Soil fertility gradients in smallholder farms of western Kenya.

Their origin, magnitude and importance

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MSc Thesis Production Ecology

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Preface and acknowledgements

Since the first contact I had with Prof. Dr. Ken Giller and Dr. Bernard Vanlauwe I had the chance to express my personal motivations concerning this thesis: to learn by putting into practice the knowledge and skills acquired during my education, and to produce a piece of work that could be useful for others (literally, that would not 'sleep' forever on the shelves of a university library). As for the first one, I have no doubt I have achieved it. I hope the information compiled here on the origin, the magnitude and the importance of within-farm soil fertility gradients can be used in further efforts to improve the livelihood of poor farmers in sub-Saharan Africa, by enhancing the agroecosystem production and environmental service functions.

This MSc thesis is based on fieldwork carried out in western Kenya in 2002, relying on the experience, the effort and the support of many people I would like to acknowledge. Thanks to the TSBF staff at Maseno, western Kenya. Specially thanks Mr. Isaac Ekise and Mr. John Mukalama for collaborating with this work and deliberately adding your experience to improve its quality. Thanks Extension Officer Mr. Walter Munyuere for your continuous support. Thanks Mr. Daniel Rotich at KARI Kakamega for sharing your experience. Thanks to the TSBF staff at Nairobi, particularly to Laboratory Technician Mr. Benson Muli for your efforts to get things ready on time (and for your patience). Thanks Mr. Alex Awiti for your support in GIS matters. Thanks Dr. Keith Shepherd and staff for your collaboration with the spectral reflectance analysis. Thanks Dr. Stephen Nandwa, Dr. Richard Coe and Dr. Jac Thissen for your advice.

Two persons helped me enormously with their critical comments, their knowledge and perspective: Dr. Joshua Ramish and Dr. Ed Rowe. Thanks Ir. Simone de Hek for your critical opinions and technical support throughout the entire process that led to this final result, and thanks *Siemtje* for your personal support. I am grateful to Wageningen University for financially supporting my studies.

Goethe once wrote: "The moment one definitely commits oneself then providence moves too. All sorts of things occur to help one that would never otherwise have occurred. A whole stream of events issues from the decision, raising in one's favour all manner of unforeseen incidents and meetings and material assistance, which no-one could have dreamt would come their way". For influencing my commitment, and for the consequences of it, I am indebted to my supervisors at Wageningen University, Prof. Dr. Ken Giller and Dr. Ir. Peter Leffelaar, and at the Tropical Soil Biology and Fertility (TSBF) program - Nairobi, Dr. Bernard Vanlauwe.

Summary

Soil fertility depletion in smallholder farms is the main biophysical process explaining the decline in per capita food production in Africa. Such a process, which is the result of continual export of produce and lack of external inputs into the farm, is not homogeneously distributed in space. Variability in soil fertility arises from differences in underlying geology and geo-morphology, and due to a number of mechanisms within the farming systems. Such is the case of the net flow of resources, which is not equal for the various fields belonging to a single farm household, creating areas of carbon and nutrient accumulation and depletion. Additionally, those nutrient flows vary strongly between farmers of different social status. The biophysical processes involved in the inherent productivity of the soils and in the mechanisms of response to interventions are subjected to this spatial heterogeneity in soil quality, defined here as soil fertility gradients. Therefore, the existence of such gradients within smallholder farms must be considered when designing integrated soil fertility management strategies.

This thesis was developed with the overall goal of identifying and defining spatial-temporal niches for targeting soil fertility strategies, and with the objectives of (i) quantifying the magnitude of the soil fertility gradients, (ii) documenting the factors driving farmers decision making processes that lead to their establishment, (iii) assessing their impact on crop productivity and (iv) studying the potential of simulation models as an approach to evaluate the effect of alternative management practices. Additional objectives, which were necessary to characterise the system under study, responded also to the information needs for the development of NUANCES (Giller and van Keulen, 2001), the framework project into which this thesis was carried out. Potential answers to the research questions were formulated into the hypothesis that are summarised as follows. The soil fertility gradients are originating from the inherent productivity plus the effect of the differential management practices that farmers consequently apply. The magnitude of such gradients, strongly affected by (site-specific) biophysical and socio-economic conditions, is sufficiently large to affect the basic soil and plant processes that dictate the efficiency of resource use and capture within the system. Their importance should be recognised (exactly as farmers do) and they should be targeted when designing soil fertility management strategies.

The various sources of variability affecting soil fertility and operating at different scales were categorised as Site-specific factors, Wealth, Inherent biophysical properties and Management factors (SWIM – Vanlauwe, 2001). The methodological approach combined different techniques to study these (Chapter 2). Three sites (Emuhaia, Shinyalu and Aludeka) were selected in western Kenya to represent the regional variability in terms of the SWIM factors. Background information and expert knowledge, transect walks and soilscape delineation, and 'first-approach' interviews were used to describe and categorise the socio-economic and biophysical variability at different scales. A farm typology was developed according to household wealth, objectives and factor constraints. The concept of farm developmental cycle and the importance of off-farm income were also considered in the farm stratification. Interviews, farmers' rankings and resource flow maps, complemented with partial nutrient balances, conducted at case-study farms were used to identify resource allocation patterns.

Allometric models were developed to estimate on-farm maize yields from non-destructive plant measurements. All aspects of crop husbandry (i.e. the 'management' factors) were recorded for the (geo-referenced) points where the plant measurements were taken. The biophysical characterisation of the fields included slope and area measurements, soil profile observations and soil sampling for analysis by standard methods and by spectral reflectance. Ten soil fertility indicators plus a spectral soil fertility index were used in combination with a number of indexes representing the various management factors to build multiple linear regression models to explain maize yield variability. A dynamic simulation model combining well-known and relatively data-undemanding sub-models to calculate nitrogen balances at plot scale was developed in a FST (Fortran Simulator Translator) format. The model was parameterised with the field data and simulation scenarios were developed from the resource flow map information. The model was run to study the synergistic effect of soil fertility and management factors and to illustrate the importance of the soil fertility gradients in determining the efficiency of resource use when different management strategies are applied.

Widely different resource allocation patterns at farm scale were identified when the between-farm variability was categorised by adding household objectives and factor constraints to the wealth ranking criteria (Chapter 3). The type and magnitude of the off-farm income (labour: income ratios) had an important impact on the nutrient flows to and from the farm. Five farm types were identified. The small and wealthy type 1 farms, largely dependent on off-farm income, tended to remove their land and labour limitations by hiring in those factors and to increase their production by intensification (i.e. input use). The large, wealthy and market-oriented type 2 farms had the highest variability in land quality and production activities, acquiring labour and inputs from the market. The relatively large, self-subsistence and labour-limited type 3 farms had the largest grain production under a low-input situation, selling their surpluses on the market, and often alternative (seasonal) enterprises were observed in those farms (e.g. oxen services, buying and retailing grains at farm gate). The land-limited type 4 and type 5 farms differed in their factor allocation strategy. Type 4 farms had basically a similar strategy as that of type 3, but were not self-sufficient in grain production. The poorest type 5 farms sold most of their labour to the wealthier farm types. The resource flow maps conducted at case-study farms of those types revealed differences in food production, fertiliser use and crop residue management between farm types and between field types within a farm. Particularly for the poorer types (4, 5 and to some extent 3) areas of depletion and accumulation of C and N were revealed by the partial nutrient balances. The home gardens sustained an important proportion of the food production and some cash crops in those farm types. A notoriously different intensity of resource use was observed for the different land quality classes (i.e. 'fertile', 'average' and 'poor') identified by farmers in all farm types. Despite the district surveys and the interviews indicated that most farmers used fertilisers, the partial nutrient balances were negative, indicating that the amounts used are not sufficient to compensate the amounts of nutrients removed from the fields and exported from the farm.

Differences in soil fertility between sites were mainly explained by inherent properties, such as soil texture, which determined to a large extent the C and related total N and P contents, and the effective cation exchange capacity of the soils (Chapter 4). At farm scale, certain nutrients such as P and K showed important differences between field types, due to concentration of resources and use of ash inputs in the fields near the homestead. Indicators such as soil C and pH varied strongly at farm and at individual field scales, though such differences were not reflected by their average values (n = 20 farms per site). Most soil fertility indicators varied between the land quality classes ranked by farmers. The nutrient status of most soils sampled was below the critical limits given in literature, which was confirmed by the negative values of the soil fertility index (SFI) obtained by spectral reflectance. However, the SFI explained a disappointingly small amount of the maize yield variability. Instead, the intensity of resource use, particularly in the densely populated areas, explained ca. 50% of that variability. Other *management* factors explained between 40 and 60% of the yield variation. They differed between farmers' land quality classes, and were associated to some extent with the various soil fertility indicators and with the distance from the homestead. Up to 85% of the maize yield variability was explained by the combination of soil fertility and management factors. Their relative importance as explanatory variables differed from site to site, depending on the socio-economic and biophysical backgrounds. Nevertheless, these results indicated that management factors are inextricably related to (farmer perceived) land quality in general, and to soil fertility in particular.

The interrelationships and their synergistic effects of the various SWIM factors could be also illustrated with use of the simulation model (Chapter 5). The N balance proved an interesting overall resource use efficiency indicator that can be temporally aggregated to reveal trends in N depletion and accumulation when adopting a certain management strategy. Variations in the resource use efficiency indicators revealed widely different results for the various fields of a farm when 'blanket' management strategies were simulated, indicating that the magnitude and complexity of the soil fertility gradients should be considered when designing such strategies.

The interaction of factors and the processes leading to the establishment and maintenance of the soil fertility gradients were summarised in a conceptual 'resource allocation cycle' (Chapter 6). The implication of such a cycle for the characterisation of farm system previous to the development of farm models, and the importance of considering the soil fertility gradients in that respect, were exemplified with the results of this thesis. Conclusions were drawn from the adaptation of the original methodology, which helped in increasing the understanding of the managerial aspects of the household that affect the origin and magnitude of the soil fertility gradients. From the assessments of the variability in crop performance and in resource allocation it was concluded that it is impossible to unravel the effects of soil fertility and management, and that their relative importance vary from site to site, strongly influenced by population density, access to markets and to off-farm income. In line with these observations, it was further concluded that in densely populated areas the intensity of input use overrides the inherent properties in determining the origin and magnitude of the soil fertility gradients. In contrast, in sparsely populated areas and with higher variability in soil types the resource allocation pattern emerges from the perceived land quality, normally operating in the direction of increasing the magnitude of the soil fertility gradients.

1 Introduction

1.1 General introduction and objectives

Soil-fertility depletion in smallholder farms is the main biophysical process explaining the decline in per capita food production in African countries during the last 30 years (Sanchez *et al.*, 1997). The Lake Victoria basin in East Africa supports one of the densest rural populations in the world, as a result of large initial settlements attracted by the originally high soil fertility in the area. As population grew, this fertility was gradually depleted by crop-harvest removals, leaching, and soil erosion, when farmers were unable to sufficiently compensate these losses by returning nutrients to the soil via crop residues, manure and mineral fertilisers (Shepherd and Soule, 1998).

At farm scale, however, it becomes evident that the set of processes leading to soil-fertility depletion is not homogeneously distributed in space. Variability in soil fertility arises from differences in underlying geology and geo-morphology, and due to a number of mechanisms within the farming systems (i.e. farm management practices). Farmers manage several organic and mineral resources in order to attain their production goals. The net flow of resources is not equal for the various fields belonging to a single farm household but varies substantially, creating areas with carbon and nutrient accumulation and depletion (Vanlauwe *et al.*, 2001). Some of the nutrient flows and transfers involved vary strongly between farmers of differing social status, notably between cattle owners and non-cattle owners (Giller and van Keulen, 2001).

The biophysical processes involved in the inherent productivity of the soils and in the mechanisms of response to different interventions are subjected to this spatial heterogeneity in soil quality, defined here as *soil fertility gradients*. Therefore, the existence of such gradients within smallholder farms must be considered when designing integrated soil fertility management strategies. Farmers are often aware of the existence of soil fertility gradients and use local terms to ascribe different soil quality features to different fields within their farm (TSBF, 2001). As it was indicated for small farms in western Kenya, resource and production activity allocation, as well as decisions on management practices and investments, are affected by that heterogeneity in soil quality (Crowley and Carter, 2000; Mango, 1999; Place *et al.*, 2001).

A differential long-term management of the different fields of a farm adds an important source of variability, creating zones of soil fertility due to concentration of agricultural produce and organic wastes around the homesteads. This is verified by the existence of positive and negative carbon and nutrient balances for different fields within a farm (Scoones and Toulmin, 1999; Smaling *et al.*, 1997). In other words, farmers are able to induce the establishment of soil fertility gradients through management, and the decision-making processes related to resource allocation are driven by endogenous and exogenous factors from different origin (e.g. soil types, markets, family size). Due to the many possible combinations of such factors, the magnitude of the soil fertility gradients is likely to vary from farm to farm as well as for different regions, affected by both biophysical and socio-economic conditions.

Whether the inherent soil properties are more important than the management-induced effects in creating, maintaining and increasing the magnitude of soil fertility gradients is

also likely to vary between and within regions. Nevertheless, in spite of the origin and absolute magnitude of such gradients, their relative importance in terms of crop performance and response to soil management practices (interventions) needs to be embraced. In the absence of pests and diseases, crop performance is the best natural integrator of all sources of variability within the farm, namely land quality and management variability. Crop response to fertilisers is likely to vary for the different fields of a farm according to (the origin) and magnitude of the soil fertility gradients.
Nutrient balances in African farming systems have become an important tool in assessing soil fertility issues, as concerns about soil depletion have increased and the limitations of standard chemical fertiliser testing programmes have been recognised (Van Duivenbooden, 1992; Smaling and Braun, 1996). As a tool for monitoring, nutrient balances at field or farm scale are normally carried out on a seasonal or annual basis. Management decisions, however, are usually taken on a shorter (weekly, daily) time horizon. Decisions on planting or weeding dates, for instance, may affect crop performance and therefore other variables like soil cover or nutrient uptake are affected. To study the effect of short-term management decisions that will eventually build up the above-mentioned long-term effects along a time axis, a dynamic dimension should be added to the calculation of nutrient balances.

