirk, Claudius, Glaciela, Ousmane, Kenneth, Amos, Ilse, Jochem, Crispen, Frank, Maja, Martin, Sander, Jens, Bert, Marcel, Eelco, Ria, Charlotte, and more recently Peter, Yen, Michiel, Myriam, Lenny, Argyris and Sander as colleagues. I apologise for not having participated more frequently of coffee breaks and other social events – I've always been in such a rush while in Wageningen.

The first week I stepped in Wageningen back in August 2000 I met Eduardo Cittadini, who became a friend and an influencing colleague ever since. Outside the University, my friends Marcos and Roxy (thanks to both for reviewing the summary in Spanish!), Michilio, Luis, Edward, Benoit, Adriana, Rebeca, Gabriela, Alejandra, Gustavo, Riannon, Jan, Melchert, Jaime, Mariana, my anti-kraak housemates Joost and Noor, and all of Simone's friends and family who became also mine, made my life better. Mark, Sandra, Hans, Marian, Herman, Aad: your affection has been very important for me. Thanks Els and Rienk for hosting us!

Thanks to all friends and family in Argentina and the world for their continuous support manifested mostly through e-communication and in the warmest welcome every time I go back home. Thanks specially to my parents, who have to bear with having a child living and working so far from home.

Finally, I want to thank a person who is largely responsible for my being where I am and working on what I do. If I have to find an analogy or an image to synthesise what Simone meant for me all these years, I immediately think of light. But not like in 'I saw the light with her…' or anything like that. Simply, she *was* a kind of light, or different kinds at different times. A light that shone a new path in my career, awakening my enthusiasm in doing research for development. A green light telling me: go for it! Or, very often, a red light that stopped me from deviating my way or from going too fast. Thus, I do not want to thank her for her unconditional love – I wouldn't do that at the back of a thesis – but for being one of the toughest reviewers of my work, in all senses, and a guardian of my integrity.

Curriculum Vitae

Pablo Adrian Tittonell was born on January 29, 1971 in Lomas de Zamora, Buenos Aires, Argentina. He pursued all his education in public institutions, from primary school to university, including his passage through the 'Otto Krause' National School of Technical Education, Buenos Aires, where he graduated as a technician in chemistry in 1989. After taking one year of biochemistry at the University of Buenos Aires, he quit his course, and joined a study group on ethnography and indigenous cultures – it was 1992 – with whom he co-funded a short-lived magazine '*Milenaria*', and took to travel through South America. From 1993 to 1997 he studied agronomy at the National University of Lomas de Zamora (UNLZ), where he was engaged in the Department of Soil Science as a student assistant. During 1997 he took courses on Oliviculture at the University of Cordoba, Spain as part of an academic exchange program, and wrote his final academic project on olive oil production. After graduating as Agronomic Engineer he worked in the private sector, consecutively in food processing and seed technology companies, and as a free-lance agronomist, while keeping a part-time involvement in research and education at the university. In 1999 he started an MSc in Soil Science at the University of Rio Cuarto, Argentina. His thesis project, which dealt with assessing variability in soil carbon stocks in agricultural landscapes of central Argentina, was interrupted due to financial reasons. He was briefly employed as research assistant at the Department of Horticulture of UNLZ, before obtaining a NUFFIC fellowship to pursue MSc studies at Wageningen University, from September 2001. He joined the Plant Production Systems Group (PPS), and spent the fieldwork period for his thesis at the Tropical Soil Biology and Fertility Institute of CIAT (TSBF-CIAT) in Kenya, analysing causes and consequences of human-induced soil fertility gradients in smallholder farming systems. He graduated (*Cum Laude*) as the last ever MSc in Theoretical Production Ecology in March 2003. He lived in Santiago de Chile during 2003-2004, from where he worked as free-lance research consultant, engaged in commercial farming, and obtained means to finalise his first MSc thesis project from Argentina in October 2004. In December 2004 he re-joined PPS as a PhD fellow to develop his thesis in the framework of the EU-funded AfricaNUANCES project. He was based for two years at TSBF-CIAT with intermittent periods spent at Wageningen during the completion of this PhD thesis. He has collaborated with different NGO's since the last years of his studies of agronomy, and continues to do so. He is currently employed as researcher at PPS.

Publications[†]

1. Journal articles

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PE&RC PhD Education Certificate

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

Review of Literature (5.6 ECTS)
- The impact of sol improving technologies within the wider livelihood strategies of African farmers; opportunities for a participatory modelling approach (2004)

Writing of Project Proposal (7 ECTS)
- Exploring options, analysing tradeoffs and deriving indicators of efficiency for integrated nutrient management in smallholder farming systems of East Africa (2004)

Laboratory Training and Working Visits (4.3 ECTS)
- Long-term changes in soil carbon and grain yield of millet and sorghum on sandy soils (ICRISAT – Niger, 2005)
- Field visit AfricaNUANCES project sites in Tanzania (LIZARDI, 2005)
- Field visit AfricaNUANCES project sites in Uganda (NARO, 2005)
- Field visit AfricaNUANCES project sites in Zambia (Ministry of Agriculture, 2005)
- Field visit AfricaNUANCES project sites in Zimbabwe (University of Zimbabwe, 2007)
- Field visit AfricaNUANCES project sites in Mali (IER Sikasso, 2007)

Post-Graduate Courses (7 ECTS)
- Multi-criteria decision-making (Mansholt Gaduate School, 2005
- Multivariate analysis (PE&RC, 2006)
- Land science: Bringing concepts and theory into practice (PE&RC, 2007)

Competence Strengthening / Skills Courses (1.4 ECTS)
- Use of data-mining statistical packages (Salford-Systems, 2005)

Discussion Groups / Local Seminars and Other Meetings (4.7 ECTS)
- Monthly meetings of PhD students at TSBF (Nairobi, Kenya, 2005/7)
- Annual TSBF planning meeting (CIAT, Nairobi, Kenya, 2005/7)
- Annual CIALCA planning meetings (IER, Kigali, Rwanda, 2005/7)
- Annual AfricaNUANCES workshops (Wageningen/ Arusha, Tanzania, 2005/7)
- Seminar on AfricaNUANCES analytical approach (Florence University, Italy, 2005)
- Seminar on Framing Systems Analysis, ATP Project (CIRAD, Montpellier, France, 2007)

PE&RC Annual Meetings, Seminars and the PE&RC Weekend (0.6 ECTS)
- PE&RC day: Biological disasters (2004)
- PE&RC day: COLLAPSE : Is our civilization able to stand the test of time? (2007)

International Symposia, Workshops and Conferences (7 ECTS)
- 14th International N Workshop, Maastricht, The Netherlands (2005)
- Farming Systems Design. An international symposium on methodologies for integrated analysis of farm production systems. Catania, Sicily (2007)
- International meeting of the Africa Soil Fertility Network (AfNet). Innovation as Key to the Green Revolution in Africa: Exploring the Scientific Facts, Arusha, Tanzania (2007)
- XVII Congreso Latinoamericano de la Ciencia del Suelo, León Guanajuato, México (2007)