The overall goal of this work is the identification and definition of spatial-temporal niches for targeting soil fertility strategies and technologies (interventions). The two research questions guiding this thesis, which were initially put forward by Vanlauwe (2001), are: how steep are these soil fertility gradients, and which are the factors and processes affecting that steepness? The assessment of the origin and magnitude of soil fertility gradients aims at answering them. However, they give little insight in the importance of those gradients in terms of how relevant such steepness is when fertilisers are applied; or which type of gradients according to their origin (nutrients, soil organic carbon, soil erosion?) are more difficult to remove or reduce with management practices. The formulation of all these questions into objectives follows:

1. To quantify the magnitude of within-farm soil fertility gradients as affected by biophysical (e.g., variation in soil types within one farm) and socio-economic (e.g., population density) conditions.

2. To document the factors driving the farmers' decision making processes resulting in farmer-induced soil fertility gradients, and their perception of such gradients.

3. To assess the impact of existing within-farm soil fertility gradients on crop performance and to identify the main factors affecting crop growth variability.

4. To study the potential of simulating nutrient balances with dynamic models using a small time step (i.e daily, weekly) as an approach to assess the effect of management practices on the magnitude of soil fertility gradients

From these original, guiding objectives secondary but not less important objectives were formulated. They are more related to NUANCES (Nutrient Use in Animal and Cropping systems – Efficiency and Scales), the framework project into which this thesis was carried out. Knowledge integration by modelling of farming systems and their use for scenario analysis, as well as within farm variability (i.e. soil fertility gradients), are the core topics in this framework. Both modelling and scenario analysis require heavy loads of basic field information for initialisation, parameterisation, validation and sensitivity analysis. Modelling of farming systems also requires a basic system analytical framework to characterise farm types, their components, their internal and external flows and a systematic characterisation of their internal variability (i.e. microenvironments, field types). According to these needs the following objectives were formulated:

5. To gather basic socio-economic and biophysical information at different localities of western Kenya, from samples of farms that include the whole range of resource endowments and production situations to be found in each area.

6. To develop a common framework to describe and categorise farm variability at different scales of analysis, which can be used as an initial step for modelling farming systems of the smallholder sector of western Kenya.

The objectives outlined under 5 and 6 constitute at the same time the basic background to understand and characterise the system for which objectives 1 to 4 were developed.

1.2 Problem definition and hypothesis development

Inherent geological and geo-morphological properties determine the capacity of soils for different production activities, affecting short and long-term management, and susceptibility to degradation (e.g. soil erosion). These differential management practices caused by the inherent variability in combination with other endogenous (e.g. position of the homestead) and exogenous (e.g. markets) factors induce a 'new' variability in (farmer-induced) land quality. Thus, in areas of high variability in soil types the magnitude of the soil fertility gradients is likely to be higher. However, the reaction to such cyclic process depends on the biophysical background, basically on the characteristic resistance and resilience of the agro-ecosystem.

A second possible source of factors affecting the establishment of soil fertility gradients may be represented by population density. As population pressure increases, farm sizes tend to decrease due to inheritance and sub-division. This implies that the inherent variability within the farm tends to decrease as well and farmers face a narrowing range of soil qualities to allocate production activities and resources. This effect may contribute to reduce the variability within the farms, with the net effect of eventually reducing the magnitude of the soil fertility gradients. When farm sizes become too small to sustain the household requirements, farmers react by accessing different sources of off-farm income, leading to either shortage of labour or increased input use. Both effects act by reducing the magnitude of soil fertility gradients, though in different directions.

Continuous concentration of nutrients in the smaller areas around the homestead, at expenses of nutrient depletion in further and larger fields, coupled with continued export of produce and a lack of external inputs into the farm, lead to an overall negative nutrient balance at farm level. Due to the presence of other growth-limiting factors nutrients (supra-optimally) concentrated in these small areas may not be efficiently used and thus subject to leaching, volatilisation, etc. The areas being depleted are larger and require comparatively much more of the scarce labour to be cropped. Crop types and management practices vary

for the different fields within a farm but not always in a way of increasing factor (land, labour, capital) efficiency. Moreover, an important part of the variability affecting the overall efficiency arises from day-by-day management decisions and the co-existence of competing activities within the farm system, operating on a temporal scale. Recognition of such differences within the farm, of their origin, magnitude and importance, and targeting them when planning resource allocation may help in improving the overall efficiency of the system.
Five basic hypotheses are to be tested in this thesis. Some of them are similar to those formulated in the project *Valorisation of within-farm soil fertility gradients to enhance agricultural production and environmental service functions in East and Southern Africa* (Vanlauwe, 2001), prepared and implemented by TSBF – CIAT. The relevant hypotheses regarding the origin, the magnitude and the importance of soil fertility gradients are the following:

1. Farmers deliberately manage their fields following inherent production potentials and socio-economic considerations that lead to the establishment of soil fertility gradients.

2. The magnitude of within-farm soil fertility gradients is affected by socio-economic and biophysical factors and it will be larger in regions with lower population density and a larger variation in soil types.

3. Within-farm soil fertility gradients are large enough to allow a farmer to take these into account when planning the allocation of the available organic and mineral nutrient sources, and targeting them will lead to improved nutrient use efficiencies at farm scale relative to blanket recommendations.

4. The variability often seen in crop performance cannot be only explained by actual soil fertility but other variables originating from management decisions play a major role, and may compensate or enhance their effect.

5. Dynamic simulation of nutrient balances at field level will help in understanding not only the trend in nutrient depletion and accumulation within the farm but also the effect of management decisions and their opportunity in time on the establishment of soil fertility gradients.

Coping with the whole set of objectives and testing the above-mentioned hypotheses imply that not only within-farm, but higher levels of variability (i.e. local, regional) and from widely different sources (e.g. landscape, education) must be included due to their potential interaction. Different localities within the region must be selected to represent contrasting biophysical and socio-economic conditions. An approach must be developed and/or adopted to categorise the variability to be found at each level of analysis. Tools are needed for studying farmers' decision-making processes that govern resource allocation and management practices and for quantifying their effect. A method for assessing the impact of soil fertility gradients on crop responses has to be designed, including all sources and levels of variability, and involving the farmer in the identification of relevant land quality features.

1.3 Sources of variability and approaches for their categorisation and study

To categorise different factors affecting soil fertility at the various scales of analysis Vanlauwe (2001) adopted the acronym SWIM (Site, Wealth, Inherent and Management factors). Although the effect of each individual factor can be somehow isolated for its study, they are clearly *interdependent*. Nevertheless, the same denomination is used here though with adaptation to regional and socio-economic characteristics of western Kenya. Site is used here as a synonym for locality, including a group of villages (c. 4 – 6) that have no real boundaries between them and show homogeneous characteristics. In western Kenya, due to high population, villages have overgrown and are physically joined, making it difficult to differentiate one from another. The administrative hierarchy of Kenya is organised in provinces, districts, divisions, locations, sub-locations and villages. The Site level may be identified with either the division or location administrative levels, or even with sub-location, but not with village.
The sources of variability affecting soil fertility management at different scales of analysis are biophysical (climate, soil type, topography, vegetation) and socio-economic (farm size, markets, crop choices, etc.). According to their origin they can be grouped into these four categories, related to site characteristics [factor S], wealth [factor W], inherent biophysical properties [factor I] and management [factor M]. According to their spatial scale they can be categorised as follows:

'Region' scale variability - different sites in a region, Western Kenya
The regional scale as determined by climate (rainfall), dominant soil types (texture), presence of and access to markets, average farm size and socio-cultural aspects (ethnic groups) defines land use, sets priorities for different activities, and offers alternatives in terms of access to cash and/or off-farm opportunities.

'Site' scale variability - different farm types within a site, production orientations
Associated with differences in soil fertility management between poor and wealthy households (cattle ownership, land availability for fallow and rotation, input use, etc.) (Table 1.1), different soil fertility management for different crops and presence of competing cash crops, according to site biophysical attributes. Different production situations and orientations (i.e. low or high input use, market-oriented or self-subsistence) are the consequence of the interaction between this and the immediate upper level (Region x Site interactions).

Table 1.1: The influence of wealth on soil fertility management. Adapted from *Soil management practices of wealthy and poor households in Vihiga* (Crowley and Carter, 2000).

Management practice	Wealth class	
	Wealthiest	Poorest
% that fallow some land	12	0
% that practice crop rotation	32	22
% that regularly apply cattle manure	91	59
% that make compost	53	42
% that have ever used inorganic fertiliser	68	42
% that have terraces on some of their land	91	39

'Farm' scale variability - different fields within a farm, niches
This variability is associated with topography and soil type (topo-sequence of soil types and degradation intensities), physical discontinuities (rocky outcrops, swamps, valley bottoms, hillsides, etc.), distance from the homestead and/or from livestock facilities. This variability is normally perceived through crop performance in terms of growth (colour, height, etc), plant density, weed infestation, pests and diseases and may drive farmers' decisions in terms of resource allocation (Table 1.2). It is at this level where soil fertility gradients become relevant at showing the consequences of short and long-term management effects and as an approach to explain crop growth variability.

Table 1.2: Households (%) applying various nutrient sources to different niches, Mutoko area, Zimbabwe (Chikuvire, 1998). Adapted from *Soil fertility management strategies and practices by smallholder farmers in semi-arid areas of Zimbabwe* (Mapfumo and Giller, 2001).

Nutrient source	Type of niche			
	Homestead environments	Termite mounds	Under trees	Open areas
Cattle manure	19	0	10	49
Leaf litter	5	0	0	18
Compost	19	0	0	19
Ammonium nitrate	69	67	68	86

To cope with the Wealth factor, the main source of variability operating at Site level, a classification of farm household types must be introduced, clustering them according to similar reaction patterns that are relevant to the objectives. A distinction is made between a structural typology, i.e. production factors and how they are managed, and a functional typology, i.e. decision-making by farmers given the constraints and their behaviour in the face of climatic fluctuations or changing socio-economic situations (Mettrick, 1993). Several methods can be used and particularly classifications based on resource endowment have been widely adopted for western Kenya (e.g. Crowley, 1997; Wangila, 1999; Crowley and Carter, 2000; Soule and Shepherd, 2000; Place *et al.*, 2001). An alternative way to develop a typology of farm households is to classify them by differences in their objective functions, a concept closely related to optimisation models for land use by multiple goal linear programming (Van Keulen and Veeneklaas, 1993; Romero, 1993; Schipper *et al.*, 1995; de Haan *et al.*, 2000). Additionally, the multiple constraints restricting the 'feasible area' (i.e. window of opportunities, Van Itersum *et al.*, 1998) for the optimisation of such objective functions can be grouped according to their origin (e.g. land or labour limitation, socio-cultural constraints) and used as complementary criteria for a farm typology.
Wealth stratification can be done by formal methods using socio-economic and productive data collection (Crowley, 1997), by participatory wealth ranking or with wealth indicators chosen by farmers (Mango, 1999; Place *et al.*, 2001), or by using micro-economic indicators such as distance to markets or land/labour ratios (Ruttan, 1978). The latter presents limitations as it does not account for agro-ecological differences within and between regions (de Haan *et al.*, 2000). Information on relative factor scarcity is also necessary, as determined by household-specific variables such as market information and access to factor

(labour, capital) markets (Kuyvenhoven *et al.*, 1995). Particularly access to off-farm income was shown as having serious implications for farm productivity in western Kenya by allowing farmers to increase the size of their farms, purchase agricultural inputs, save on their own labour, and educate children (Crowley *et al.*, 1996). Access to off-farm income as well as other socio-economic indicators (e.g. farm size, type of houses, self-sufficiency of a certain food produce, etc.) are site-specific, making it difficult to develop stratification criteria that are consistent across sites.

Studying soil fertility issues in Kakamega district, western Kenya, Rotich *et al.* (1999) used a participatory approach in which farmers classified themselves into 'Good', 'Regular' and 'Poor' soil managers, according to a list of criteria developed by them. An interesting approach in terms of responding to the objectives, but highly site-specific. Another aspect to consider is the dynamics of the system. The 'developmental cycle' is a concept developed by Fortes (1949) and used by Crowley and colleagues (1996) in western Kenya. It implies that households undergo a common evolution from establishment to growth, maturity, decline and dissolution. Over the lifetime of a farm household the relative resource endowments fluctuate and therefore farmers' decisions and resource allocation strategies will vary accordingly.

A common approach used by economists to stratify farm households according to their objective function was to use only the profit maximisation objective. This approach is not sufficient to account for technological choices made by farmers in developing countries (Kuyvenhoven *et al.*, 1995) and a method for identifying and weighting multiple objectives is required. Romero (1993) developed a procedure for weighting farm-level objectives grouped within three categories of tentative goals defined *ex ante*: (i) consumption utility maximisation, (ii) risk management and (iii) reproduction of the resource base. Another approach considers a stratification according to the objective function but using less elaborate techniques, accounting for differences in terms of availability and access to productive resources (land area, soil quality, family labour, credit) and in terms of production strategies (risk taking, factor intensity, cropping choices). In this approach both criteria (i.e. resource endowment and objectives) are combined (de Haan *et al.*, 2000).

Similarly, the variability found within farms requires systematic classification criteria that allow for the identification of field types and/or niches, summarising and categorising the effects of the 'Inherent' and 'Management' factors. The ecological concept of niches is often used to conceptualise variations in soil fertility, to define microenvironments within the farm that are managed in a particular way according to farmers' perceptions, or to identify spatial and temporal opportunities to target technological interventions. The last concept is mostly adopted here and therefore different units/microenvironments within the farm are termed *Field types*, and the criteria to classify them, *Field typology*. However, since farmers tend to 'create' favourable microenvironments by shifting of homesteads and/or kraals, the concept of niches seems consistent with the second definition and the term *Special niches* is applied to them.

Field typologies have largely included distance from the homestead (Home fields, Out fields), biophysical discontinuities (Termite mounds, Valley bottomlands, etc.) and history of use (Old hut-site, old Kraals, etc.) as criteria to classify microenvironments (e.g Scoones and Toulmin, 1999; Carter and Murwira, 1995; Chikuvire, 1998; Campbell *et al.*, 1996). However, there is a wide variation in the occurrence of different field types between farms and between regions. Moreover, the soil fertility or more broadly the soil quality of these field types may vary from farm to farm, in particular for the less fertile microenvironments.

Wealth and/or production orientations are likely to interact with field type in determining soil quality, e.g. soil C contents in the outfields of poor vs. 'rich' farmers.

A soil fertility and/or land quality classification by farmers, though highly subjective, has advantages in terms of identifying farmers' perceptions and associated management decisions, and for a consistent identification when communicating with them. A methodological guide has been developed and used in Latin America and the Caribbean (Honduras, Nicaragua, Colombia, Peru, Venezuela, Dominican Republic) and Africa (Uganda, Tanzania) in order to identify and classify local indicators of soil quality related to permanent and modifiable soil properties (Barrios *et al.*, 2001). In western Kenya, the Folk Ecology project of TSBF has already gathered much valuable information regarding local names used to identify soil types and environments and their correspondence with physical properties and technical names.

Part of the variability in soil fertility is inherent and related to the catenary position, which can be addressed through delineation of soilscapes (Deckers, 2002). Varying responses to P for different positions in the landscape were observed in the Northern Guinea savannah of West-Africa, demonstrating that this source of variability should be considered when designing soil fertility management strategies (Vanlauwe *et al.*, 2000a and b). Much biophysical and socio-economic information can be obtained by transect walks through the village and across farms, recording direct observations by means of questionnaires and drawings (Mettrick, 1993). Both soilscape delineation and transect walks can be accomplished with local soil classification, for which farmers' participation in the process is crucial.

The spatial within-field micro-variability in sub-Saharan African farms was addressed in previous works by mapping crop yields and nutrient concentrations measured by sampling systematically following a grid on the fields (Brouwer and Bouma, 1997; Tiessen *et al.*, 2000). This approach gives very detailed, valuable information on underlying inherent properties and the effects of long-term management practices on a field scale. However, it is highly case-specific and farmers' recognition of such micro-variation is not always considered (Vanlauwe, 2001). Though smallholder farmers may exploit that microvariability to reduce risks in certain areas (see Brouwer *et al.*, 1993, for examples in West Africa), management decisions and resource allocation strategies aiming at a scale of spots of fertility within a field are usually particular for each farmer, and difficult to generalise.

Crop performance: an integrating variable

The first visual indication of the existence of soil fertility gradients is crop growth performance. Crop growth in a certain location is (potentially) the result of genotype and climate, and is affected by the growth-limiting and growth-reducing factors present in that particular environment (Lövenstein *et al.*, 1995). Crop growth variability reflects the effect and distribution of these factors, thereby integrating them, and shows at the same time the direct influence of management decisions. Thus, crop performance and its variation within a farm appears as a good integrator of the different sources of variability.

Crop performance can be assessed by direct methods, such as grain yield or biomass production at harvest, or by indirect methods. The latter have the advantage of being non-destructive, quicker, and therefore they can be used for yield estimations in farmers' fields. Indirect methods to evaluate crop performance include, among others, chlorophyll colour intensity (e.g. Schröder *et al.*, 2000), direct scoring of growth performance or use of allometric models, relating plant morphological features to crop yield by means of regression techniques (e.g. Vega *et al.*, 1999). The development of allometric models requires the previous steps of calibration and validation with field data. They proved reasonably accurate in predicting maize yields (Vega *et al.*, 1999 and 2001).

The use of diffuse reflectance spectroscopy to characterise soil properties

Diffuse reflectance spectroscopy is nowadays used as a rapid, non-destructive method for characterisation of a wide range of materials based on their particular reflectance, as a function of wavelength in the electromagnetic spectrum (Davies and Giangiacomo, 2000; Shepherd and Walsh, 2000). This approach has been proposed to provide a rapid prediction of soil physical, chemical and biological properties (Janik *et al.*, 1998). Some success has been reported in sensing soil organic matter in the field (Sudduth and Hummel, 1993) as well as in discriminating soil types from satellite multi-spectral data (Coleman *et al.*, 1993). More recently, Shepherd and Walsh (2002) developed a scheme for the development and use of soil spectral libraries for rapid estimation of soil properties based on analysis with this technique, using a library of over 1000 archived topsoils from eastern and southern Africa. Using a multivariate regression approach they calibrated 10 different soil properties to soil reflectance and developed screening tests for various soil fertility constraints using classification trees.
Assessing soil spatial variability requires dense sampling to be adequately characterised. However, soil analyses are expensive and time-consuming, making broad-scale quantitative evaluation difficult to achieve (Dent and Young, 1981). Therefore, new possibilities open up form the adoption of the spectral library approach for the assessment of spatial variability in soil properties. Moreover, prediction of soil fertility can be further simplified by means of a soil fertility index that summarises the soil fertility constraints resulting from the different properties measured in a sample. A model was recently developed for a rapid characterisation of soil samples through a soil fertility index according to their spectral signature (Shepherd, personal communication, see Appendix 2.3.4). Relating the on-farm variability in crop performance to the variation of a soil fertility index measured in samples from the different fields of a farm appears a promising approach for further studies of soil and crop variability.

1.4 Approaches and tools to assess the effects of management

Studies at field, farm and village scale demonstrated that farmers use widely different strategies to cope with low levels of soil fertility. Niche management, by which nutrients are concentrated in certain fields at the expense of others, has been well documented (e.g. De Jager *et al.*, 2001; Scoones and Toulmin, 1999). Resource flow maps appear a valuable tool for assessing the heterogeneity in soil fertility status resulting from the farmer-driven variability in resource allocation. They have been carried out in a number villages in East Africa (Western Kenya, Uganda and Tanzania) to quantify the internal and external flows of resources. They have also been used as a tool for participatory farm planning (Rotich *et al.*, 1999).

Resource flow mapping in combination with partial nutrient balances (e.g. the NUTMON approach, see below) allows estimation of the nutrient depletion and accumulation areas within one farm, and is strongly farmer focussed, but lacks the quantitative rigour of formal analysis (Vanlauwe, 2001). However, the resource flow map exercise represents an opportunity not only for gathering information to calculate nutrient budgets but also for gaining insight in decision making processes on resource allocation that leads to the establishment of soil fertility gradients. Additionally, it can be used to improve the communication channel with farmers in technology transfer processes on the one hand and to gather information on labour allocation on the other.

Many studies are available on nutrient balances at regional, farm and plot scale (e.g. Stoorvogel and Smaling, 1990; Smaling, 1993; Smaling *et al.*, 1993, 1996; De Jager *et al.*, 2001). Most studies, however, are focused on nitrogen (N) and phosphorus (P), few on potassium (K), while carbon (C) and micronutrients are rarely considered (Scoones and Toulmin, 1999). In western Kenya, a static model of nutrient flows have been used to identify a range of agroforestry interventions (Shepherd *et al.*, 1996), and a dynamic ecological and economic model was coupled with nutrient balance calculations to study the impact of different farmers' soil management strategies (Shepherd and Soule, 1998).

Defining the boundaries of the system is the first step to calculate nutrient balances. Even at plot or field scale a distinction is made when only the soil or the soil plus the crop (soil/crop unit) are considered. Then key inputs and outputs in the various sub-components of the system are identified and a simple routine of accounting exercises through summation is followed (Scoones and Toulmin, 1999). The definition of system boundary, its sub-components, input and outputs can be done by the researcher or by the farmer (Defoer *et al.*, 1998). Studies at plot scale require an initial distinction of cropping units within the farm according to crop type, landscape position or intensity of management. When differences in nutrient flows over small areas are considered, important differences in patterns of fertility management, types of nutrient cycling and nutrient contents are revealed (Carter and Murwira, 1995; Scoones, 1996; Eyasu *et al.*, 1998; Baijukya and De Steenhuijsen Piters, 1998).

Table 1.3: Types of nutrient flows at farm scale in the NUTMON approach. Adapted from *Monitoring nutrient flows and economic performance in African farming systems (NUTMON). I Concepts and Methodologies* (De Jager *et al.*, 1998)

Inflows	Outflows	Internal flows
1 Mineral fertilisers	1 Farm products sold	1 Feeds
2 Organic inputs	2 Other organic products	2 Household waste
3 Atmospheric deposition	3 Leaching	3 Crop residue
4 Biological nitrogen fixation	4 Gaseous losses	4 Grazing and vegetation
5 Sedimentation	5 Runoff and erosion	5 Animal manure
6 Subsoil exploitation	6 Human faeces	6 Farm products to household

Nutrient balances are *partial* when they only consider flows of inputs (e.g. fertilisers) and outputs (e.g. crop produce) that are easy to measure, and are normally regarded as more useful for farmers. Other balances cover a wider range of inflows and outflows, including atmospheric deposition of nutrients, fixation, sedimentation, erosion, leaching and gaseous losses, among others. Such types of balances are calculated in the multi-scale Nutrient

Monitoring (NUTMON) approach, considering all the flows listed in Table 1.3 for applications at farm scale (De Jager *et al.*, 1998). Some of the flows can be determined by asking the farmer (as during a resource flow map exercise) while others require the use of transfer functions (Van den Bosch *et al.*, 1998). The reliability of the transfer function estimations in the low-data environments of the tropics may be low, since there are not many examples of sites where all these parameters have been measured simultaneously over long periods (Smaling *et al.*, 1997).

When nutrient balances are calculated at plot (field) scale some inflows and outflows in Table 1.3 become less or not relevant, whereas some internal flows become inputs (i.e. household waste) or outputs (i.e. crop residue) to and from the field. Inflows 1 and 2 plus outflows 1 and 2 are normally used for calculating partial balances at field scale, because they are relatively easy to determine and strongly influenced by resource allocation and management decisions. Since they show the degree of human involvement, capital and labour allocation, income generation and food security, Smaling *et al.* (1997) proposed their use for building indicators of productivity and sustainability. Partial nutrient balances at field scale will be used here in combination with resource flow maps as an approach to identify and define soil fertility niches and management-induced trends in nutrient depletion and accumulation within smallholder farms of western Kenya.

Using dynamic simulation models with a 'bottom-up' approach

Incorporating soil-crop simulation models into decision support systems has been proposed for improving the application of integrated nutrient management technologies by identifying the principal causes of existing limitations, thus prioritising research efforts (Singh *et al.*, 2001). Models are normally used for system analysis, scenario generation and impact assessment, though the final test for any of these efforts is, according to Thornton and Herrero (2001), the successful adoption of the strategies selected and their beneficial impact. These authors pointed out that to avoid "models remaining in academic circles" there is a need to increase the understanding of the behavioural and managerial aspects of the household which, together with the biophysical aspects of the production system, will determine the feasibility of the alternatives proposed. To tackle this, Herrero (1999) proposed a methodology that integrates models and participatory methods, including stakeholders at all stages of model development (i.e. 'Participatory modelling'). Such methodology (Fig. 1.4.1) involves the steps of (i) characterisation of the system at different levels of aggregation, (ii) identification of the main types of production systems prevailing within a region, (iii) monitoring of farm household activities and management practices and (iv) analysis of the sensitivity to the key management practices, to evaluate a range of alternative strategies. These steps will be followed to a large extent here (see Section 1.5).

A wide range of dynamic models is available to simulate crop growth and soil processes that allow for the inclusion of the various aspects affecting nutrient balances at field scale. They present different levels of complexity depending on the number of mechanistic processes involved, the number of parameters that is necessary, and on the level of detail concerned. Under data-sparse conditions the benefit of including a high degree of complexity may not be exploited in full due to the uncertainty derived from the multiple assumptions that need to be taken (Smaling *et al.*, 1997). Then, in agreement with the NUANCES perspective: "the approach used must be simple enough to avoid being overwhelmed by detail, but yet detailed enough to allow scenarios of sufficient reality to be analysed" (Giller and van Keulen, 2001).

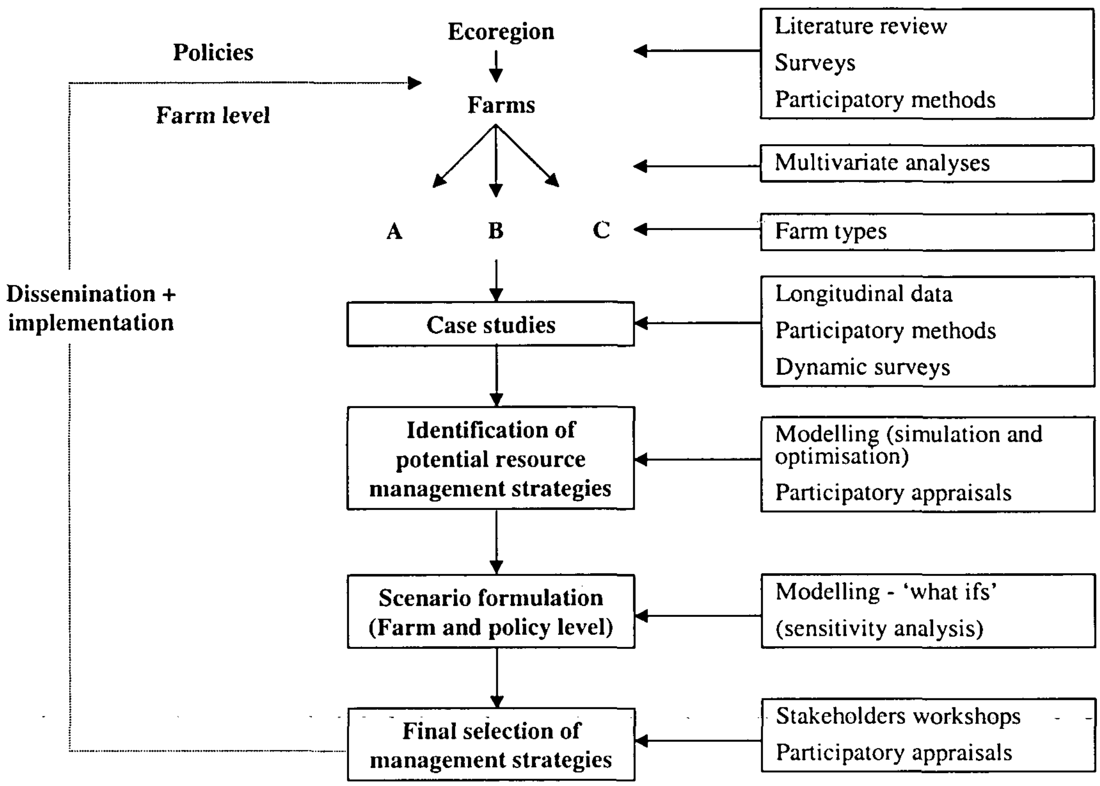


Figure 1.4.1: Illustration of the 'Participatory modelling' methodology as proposed by Herrero (1999). Most of the methodological instances up to the simulation modelling are followed in this thesis.

Simple approaches to crop growth simulation have been proposed to analyse resource capture by crops, particularly for simulating leaf area development under shortage of nitrogen (Goudriaan, 1994), assuming plant growth as proportional to the radiation intercepted by the crop and following an expo-linear growth curve (Goudriaan and Monteith, 1990). A higher degree of complexity has been included by adding water and nutrient balances, nutrient uptake and nutrient status of the crop to this original approach (e.g. Ten Berge *et al.*, 1997). LINTUL, Light INTerception and UtiLisation simulator is a simple general crop growth model, which simulates dry matter production on the basis of light interception and utilisation with a constant light use efficiency (van Oijen, 1991). LINTUL2 is an extended version of the original (the version for optimal growing conditions) that includes a simple water balance for studying effects of drought (Spitters and Schapendonk, 1990), whereas LINTUL3 includes nitrogen limitation, but no water limitation (Goudriaan, 1997).

Several models that simulate soil processes affecting nutrient balances have been developed. Such processes may be involved in the organic matter and organically held nutrients dynamics (e.g. Seligman and van Keulen, 1981; Parton *et al.* 1987; Yang, 1996), or organic and inorganic N dynamics, with associated mineralisation-immobilisation, urea hydrolysis, nitrification, denitrification, uptake and nitrate leaching (e.g. Ten Berge *et al.*, 1997; Smith *et al.*, 1996; Shepherd and Soule, 1998). Some of these models or parts of them simulating a certain process have been tested, validated and used in a number of regions in Africa (Shepherd and Soule, 1998; Thornton *et al.*, 1997; Singh *et al.*, 1993, 2001) and they offer a wide range of options for linking soil processes with crop growth to calculate nutrient balances.

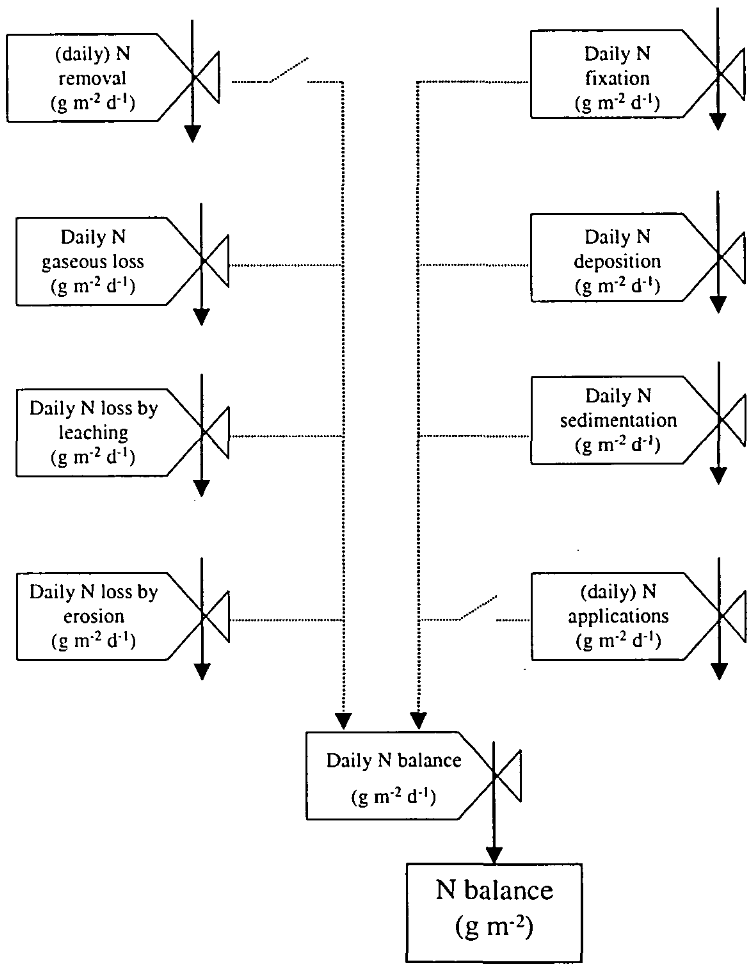


Figure 1.4.2: Diagram of the modelling approach proposed for calculation of dynamic nutrient balances, in this case for nitrogen. The balance between all N inflow and outflow daily rates is integrated over time to calculate the overall N balance at field level for a certain period. The rates of N removal and N applications show discontinuities due to their intermittent character.

Dynamic nutrient balances are proposed here as a tool for simulating the effects of management decisions on the establishment and evolution of soil fertility gradients. The simplified diagram in Figure 1.4.2 illustrates this approach, in which daily rates of inflows and outflows are balanced (daily balance) and integrated over time. The evolution of the nutrient balance as the season progresses presents a clearer picture of how management decisions may affect it. To incorporate this temporal dimension a crop growth simulation model will be coupled with different sub-routines simulating the different inflows and outflows of nutrients that are relevant at field scale, following to a large extent the NUTMON approach. Management practices, derived from the resource flow mapping of representative case study farms (cf. Fig. 1.4.1: farm types – case studies; participatory methods; identification of management strategies), and biophysical longitudinal data gathered from their fields, will be included as parameters and/or initial conditions for the model.

1.5 Methodological approach

To cope with the variability found at different scales and with the multiple objectives, this thesis has been outlined in four working steps sequentially operating at each site (Figure 1.5.1). Each step had a certain methodology, depending on information from the preceding step and providing information to the following one. An *Initial (Zero) Step* consisted of using background socio-economic and biophysical information, expert knowledge and study tours around the area to select the working sites and to design the methodological aspects of the following steps (e.g. information requirements, sampling size and criteria, 'soilscape' delineation, etc.).

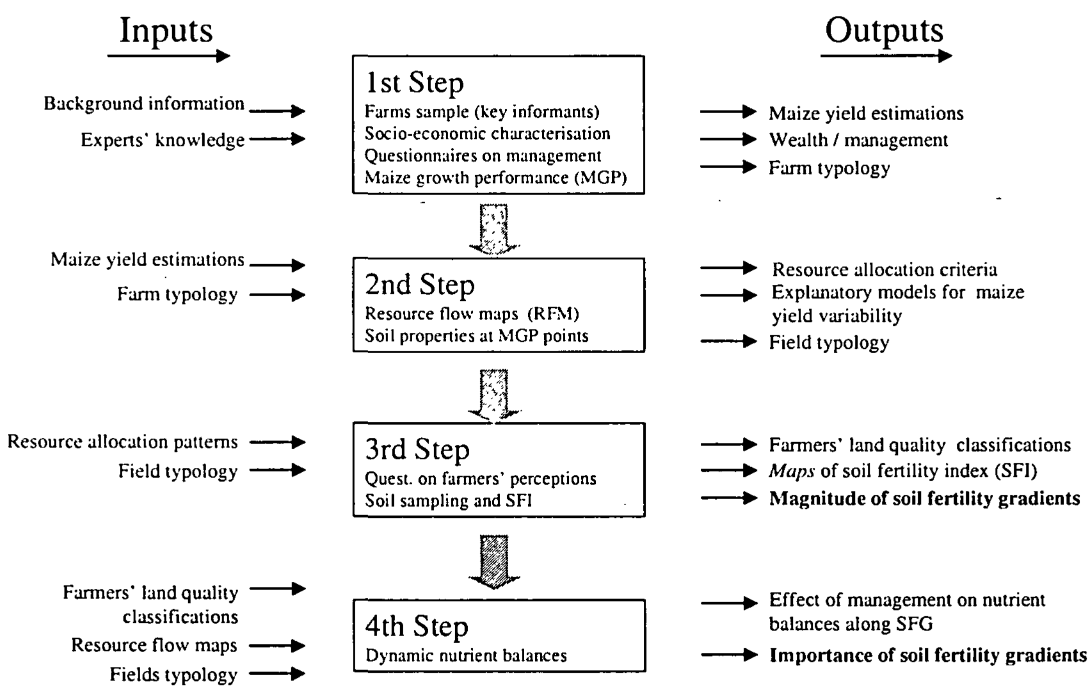


Figure 1.5.1: Illustration of the methodological approach adopted. Four working steps were followed. Some of the outputs from each step were used as inputs for the following ones. The origin, the magnitude and the importance of within farm soil fertility gradients (SFG) were assessed stepwise.

During the *First Step* the selected sites where visited and key informants interviewed in order to get the necessary information and criteria to perform the farm sampling (20 farms per site, 60 farms in total). The samples of farms were socio-economically characterised by means of interviews and transect walks together with the farmer (First approach questionnaires and Farm transects). Information on current management practices adopted by each farm was gathered as well. During the same visit, measurements of maize growth performance (MGP) were done at several (2 to 6) points within the farm where differences in crop growth were evident. Questions on all aspects of crop management at that particular point were put to the farmer and answers recorded. The outputs of this step were the necessary information on wealth indicators, land use and management practices in order to develop a Farm Typology, and the information used to estimate maize yields at more than 80 points per site by means of regression models (see later, development of allometric models).

The *Second Step* made use of the Farm typology to select case study farms (1 per farm type per site, 15 in total) where Resource Flow Maps (RFM) were drawn by the farmers, while an accompanying questionnaire inquired about labour demands. At (some of) the same points[1] where maize growth performance was assessed, soil physico-chemical properties were studied for the top and subsoil by soil profile observations and sampling for laboratory analysis. The outputs of this step were: (i) information on resource (land, labour, capital and knowledge) allocation criteria to different fields within the farm, as a first approximation to the origin of soil fertility gradients (SFG); (ii) a systematic Field Typology to classify the different production units and niches within the farm according to management patterns and (iii) explanatory models for the observed yield variability, including management factors, inherent properties and soil fertility attributes for a deeper insight in the **origin** of observed soil fertility gradients.

In the *Third Step* farmers' perceptions about SFG were assessed by means of interviews in which they were asked to classify their land into different quality classes (i.e. fertile, average and poor) and to give their reasons behind that (3 farms per type per site, 45 in total). During this third visit each field within the farm was also classified according to the proposed Field Typology. The area and the slope of the production units of the farm (i.e. fields) were measured (GPS-aided), their relative position on the farm and production activity recorded, and a composite top-soil sample from each was taken (around 15 per farm, more than 600 in total). About half of those samples (i.e. 334) were subject to physical and chemical analysis at the laboratory. Sub-samples were taken from all (i.e. 674) and screened for near infrared spectral reflectance to obtain a soil fertility index (SFI) from their characteristic spectrum profile. The outputs of this step included a land quality classification under farmers' criteria that could be crosschecked with the proposed field typology and a measure of the **magnitude** of the soil fertility gradients across field types, farm types and sites.

In the *Fourth Step* simulation modelling was used to assess the **importance** of soil fertility gradients on basic production processes and to study the effects of management decisions. A dynamic simulation model to calculate nutrient balances at field level with a daily time step was developed. It was initialised and parameterised for a maize crop according to the results of the RFM and to the soil/landscape information previously gathered, and run for different field types. The outputs from this step gives an indication of the potential of dynamic nutrient balances (DNB) to assess the importance of soil fertility gradients by simulating the effects of management [M] and inherent properties [I] on farms from the various wealth classes [W].

Spatial and temporal scales

During the selection of sites, farms and fields, the concept of scaling up and down in space was adopted in order to make sure that the selected instances were representative of the variability found at different levels. The scheme in Figure 1.5.2 illustrates the

[1] Only in those points where clear differences in yield and management were found.

conceptualisation of this approach (Giller, K., personal communication). The sources of variability at different levels are nested within each other, and the smaller scale variability contributes to the variability at larger scale. The need to consider temporal scales arises from the underlying idea that current soil fertility gradients have been created by long-term soil fertility management. Most methods adopted here (i.e. resource flow maps, nutrient balances, soil analyses, etc.) are reflecting short-term (mainly seasonal) processes and their effects, and therefore show limitations when dealing with long-term aspects. During the interviews with farmers emphasis was placed on this issue, ensuring that the answers were given according to either the last season events or the commonly adopted practices.

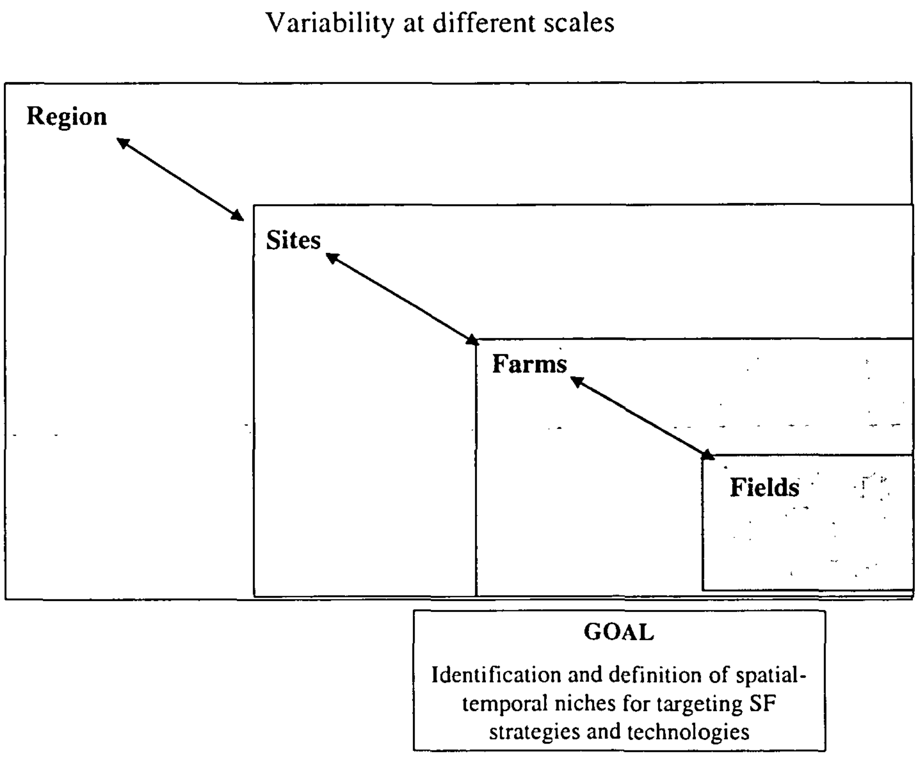


Figure 1.5.2: Illustration of the conceptual approach followed during the selection of sites, farm samples and fields within the farms, after Giller, K. (Personal communication).

1.6 Outline of the thesis

The following chapter (Chapter 2) introduces the methodology used during the different steps, though in some cases it was slightly modified to adjust it to what was found in the field (e.g. Farm typology). Such adaptations are made explicit in each particular chapter in which the topic is introduced and discussed. Chapter 3 describes farm heterogeneity, integrating different scales of analysis and introducing an approach to categorise it. The results of the resource flow maps are also presented here. Chapter 4 presents the results of statistical analyses used to explain the variability found in crop performance, relating it to soil and management variables. Chapter 5 shows and discusses the performance of dynamically simulating nutrient balances as an approach for studying management-induced soil fertility gradients. A general discussion and relevant concluding remarks are presented in Chapter 6.

Each chapter gives a brief introduction about the contents and their organisation in an attempt to facilitate their interpretation. Much of the information collected in the field (and the data derived from it) is presented in Appendices, together with illustrations, pictures, auxiliary methodology, model listings and statistical analysis. Explicit reference to the appendices is made within the main text.

2 Materials and methods

2.1 The working sites

2.1.1 Selection criteria and procedure

The sites were selected in order to represent the regional variability to be found in western Kenya in terms of biophysical, socio-economic and ethno-cultural aspects. According to the objectives of this thesis, a gradient of soil types and climatic conditions (rainfall regime and altitude) were included to represent biophysical variability. Additionally, the three working sites present differences in access to outputs and inputs markets, to off-farm job opportunities and to high level education. Ethnic aspects in each site determine crop choice (production activity choice), in close relation with food habits, and affect decision-making to a large extent when dealing with resource allocation. Because of all these sources of variability, the farming system in general and soil fertility management in particular show considerable differences between sites.

Nine sites were pre-selected by means of secondary information and visited in western Kenya. In all cases the extension officer in the area was contacted and interviewed about the above-mentioned aspects. With his/her aid contrasting farms were selected and visited, and the farmer interviewed through unstructured, informal questionnaires. Aspects related to accessibility and distance, and the existence of previous information on the site were also considered. This thesis is at the same time part of the framework project NUANCES (Giller and van Keulen, 2001) within which other studies are being developed in the region. Site selection was accomplished in close collaboration with those responsible for the other projects to take place in western Kenya, to agree on the type and magnitude of variability to be included.

2.1.2 Biophysical and socio-economic description

The highlands of western Kenya are broadly representative of the situation found in other areas of the East African highlands (Uganda, Ethiopia and Madagascar) in terms of soil types, climatic conditions, technology and production potential (Braun *et al.*, 1997). A common denominator of these highland areas is a high agricultural potential severely restricted by nutrient depletion (Shepherd *et al.*, 1996) as a consequence of naturally weathered soils and because most farms have been farmed for a long time with few external inputs (Sanchez *et al.*, 1997). Western Kenya is one of the most densely populated areas in Kenya (30% of the population in 15% of its landmass), with densities in rural areas ranging from 400 to 1300 inhabitants km^{-2} (Kenya Ministry of Agriculture and Rural Development[2], 2001), and the family land is sub-divided for inheritance. The dominating ethnic group in western Kenya is the Luhya, with several sub-tribes showing important differences in language and culture, but with a common agricultural background. Along the shores of Lake Victoria and several km inland the Luo people are found, considered earlier as fishermen. On the border with Uganda live the Teso people, which are more broadly represented in that country than in Kenya.

[2] The governmental authorities at the District Offices of Vihiga, Kakamega and Teso are thankfully acknowledged for providing this information.

Table 2.1.1: Main biophysical characteristics of the selected working sites (Kenya Ministry of Agriculture and Rural Development, 2001; Braun *et al.*, 1997; FURP, 1994; Jaetzold and Schmidt, 1982).

Variable	Unit	Site		
		Emuhaia	Shinyalu	Aludeka
Altitude	m	1640	1820	1180
*Rainfall***				
Total annual	mm	1850	2145	1463
Long rains (66% prob.)	mm	800	1094	830
Short rains (66% prob.)	mm	660	727	540
Rain distribution				
Long rains		Beg. March – mid July	March – mid July	Beg. Feb.- mid July
Short rains		End July – beg. December	July – beg. December	End July – end December
Temperatures				
Annual mean	°C	20.4	20.8	22.2
Mean maximum	°C	28.3	28.6	28.6
Mean minimum	°C	12.5	12.8	15.8
Annual potential Evapo-transpiration	mm	1794	1836	1803
Topography		Moderately undulating (slopes 2 – 15%)	Very undulating (slopes up to 45%)	Gently undulating (slopes 2 – 5%)
Soil type (dominant)				
Local name		*Ingusi*	*Ingusi*	*Apokor*
FAO		Nito-humic Ferralsol and dystro-mollic Nitisol	Humic Nitosols and dystro-mollic Nitisols	Ferralo-orthic Acrisol, petroferric phase*
Description		Well drained, deep to extremely deep, dark red, very friable clay; in many places bouldery and rocky	Well drained, very deep, dark reddish brown to yellowish red, friable clay. On the interfluves and phases on slopes.	Well drained shallow to moderately deep, dark reddish brown to yellowish, friable sandy clay loam; over petroplinthite
Moisture storage capacity		High	Very high	Moderate***
Inherent fertility		K, Ca, Mg and N are adequately supplied but C is moderate and P is low. Low CEC	N, K and Mg are adequately supplied but Ca is low to moderate and P is low. C and CEC are high	Variable. In moderately acid soils K, Ca and Mg are adequate but P and N are low and C moderate

*with adjustments according to the Kenya concept (1980). **Average over 26, 14 and 21 years, respectively
*** scattered sandy , sandy clay loamy and clayey soils with low to high capacity

Rainfall in western Kenya ranges from 1400 to 2000 mm annually, decreasing westwards, and distributed in two cropping seasons: the long rains from March to July and the short rains from August to November. They are also known as first and second rains, respectively, and their onset and duration vary for the different areas within the region. The landscape is gently undulating in the East to fairly flat in the West, with the exception of the groups of hills scattered here and there. Nitisols, Ferralsols and Acrisols are the predominant soil types (Jaetzold and Schmidt, 1982; Andriesse and van der Pouw, 1985). Nitrogen and phosphorus are mentioned as the main limiting nutrients in food crops (Shepherd *et al.*, 1997), although potassium deficiencies are locally important.

Table 2.1.2: Main socio-economic characteristics of the selected working sites (Kenya Ministry of Agriculture and Rural Development, 2001; Braun *et al.*, 1997; Jaetzold and Schmidt, 1982; Crowley and Carter, 2000)

Variable	Unit	Site		
		Emuhaia**	Shinyalu	Aludeka
Average farm size	ha	0.69	1.25	2.13
Population density	Inh. km^{-2}	930	650	310
Family size		7.2	6.8	8.0
Ethnic group*		Luhya (Munyore)	Luhya (Isokha)	Teso
Production activities				
Food crops		Maize/beans	Maize/beans	Maize, cassava, finger millet
Cash crops		Tea, Napier grass, fruits and vegetables	Tea, coffee, sugarcane, fruits and vegetables	Cotton, tobacco, rice and finger millet
Livestock and grazing		Local zebu breeds but increasingly graded dairy cows. Zero grazing units or tethered in the farm	Local zebu breeds and some graded dairy cows. Zero grazing, tethered in farm or communal land	Local zebu breeds (oxen). Free ranging on natural fallow land. Affected by endemic Tripanosomiasis

*Tribe (sub-tribe)
**In certain areas of Vihiga district (i.e. Maragoli, bordering Emuhaia to the North) population density can be as high as 1500 inhabitants per km^2

The land use systems are fairly diversified and range from subsistence smallholdings in Siaya, Kakamega and Vihiga districts to more cash crop oriented farms in the sugar belt and in the northern areas (Rotich *et al.*, 1999). Due to high population in the subsistence smallholder sector, farm sizes tend to be small, ranging from 0.6 ha (Vihiga district) to 2.2 ha (Teso district) on average (Kenya Ministry of Agriculture and Rural Development, 2001). The major food crops are maize (*Zea mays*) and beans (*Phaseolus vulgaris*) with an increasing importance of cassava (*Manihot esculenta*), sorghum (*Sorghum* spp.) and finger millet (*Eleusine coracana*) towards the west. Main cash crops include tea (*Tea sinensis*) particularly in Kakamega and Vihiga districts, sugar cane (*Saccharum officinalis*) in Butere-Mumias district and secondarily cotton (*Gossipium hirsutum*) and tobacco (*Nicotiana tabacum*) in Teso district.

Most cattle kept in the region are local Zebu breeds, but there is an increasing number of grade (Fresian) cows for dairy production, especially in areas closer to urban centres. Due to the larger farm sizes oxen ploughing is increasingly adopted towards the west.

The selected working sites were chosen (according to criteria described in 2.1.1) as groups of villages within the following divisions: Emuhaia in Vihiga district, Shinyalu in Kakamega district and Aludeka in Teso district. Tables 2.1.1 and 2.1.2 give some relevant biophysical and socio-economic information on the three working sites, which set the background for the selection of a sample of farms per site. Clear gradients in altitude, rainfall, topography and soil types (mainly clay content, see later) as well as differences in population pressure, access to markets and land use introduced a considerable body of variability that allowed for several combinations of the factors **Site**, **Inherent** properties, **Wealth** and **Management** (see Chapter 1, Methodological approach).

2.1.3 Delineating Soilscapes

The distribution of soils along the landscape was used as a first approximation to study the biophysical variability at site level. Secondary information (Jaetzold and Schmidt, 1982; Andriesse and van der Pouw, 1985; FURP, 1994; Braun *et al.*, 1997; Rotich *et al.*, 1999; Kenya Ministry of Agriculture and Rural Development, 2001; TSBF, 2001) was complemented with expert knowledge (extension officers, soil scientist[3] from Kenya Agricultural Research Institute – KARI and National Agricultural Research Laboratory - NARL) and with transect walks and soil profile observations. With the agreement of the farmers, 1.2 m deep pits were dug at different points along a topographic section and soil morphological attributes were described following the criteria of FAO described by De Pauw (1985) and compared with previous observations to check the distribution of the soilscape units in the field. Appendices 2.1.3 – I, II and III give a profile description of the dominant soils at each site. With the initial aid of key informants (mainly highly exposed farmers, often chairing a soil conservation group or a farmers field school) and with the information given by farmers during the subsequent interviews the local soil classification was matched with the previously identified soilscape units. These results were contrasted with those found in previous projects (e.g. TSBF, 2001). Local soil names were included in the soilscape delineation and formally adopted for better communication with the farmers during the interviews. However, local names do not always agree with technical soil classes. Appendix 2.1.3 – IV shows the local name given to the main soilscape units in each site and their characteristics.

2.2 Farm sampling and characterisation

2.2.1 Selection criteria and methodology

Farms were selected to include the biophysical and socio-economic variability found at each site, consistently covering a range in the factors S (site), W (wealth) and I (inherent properties) with the farm samples (see above: Methodological approach). Therefore, farms from all wealth classes and sharing approximately the same soilscape units should be included. Special attention was paid to the last statement due to the frequent association between wealth and land quality seen at site level.
The first step in the selection was the identification by key informants (extension officers or knowledgeable farmers) of farmers that were 'good' and 'poor' soil fertility managers. An initial list was then developed. Although there is a clear association between wealth and soil management practices that can be used as a listing criteria, informants -especially farmers- were reluctant to classify their neighbours or themselves into rich, middle class or poor (the rich are easily identified, but the middle class usually contains many more names than the poor).

[3] Dr Stephen Nandwa is specially acknowledged for his advice and contribution at this point.

Visits to the farms started according to those lists of names. However, using key informants led to the selection of many farmers that had been involved in previous projects (one of the questions during interviews) and therefore not always representative. Moreover, a certain 'clustering' of farmers that are friendly and eloquent or that have other affinities with the informants took place. This was sorted out by breaking through the initial lists during the first visit to the farms, asking those farmers that were proactive and showed interest to introduce their neighbours for an interview. This 'randomisation' of the initial selection procedure led to a more physical clustering of farms (of different wealth class) on a certain soilscape unit, which in the end was very suitable for the study.

2.2.2 First approach interviews and farm transects

The first visit to the farms was designed to gather biophysical and socio-economic information to characterise them, identifying the main production activities and management practices affecting soil fertility and assessing the patterns of land allocation and farm layout (number and distribution of production units, components of the farm system and their interaction, farm assets and infrastructure such as type of field boundaries or soil erosion control measures). All this information was gathered at 20 farms per site by means of a semi-structured questionnaire (Appendix 2.2.2, First approach questionnaire) and by drawing farm transects together with the farmers (see later: Box 3.1.2, Example of a farm transect in Emuhaia).

Due to the unstructured, informal character of both methodologies, they were carried out during the same visit to a farm and often simultaneously: questions on management practices were normally discussed with the farmers during the transect walk across their farms. The interviews were conducted with the aid of translators who spoke the local languages[4]. In some cases, however, interviews could be held in English. The answers given by farmers were corroborated through triangulation by asking the same questions in several ways or during different visits to the farms, by confirming with other farmers (and different family members at the same farm) and with extension officers. In farms headed by men, women were interviewed as well and the information cross-checked, since women are normally involved in most activities regarding crop and soil management.

2.2.3 Developing a farm typology according to the objectives

The proposed farm typology has been developed to discriminate between farm systems that show clear differences in resource allocation and nutrient flows affecting soil fertility and its variability within the farm (i.e. different resource flow map models). The initial approach was to classify farms exclusively according to their resource endowment. However, this led to poor discrimination in terms of resource allocation decisions and nutrient flows, and made comparisons across sites difficult to interpret. A combination of the 'wealth' approach with a 'production orientation' approach was then adopted. Therefore, farms were also classified according to their objective functions (e.g. self-subsistence, market oriented) and the main types of constraints (i.e. land, labour or cash limitations) that were identified. This methodology led to the distinction of the five farm types that will be presented in the following chapter, where comparisons are also made between both classification criteria

[4] Mr Isaac Ekise and Mr Walter Munyuere are particularly acknowledged for, among other things, acting as interpreters during the visits to the farms.

(farm types vs. wealth classes). Thus, for comparative purposes, farms were still categorised according to wealth classes (Crowley, 1997) into High, Medium and Low resource endowment (HRE, MRE and LRE, respectively).

Table 2.2.1: System components defined for the farm typology and their description

System component	Acronym	Description	Example
Food crops consumed by household	CSN	Crops grown on the farm to cover the food demands of the household	Maize, beans, sweet potato, local vegetables
Food crops sold on the market	MKT	Food crops grown in excess of the household food demands that are commercialised, requiring low inputs and/or low investments	Maize, beans,* cabbage, groundnuts
Cash crops	CSH	Crops exclusively or predominantly grown for commercialisation that in most cases are not consumed by the household, requiring inputs and relatively high investments	Tea, coffee, sugarcane, cotton, certain vegetables
Livestock	LVSTK	Animal production activities demanding land and labour (sometimes inputs), generating cash or acting as investments	Dairy cows, goats, sheep, pigs
Woodlot	WOOD	On farm source of fuel and/or construction wood, sometimes sold on the market	Eucalyptus and Grevillea plantations
Other enterprises	OE	Other economic activities demanding labour (sometimes also land) and generating cash	Oxen services, honey bees
External food source	FOOD	Food items consumed by the household that are purchased on the market. **	Maize, beans
External income source	OFF-FARM	Salary, pension, earnings from casual employment, submissions, rents and gifts flowing into the household	
Household	HOME	Family members living (and eating) on the farm, and members living outside and receiving submissions	

*apparently overlapping with the previous category. The sum CSN + MKT indicates the totality of food crops produced on farm, and CSN is the amount effectively consumed by the household
** except for those that are *always* purchased, such as sugar, oil, etc.

Graphic models[5] of the farm system were schematised using the information gathered during the first interview (see Section 2.2.2). They were used, together with farm socio-economic indicators, as grouping criteria to allocate the sampled farms into different 'farm type' groups. The models included system boundaries, system components and their interactions and with external components. At each site, representative farm system models were identified that showed relevant differences according to (i) the type of system components (production activities, consumption units, income source, etc.), (ii) their relative

[5] Other examples of the application of graphic farm models can be seen in e.g. Silveira *et al.* (2001) for NE Brazil.

size/importance and (iii) the type and magnitude of the interactions between them and with external components in terms of labour, cash and nutrients. Such farm types (representative farm system models) are described in Chapter 3.

The various system components identified and used for this typology are described in Table 2.2.1, and some examples that occur frequently at the working sites are given. For the design of the graphic models (see later: Describing and categorising farm variability, Farm typology), the relative importance of each system component was represented by its size. This was also done for the system boundaries (i.e. farm size). Though land allocated to the various activities is one of the main criteria, the concept of *relative importance* is broader and integrates land, labour and input allocation to as well as cash generation by each system component. For the identification and definition of the different farm models only those components that are normally part of the system were considered. In other words, farmers were asked about what they *normally do* and not about what they *did* during the last season, since certain components such as annual cash crops may be intermittent.

The relationships between internal and external system components were defined in terms of cash (Kenya Shillings, KSh; 1 US$ = 75 KSh), labour (man-days) and nutrients (kg) flows, and used as categorisation criteria. Nutrient flows include fertilisers (organic and inorganic) and biomass (t_{DM} of food and other crop products, fodder, wood and crop residues) flows. The weight of the arrows indicates their relative importance. In the graphic models only the main flows that add to their usefulness for farm categorisation were included. For this reason, many flows that are useful for the calculation of nutrient balances at farm scale (e.g. the flow generated when crop residues are consumed by cattle) were not included.

Fodder production was not discriminated as an individual component but for Napier grass produced as a cash crop, and for a flow of biomass from external sources into the livestock component. The reason behind it is that the adoption of the few alternative ways of grazing and fodder management (basically, feeding cut grass to tethered cattle or grazing in communal rangeland) are observed across all farm types that own cattle and show no clear distribution pattern, making it useless to considered them in this case for classifying farms.

2.3 Approaches and tools for studying within-farm variability

2.3.1 Resource flow maps (RFM)

Farm selection and field procedure

Resource flow maps were drawn for one case study farm per farm type identified per site, totalling 15 farms, to visualise and identify soil fertility management practices and to analyse farmers' management strategies. The information from the first approach interview plus the biophysical site characterisation were used to group the farms in the sample into the farm types developed and to select case study farms from each one. Appendix 2.3.1-I gives a detailed description of the procedure followed during resource flow mapping (RFM), Appendix 2.3.1-II shows the forms used during the RFM exercise and Appendix 2.3.1-III illustrates the procedure with an example of a RFM drawn in a type 2 farm in Aludeka. What is important to clarify at this point is that the RFMs are drawn with a seasonal time horizon, and what was done during the last season (long rains 2002 in this case) may not always hold as a current practice.

During this visit to the farms all the production units (fields) were identified, their area measured by means of a GPS and their topsoil sampled for formal lab analysis (see later: Field biophysical characterisation). Sampling points, fields and plots drawn in the RFM were consistently coded and all sort of details regarding land use and infrastructure recorded in another form (Appendix 2.3.1-IV).

Sources of information

Most quantities indicated by farmers for inputs and outputs were given in local units, such as *goro-goros* (+/- 2 kg of maize), *debes* (+/- 8 kg of maize) or bags (80 to 90 kg of maize), and they had to be converted into SI units. Since the specific weight of different materials (grains, tubers, fertilisers, crop residues, etc.) and the actual size of the local units in different farms varied widely it was necessary to standardise them. A field weighting scale was taken to some of the farms and the weight of one *goro-goro* (the mostly used local unit) of the main crop produce (grains) determined. However, accuracy at this point does not guarantee accurate final estimations since, for instance, the yield of a certain plot is normally estimated by the farmer as something like "between 20 to 25 *goro-goros*". Many of the values in kg given to local units were taken from previous work in the region (Rotich *et al.*, 1999; van den Bosch *et al.*, 1998), especially for coarse materials like compost or crop residues (measured in wheel barrows or baskets). The same applies to the nutrient content of different materials, such as cattle manure, that were previously measured for a number of farms of different wealth classes in the region (Rotich *et al.*, 1999; Palm *et al.*, 2001, TSBF, 2001). Other parameters such as dry matter and nutrient contents in different crop products, as well as the harvest indices and partitioning coefficients of the various crops were taken from literature (van Keulen and Wolf, 1986; Marandu *et al.*, 1998; Nzuma and Murwira, 1998; Okalebo *et al.*, 1998; Janssen, 2002) and from own measurements (Appendix 2.4.1).

Data processing

Gross food production (GFP) was estimated by summing the fresh weight (FW) of the outputs (in kg or tonnes) of all fields within the farm indicated by the farmers, irrespective of their type (grains, tuber and roots, fruits, leaves). Gross food consumption (GFC) was calculated as the difference between GFP and the amount sold on the market. Gross food yield (t ha^{-1}) at farm scale is the result of dividing GFP by the area of cropped land (including annexed land). Gross food yield at field scale relates the FW of the outputs (kg or tonnes) to the area of the production unit (ha). Food production per capita relates GFP to the number of family members living on the farm. Using average values for the dry matter content (DMC, %) of the various crop products, the dry weight (DW) of the outputs was calculated. The DW of all the outputs from a field (e.g. maize, beans and cowpeas intercropped plus a strip of Napier grass) was summed (total output production per field, t_{DM}) and divided by the field area (ha) to obtain the dry matter yield (DMY, t_{DM} ha^{-1}) of the *outputs*. The yield of the *total biomass*[6] produced (TBY) per field was calculated by first estimating the total biomass produced by each crop (dry weight of the output over an average harvest index) and summing them, according to the following equation:

$$TBY\ (t_{DM}\ ha^{-1}) = [(DW_{out}/HI)_1 + (DW_{out}/HI)_2 + \dots (DW_{out}/HI)_n]\ /\ Field\ area \qquad (3.1)$$

[6] Here, 'total' refers to aboveground biomass

where DW_{out} and HI are the dry matter harvested and the harvest index of the 1, 2...n crops grown in a certain field. The components of a multiple crop may differ widely in terms of dry matter content, harvest index and potential biomass production, implying that their outputs could not be simply added to obtain an overall figure. However, the TBY calculated in the described way still results in a useful indicator when flows of C are calculated. The yield (t_{DM} ha^{-1}) of each individual crop was calculated as the DW_{out} divided by the field area times an estimation of the fraction of total area shared by each particular crop in the field. When no accurate estimates were available, a fraction 0.5 was adopted for each crop in an inter-crop. Equations 3.2 and 3.3 were used to calculate the amount of residues (DW_{res}, t_{DM}) produced by each crop and the total residue yield (TRY, t_{DM} ha^{-1}), respectively

$$DW_{res}\ (t_{DM}) = (DW_{out}/\ HI) - DW_{out} \tag{3.2}$$

$$TRY\ (t_{DM}\ ha^{-1}) = [(DW_{res})_1 + (DW_{res})_2 + \ldots\ (DW_{res})_n\ ]\ /\ Field\ area \tag{3.3}$$

From the estimates of total crop residues produced and from the amount of them indicated by farmers as used for fodder, fuel, etc., a residue management pattern was calculated for each field, expressing the percentage of total residue biomass that is consumed by animals (PRfodder, %), burnt (PRburnt, %), composted (PRcompost, %) or incorporated (PRinc, %). Fertiliser use was calculated from the local units applied to the different fields and different variables were derived. Total fertiliser use (TFU, kg) at farm level was aggregated from the amount used in each field. Fertiliser use intensity (kg ha^{-1}) was calculated from TFU divided by total area under crops (ha). Fertiliser application rates (kg ha^{-1}) were calculated for each field according to the amounts indicated by farmers and the area of the fields, and averaged for all fields in a farm that received fertilisers, to estimate the rates that are used by different farmers.

Average carbon content in the biomass dry matter was assumed to be 45% unless particular information was available. Average nutrient contents in crop products and residues were taken from previous work (see above) and multiplied by the amount of dry matter (of product and residue) yielded by each crop to obtain the nutrient yields in the outputs (NY_{out}, kg ha^{-1}) and in the residues (NY_{res}, kg ha^{-1}). Inputs of nutrients in inorganic fertilisers (NI_{if}, kg ha^{-1}) were calculated from the application rates (kg ha^{-1}) indicated by the farmers (converting local units into kg of fertiliser and dividing by field area) and the nutrient contents of each fertiliser type.

Nutrient inputs in organic fertilisers (NI_{of}, kg ha^{-1}) were calculated in the same way as for inorganic fertilisers though certain assumptions were considered in the case of mixed and/or composted materials. The broad range of nutrient content in composted materials and farmyard manure that can be found in the literature (see for example sources cited in Palm *et al.*, 2001 or in Janssen, 2002), indicates that the chemical composition of the organic resources is highly variable across sites and from farm to farm within a certain locality. The most common organic resource applied to the fields at planting or slightly earlier consists of a mixture of cow dung that is collected from the grazing sites - where it is already mixed with fodder residues and bedding materials-, and dry crop (mainly maize) residues just taken from the fields. In most cases composting times are very short for the residues to decompose before they are applied to the fields (as a consequence of the double cropping season residues are being harvested in certain fields while other fields are being planted). Thus, using nutrient content values given for composted materials might overestimate the real nutrient application rates. The nutrient content of a mixed organic source was calculated as the weighted average of the nutrient content of its components, basically cow, sheep or goat dung and crop residues slightly decomposed. Chicken manure was also considered when the sweepings from the kitchen (where they are kept during the night) were used. Amounts of these organic sources were difficult to estimate so the number of animals was used instead.

Gross and partial nutrient balances at field scale

Calculating gross and partial nutrient balances was meant as a tool to understand the underlying processes of accumulation and depletion that operate at field scale as induced by management decisions and practices. They are *gross* balances because they are calculated from rough, *ex-post* estimates of inputs and outputs given by farmers. Since they do not consider other nutrient flows (i.e. fixation, deposition, erosion, leaching, volatilisation) nor nutrients in the root biomass, they are *partial* balances. Equations 3.4 and 3.5 were used to calculate the inputs and outputs of nutrients to a certain field in kg ha^{-1}, respectively

$$INPUTS_{(X)} = NI_{if(X)} + NI_{of(X)} + NY_{res\,(X)} \times (PR_{inc} / 100) \tag{3.4}$$

$$OUTPUTS_{(X)} = NY_{out\,(X)} + NY_{res\,(X)} \times [(PR_{fodder} + PR_{burnt} + PR_{compost}) / 100] \tag{3.5}$$

where the subscript *(X)* in each term represents a certain nutrient X; when carbon balances are calculated X is replaced by C, for nitrogen by N and so on. The balances (kg ha^{-1}) were calculated as the difference between INPUTS $_{(X)}$ and OUTPUTS $_{(X)}$ to and from a certain field. In the case of carbon balances, the term $NI_{if\,(C)}$ gets the value zero.
Since the common practice in terms of grazing management is that of feeding cut grass and/or crop residues to tethered animals, or alternatively, taking the animals to communal grazing places or to permanent fallow land, the use of crop residues as fodder was considered as an output. Inputs of nutrients contained in cattle manure are only accounted for under NI_{of}. In reality, nutrients contained in the droppings of grazing animals on the field should be accounted for. However, animals grazing standing crop residues are not commonly seen at the working sites due to the intensive double cropping system. An exception was observed for certain fields in Shinyalu that are left as fallow during the short rains, and restricted to wealthier farms. Since the estimation of the variables describing the livestock system are much more difficult than those of the crop system -and far less accurate- through the RFM, the above mentioned assumption was applied to all fields under study.

Labour demands

Farmers were asked about the timing of the activities related to a typical maize/beans intercrop. The answers to questions such as "when do you start preparing the land", "when do you practice the first weeding", "when does the maize flower" or "when are the beans harvested" were recorded and their relative frequency for the set of farms computed. A distribution of the activities along a time axis was obtained in this way. To materialise the answers one of the fields in each farm was selected as an example, of which the area was known. Then, from the answers to questions such as 'how many people do you need and for how many days to weed or to harvest this plot of maize' the labour requirements in man-days per ha were calculated.

2.3.2 Developing a field typology

A field typology was developed by considering previous approaches (e.g Smaling *et al.*, 1997; Mapfumo and Giller, 2001) and by studying the results of the resource flow maps, adopting a terminology that can describe the variability found at the different working sites. This typology aimed at discriminating resource allocation patterns and internal (within farm) nutrient flows that may have a short and/or long-term effect on the development of soil fertility gradients. In principle, land use and distance from the house were considered as the main criteria for this typology, which worked acceptably for most fields. However, certain field types do not appear in all sites neither in all farms within a site. Therefore, fields were initially discriminated as ordinary fields and special niches, the latter belonging to biophysical discontinuities or to a certain land use history. Other criteria for classifying fields included type and number of crops that are grown, use or destination of the outputs, type and amount of inputs used, timing of crop and soil management activities and sequential order within the farm, average yields obtained and general crop husbandry practices adopted (e.g. plant density). Fields were classified into a certain type during the RFM exercise and during the second interview (see below).

2.3.3 Farmers' land quality classification - second interview

Three farms per farm type per site (45 in total) were selected for a second interview in which farmers were asked about their perceptions of soil fertility gradients, about the relative importance they assign to different production activities and about the way they time their activities for the different fields within the farm (Appendix 2.3.1 - II, Questionnaire on farmers' perception of soil fertility gradients). Farmers were asked to classify their production units according to qualitative aspects into Good, Regular and Poor land[7]. The area of each of the production units was measured with the aid of a GPS device.
As the interviews started this denomination was soon replaced by Fertile, Average and Poor, since that was the terminology naturally adopted by the farmers when giving their answers. However, it was made explicit during the interviews that soil fertility (nutrient capacity and intensity) was not the only criterion used by farmers, and that rather crop performance with or without fertiliser application was the main one. This exercise was carried out by walking the farm with the farmer and discussing about each field, with the aid of a map of the farm drawn by them in which the symbols +, +/- and - were used to designate land quality classes. Farmers were also asked to give their criteria underlying this land classification and the reasons they found to explain differences in crop performance among fields (taking concrete examples from their farms).
The area of Fertile, Average and Poor land of each farm was calculated by summing the areas of the individual fields and the percentage of each class relative to total farm size was computed. During this visit to the farms the different fields were also classified according to the proposed field typology. The number of times in which the different field types fell into any of these land quality classes was counted and the frequency expressed in relative terms (%).

[7] Farmers classified their own land according to the variability found in it and not -not explicitly- by comparing it with their neighbours'. Although this point was made clear to them from the beginning, comparisons with other farms were naturally unavoidable in many cases.

2.3.4 Field biophysical characterisation

Soils and landscape

In addition to the soil profile observations carried out during the soilscape delineation (cf. section 1.3) a number of 0.6 m-deep pits were dug in the points were maize growth performance was assessed (see later, Maize yield estimations) for observations of the root zone, for bulk density determinations at different depths and for subsoil sampling. Within each farm, two to three points where maize yield had shown clear differences were selected for these observations.

Soil profile (root zone) observations included identification of soil layers, colour (Munsell standard colour charts), field assessment of soil texture and structure (De Pauw, 1985), soil depth in case of limitations to root growth or presence of hardpans (ferroplinthite layers), presence of compacted layers, of termite channels, of rocks and stones, of sediment accumulation and/or eroded topsoil layers, abundance of roots at different depths and general root growth performance (Appendix 2.3.1 - IV, Form for field description). Bulk density samples were taken from the pits with 125 ml steel rings at different depths (0 - 10, 10 - 20, 20 - 30, 30 - 40 and 40 -50 cm), oven-dried at 105°C and weighed. Bulk density (kg m^{-3}) was calculated by relating the dry weight of the samples to the ring volume. Curves of bulk density against soil depth were plotted to identify compacted layers.

In all the farms visited during the second interview (45 in total) the slope was measured at three different points in each field with a clinometer and an average field slope (m 100 m^{-1}) calculated. Additionally, the presence of soil erosion control measures and the type of field boundaries (permanent or not, living fences, trash lines, etc.) were recorded.

Soil sampling and laboratory analyses

Three types of soil samples were taken during the different visits to the farms:

a) The pit samples are topsoil and subsoil samples taken from the above-mentioned root zone observation pits. The topsoil samples were taken at a depth of 0 - 15 cm from the open pit. The subsoil samples were taken at variable depths (from 20 -30 to 30 - 40 cm) from the centre of the principal subsoil layer (i.e. transition layers like AB horizons were preferably avoided to have a clearer gradient of soil properties with depth). These samples were analysed in the lab by formal methods (see below, Soil laboratory analyses).

b) Topsoil (0 -15 cm) samples were taken with an auger at five points per field from all the production units identified in the farms included in the resource flow mapping (15 farms in total). A composite sample of approximately 0.75 kg from each field was taken to the laboratory for formal soil analyses (see below, Soil laboratory analyses). Once in the lab, a sub-sample of about 0.25 kg was taken from each sample and stored at 20°C for later analysis using spectral reflectance.

c) In the farms visited for the second interview (45 in total) topsoil (0 - 15 cm) samples were taken with an auger at five points from each of their fields and a composite of 0.5 kg per field was obtained. In 15 out of the 45 farms no samples were taken, since they had been already sampled during the resource flow mapping (b). These samples were taken to be analysed by spectral reflectance.

The final number of samples was determined by the number of observations for soil fertility (SF) variables, as presented later (Section 2.5, Statistical analysis, Table 2.5.1). Samples were air-dried, sieved through 2 mm and stored at room temperature. They were analysed in the laboratory of the Tropical Soil Biology and Fertility Programme (TSBF) in Nairobi, Kenya, using standard methods widely used 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 was determined colorimetrically after H_2SO_4 – dichromate oxidation at 150°C for 30 minutes. Total N was determined by Kjeldhal 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.

Assessing soil fertility by spectral reflectance - soil fertility index

Shepherd and Walsh (2002) demonstrated the value of spectral libraries of a large number of soil samples for developing soil fertility screening tests, and showed how a spectral screening test (www.worldagroforestrycentre.org/sites/program 1) can be used to screen soils into soil fertility classes at a watershed scale using samples from the Kenya Lake Victoria Basin. The same approach is used here to screen soil samples and obtain a soil fertility index (SFI), given the fact that the soils under study are of the same type of those included in the original library. A short description of the mathematical model and procedure to calculate the soil fertility index is presented in Appendix 2.3.4, while further detail can be found in the original source. Since the SFI is a probabilistic measurement (a likelihood ratio), the interpretation of these results follows the rule that the higher the value of the SFI, the more fertile the soil is (i.e. the higher the log probability that it falls in a 'fertile' soil class, defined by a number of soil parameters). Additionally, the soil samples taken during this work extended the number of cases included in the original spectral library for eastern African soils, strengthening its predictive value for this kind of uses.

2.4 Maize yield estimations

2.4.1 Calibration and validation of allometric models

Allometric models were developed for estimations of maize yield by means of quick, easy and non-destructive on-farm measurements on the standing crops. The full description of the experiments carried out for the calibration of the allometric models for the maize varieties mostly grown at each site, and for their validation is presented in Appendix 2.4.1. The models give acceptably accurate estimates (R^2 values ranging from 0.76 to 0.91) of total biomass and grain dry matter yields per plant (TDM and GDM, respectively, in grams) by using plant height, cob length and cob diameter measurements.

2.4.2 Field measurements, yield estimations and validation

Field measurements of maize crops were carried out into 3.5 m^2 plots demarcated in the field at representative places (trying to include the variability found in each field). When fields showed high internal variability different spots were selected, demarcated and included for measurements. Consequently, the number of observations at each farm varied between 2 and 6 resulting in different final n sizes for each site (see later: Regression models to explain yield variability). All measurement points as well as the homestead, the compost pit or pile and the grazing sites were geo-referenced with a GPS. The number of plants and cobs within each plot was counted. Distances between rows (m) and between plants in a row (m) were measured at 3 to 6 points within each plot, depending on the variability observed in plant population. When the crop was established in planting holes, the number of holes and the number of plants per hole were counted. Plant height to the top of the tassel (cm), cob length from its insertion in the main stem (cm), and cob diameter in its central section (cm) were measured with a scaled wooden stick, a measuring belt and a calliper, respectively. A score (0 = absent, 1 = low, 2 = medium and 3 = high) was adopted to estimate general growth performance and intensity of green colour, symptoms of nutrient and/or water deficiency (purpling, yellowing and browning), general weed infestation and *Striga* sp. infestation levels (Appendix 2.4.2, Form for maize growth performance). Other relevant observations like pests or diseases attack were also recorded. Farmers were asked about planting date, maize variety used, proportion of maize and beans in the inter-crops, frequency and timing of weeding, organic and inorganic fertiliser use (type and amount) and expected yields.

Plant density (plants m^{-2}) was calculated by considering the average (over at least three measurements) between-rows and between-plants spacing to calculate the expected plant population (PP_{exp}, plants m^{-2}), and corrected by the actual plant population (PP_{obs}) counted in the field within the 3.5 m^2 plots, and standardised to plants m^{-2}. A plant population correction factor (PPCF) was calculated as PP_{obs} / PP_{exp} as a rough indicator of crop survival and soil cover during the growing season. Total biomass and grain dry weight yields (TDW and GDW, respectively, in t ha^{-1}) of maize at field level were calculated by equations 4.1 and 4.2, in which a factor 0.01 is used to transform the units g m^{-2} into t ha^{-1}

$$TDW\,(t\ ha^{-1}) = TDM\ (g\ plant^{-1})\ x\ Pl.\ density\ \ (plants\ m^{-2})\ x\ 0.01 \quad (4.1)$$

$$GDW\,(t\ ha^{-1}) = GDM\ (g\ plant^{-1})\ x\ Pl.\ density\ \ (plants\ m^{-2})\ x\ 0.01 \quad (4.2)$$

Each yield estimation point was representative of a certain area within the farm (a group of maize fields, a single field or a sector within a field) depending on the variability found. The proportion of total farmland under maize that was represented by each of the measurement plots was assigned in agreement with the farmer, who participated in the selection of the yield estimation points as well. A weighed averaged maize yield (t ha^{-1}) was calculated for each farm visited by considering the yields estimated at field scale (TDW or GDW) and the proportion of total land of which they were representative within each farm. These estimations at farm scale were validated against the yield estimations calculated from the Resource Flow Map exercise (See above, Tools for studying within farm variability).

A resource use index

To account for the intensity in the use of organic and inorganic resources (fertilisers) on the maize crops a resource use index (RUI) was developed. A score (0 = no use, 1 = low, 2 = medium and 3 = high) was adopted to estimate such intensity. This index, though arbitrary, was meant to establish a comparative indicator between different fields and farms and appeared as more reliable than trying to establish the exact amount (and application rate) applied to the crop by interrogating the farmer. The score was assigned to each situation according to what was done during the growing season under study. However, farmers tended to answer on what they normally do in a certain field, season after season, rather than on what they did in the last one.

A score 3 corresponds to a situation in which organic and inorganic fertilisers where used in what seemed to be adequate or high amounts, like when a compost application at the beginning of the season, a base fertilisation with di-ammonium phosphate together with the seeding and a top-dressing with urea are done in a certain field. A score 1 may be the case when only kitchen wastes are applied to a field or when the remaining fertiliser from the home fields is applied in a remote field in extremely low doses. The index cannot be used for comparisons between sites due to the particularities in terms of agro-ecological conditions (crop demand and response), and due to socio-economic aspects; e.g. farmers in Emuhaia were more exposed to extension services and research projects and closer to input markets than in the other sites, for which fertilisers are better known and more widely adopted.

2.5 Statistical methods[8]

2.5.1 Comparisons at site, farm and field scales

All sources of variability were categorised according to the spatial scale to which they belong -between sites, between farms and within farm - by means of the proposed farm and field typologies. Categorisations of between and within-farms variability by wealth class and by farmers' land quality classes, respectively, were also adopted for comparative purposes. The measured variables were differentiated into three categories: Management Factors (MF), Inherent Properties (IP) and Soil Fertility indicators (SF). Appendix 2.5.1 shows the variables included in each category, their units and the calculation procedure for some of them. A fourth variable type is the Soil Fertility Index (SFI) obtained by scanning topsoil samples under near infrared reflectance, which basically belongs to the same category as SF but was measured for a larger number of samples (see below, Table 2.5.1). The data from the measurements of these different variables was displayed in box-plots to identify outliers and to study the width of their range. Extreme outliers, such as certain soil fertility variables showing extremely high values (e.g. phosphorus or carbon contents measured in samples from swampy areas that are not found in all farms) were eliminated from the pooled analysis.

Data were then subjected to analysis of variance under the above-mentioned sources of variability (Site, Farm type and Field type), and means were compared by the 5% LSD. Due to the particular experimental design (3 sites, five farm types and a variable number of field

[8] Dr. Richard Coe at ICRAF Nairobi, and Dr. Jac Thissen at Wageningen University are especially acknowledged for their advice during the different steps of the experimental design and data analysis

types) the ANOVAs were conducted under the unbalanced treatment structure case offered by *GenStat* 6th version. Additionally, and because of the (exploratory) characteristics of the experimental design, the number of observations within each factor was also variable. Table 2.5.1 summarises the final number of observations for each factor included in the ANOVAs. Note that in the case of the field types only the *Ordinary Fields* group (see later: Field typology) was included because they appear in all farms. More than one observation per field type per farm was also common, like two remote fields (RF) in one farm, as reflected by the number of observations in Table 2.5.1.

Table 2.5.1: Sources of variability, factor levels and number of observations for the different categories of variables included in the analyses of variance

Source of variability	Factor levels	Number of observations*			
		Management factors	Inherent properties	Soil fertility variables	Soil fertility index
Site	Emuhaia	71	55	55	150
	Shinyalu	62	53	53	158
	Aludeka	60	52	52	188
Farm type	Type 1	30	26	26	-
	Type 2	42	52	52	-
	Type 3	51	33	33	-
	Type 4	39	28	28	-
	Type 5	30	32	32	-
Field type	Home gardens	28	26	26	-
	Close Fields	43	32	32	-
	Mid-dist Fields	63	37	37	-
	Remote Fields	45	34	34	-

*the sums of observations are not the same for each source of observations due to the farms excluded after the first step and due to the existence of other field types that are not represented in all farms

2.5.2 Regression models to explain maize yield variability

Different regression models were developed to explain maize yield variability at site scale including all the categories of variables described above (MF, IP, SF and SFI). The preliminary screening of the data revealed wide differences across sites (particularly for IP and SF data) so as to build regression models with all the data pooled (see Chapter 3, Range of soil properties at site level). For that reason, the multiple regression analyses were carried out for each site independently. This approach also helped in identifying the MF, IP and SF variables that better explained the variability found in the field at each site. The introduction of the different types of variables for the construction of the models was done stepwise, to study their relative explanatory power at each site. The number of points used in the regression analyses at each site varied with the type of explanatory variables, with a different number of observations available per site (Table 2.5.2). The lowest numbers correspond to IP and SF variables and therefore they set the maximum number of points to be included when building models that included all types of variables. Finally, the SF and IP variables except for field slope (m 100 m^{-1}) and soil depth (m) were replaced by the SFI (see Section 2.3.4 above: soil fertility index) and combined with MF variables for the development of explanatory regression with fewer terms (with more degrees of freedom for the inclusion of MF variables).

Table 2.5.2: Number of points included in the regression analyses to explain maize yield variability site by site with different types of variables

Site	Number of observations by type of variable			
	Maize yield estimations	Management factors	Inherent properties* and soil fertility	Soil fertility index
Emuhaia	71	71	22	71
Shinyalu	62	62	19	62
Aludeka	60	60	19	60

*Except for slope (%) which was measured together with management factors (71, 62 and 60 observations)

The multiple regression models were built by means of the *All Subsets Regression* option offered by the *GenStat* 6[th] version (RSEARCH procedure). With this procedure the entire set of explanatory (groups of) variables could be introduced at the same time and the program selected the best sub-set (with those that showed the lowest internal covariance) to build 1 to n-term models under the specified type of relationship (linear, polynomial, etc.). This procedure was followed for each set of variables and their combinations, i.e. MF, IP and SF separately, MF + IP, MF + SF, IP + SF and MF + IP + SF. The best models to explain yield variability at site scale with different numbers of MF, IP and SF variables were of the multiple linear regression type. Correlation analyses were also carried out between the explanatory variables by using *GenStat* 6[th] version.

2.6 Dynamic simulation of nutrient balances at field scale

A model was developed to calculate nutrient balances considering daily rates of inputs and outputs to and from a certain field within a farm, defined here as soil/crop system in agreement with the concept adopted within the NUANCES framework (Rowe, E.; personal communication). As a first approach to the potential use of a dynamic model for studying the effect of management decisions on soil fertility, the model was programmed and parameterised focusing on nitrogen balances. Therefore, both the dynamics of the organic fraction as well as of the soil water had to be simulated in order to estimate important inputs and outputs (e.g. N mineralisation, N leaching). The model includes four different sub-models or modules (i.e. crop growth, organic matter dynamics, water balance and soil erosion) that provide the necessary information for the N balance calculation (Fig. 2.6.1).
The different sub-models were derived from (well-known) existing models that had been applied and validated under several conditions and proved sensitive, accurate and relatively undemanding of data (Spitters and Schapendonk, 1990; Goudriaan, 1994; Habets and Oomen, 1994; van Keulen, 1975). They were parameterised for the conditions of this study and adapted to meet the information needs for the calculation of N balances. The principle of low data requirements was prioritised due to the dominant conditions for which this model is to be used. To simulate certain inputs and outputs of N the more descriptive models (regression equations) developed for the region by Stoorvogel and Smaling (1990)

were initially used. These flows[9] (i.e. gaseous losses, non-symbiotic N fixation and atmospheric deposition), however, have been shown in most examples (see for instance Giller *et al.*, 1997) as fluctuating around relatively low values when compared to the major ones (i.e. soil erosion, leaching, fertilisation, harvest/removal). For that reason, the estimation of the minor flows was done for a seasonal period and considered constant across scenarios (see later Table 2.6.1 and related text), excluding them from the simulation program.

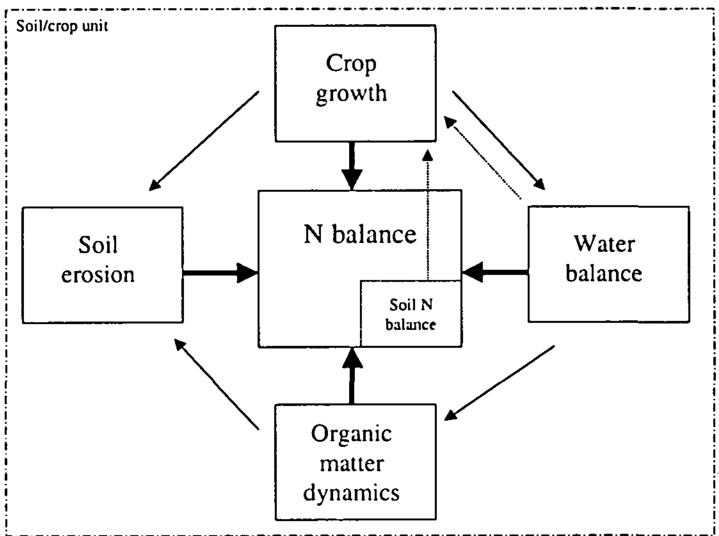


Figure 2.6.1: Scheme illustrating an overview of the model with the different sub-models (modules) and the main direction of their interrelationships. The dashed line represents the limit of the soil/crop unit, a space defined by an area of 1 m^2, a soil depth of 0.3 m and an upper limit represented by the top of the crop canopy.

2.6.1 Model for dynamic nitrogen balances at field scale

The model for N balance at field level considers a soil/crop system defined by the area of a certain field within a farm. The crop chosen for simulation is maize since, as explained in the previous sections, it is the main grain crop grown in the region (across sites, farm types and field types). The top of the canopy is considered as the upper limit of the soil/crop system, while the depth of the topsoil layer [TKLT] determines the lower one. This practical simplification must be carefully handled when aggregating the results up to a field scale, due to the high within-field variability. Soil and management parameters measured for an entire field were averaged, and the mean values used to characterise a 'representative' soil/crop unit (see below).

[9] The term 'flow' in this case refers to the total amount of N 'flowing' into and out of the soil/crop system (field) and it is measured, for instance, in kg. Since the model considers a soil/crop unit of 1 m^2, the term 'flux' (i.e. flow density), expressed in g m^{-2}, is more appropriate. For example, leaching is an output flow of N from the soil/crop system, and is calculated as a flux (i.e. g N m^{-2}) on the basis of a soil/crop unit of 1 m^2. To calculate the leaching flow the flux must be multiplied by the field area.

An arbitrary topsoil depth of 0.3 m was chosen to be able to compare the results with those from other approaches, most of them considering similar values. On the other hand, soil samples were taken in the field at depths 0 – 0.15 m and 0.15 – 0.3 m (Section 2.3.4, Soil sampling), and values from the soil analyses are used for initialisation of the model. This implies that nutrients leached to soil depths below 0.3 m are considered outputs from the system. A soil/crop unit is defined as a portion of the soil/crop system of 1 m^2 and used for calculation of the N balance, expressing the results in g N m^{-2} of soil. The temporal limit of the system is the growing season, starting with soil preparation for sowing (second ploughing, drilling) and finishing after harvest (of grains and crop residues), when the first soil preparation for the next growing season starts.

The time step of simulation to be adopted depends primarily on the characteristic time coefficient (TC) of the processes simulated (see below). On the other hand, a daily time step of simulation is of interest here in order to represent events related to day-by-day management decisions and practices. Thus, the nitrogen balance [NBAL, g N m^{-2}] for the growing season integrates the daily N balance [DNBAL, g N m^{-2} d^{-1}] over time with a daily time step [DELT]. Due to the discontinuity of certain processes simulated (e.g. fertilisation) the integration method adopted is the rectangular (Euler's), for which the upper limit to DELT is determined by the TC in the differential equation (i.e. the time characteristic of the process under simulation). The TC is the time that would be required by the model to reach its equilibrium state if the rates of change were fixed. In models such as this one, containing more than one rate variable, a first approximation to the proper time step can be obtained by considering a DELT smaller than one tenth of the smallest TC in the model (Leffelaar, 1993). This does not impose a modelling problem though, since all the sub-models (modules) used for the different processes involved in the N balance (i.e. models for crop growth, organic matter dynamics, water balance and soil erosion, developed by others – see later) use daily time steps or longer (e.g. weekly). The weather data file consists of daily values for the different meteorological variables. As an illustration, the figure in Appendix 2.6.1 shows that no improvement in the calculation of the different N flows was achieved when the time step of integration was reduced from 1 day to 0.1 day.

The daily nitrogen balance [DNBAL] is the result of daily N inputs and outputs to the soil/crop unit and it is calculated as follows, using the initial FST expression:

```
DNBAL = (DNIF + DNOF + DNHW + DNDEP + DNFIX) - (DNLG + DNREM + . . .
        DNLEA + DNLE)
```

Where,

DNIF: N applied as inorganic fertiliser [g N m^{-2} d^{-1}]

DNOF: N applied as organic fertiliser [g N m^{-2} d^{-1}]

DNHW: N applied as household wastes [g N m^{-2} d^{-1}]

DNDEP: N input as wet and dry depositions [g N m^{-2} d^{-1}]

DNFIX: N input as non-symbiotic fixation [g N m^{-2} d^{-1}]

DNLG: N output as gaseous losses [g N m^{-2} d^{-1}]

DNREM: N removal (harvests) [g N m^{-2} d^{-1}]

DNLEA: N leaching [g N m^{-2} d^{-1}]

DNLE: N loss by soil erosion [g N m^{-2} d^{-1}]

The rates of N application as fertilisers are, indeed, not strictly daily. This approach was adopted because it is possible to control the date in which they take place [IFDATE, OFDATE]. However, application of organic fertilisers may take place during several days under labour shortage due to the time required to carry coarse materials to distant fields. Successive applications of fertilisers (e.g. top-dressing) are simulated separately, mostly because the types of fertilisers used are not the same. The application of household wastes is only relevant for the home gardens and is typically daily. For each of these rates the N content of the fertiliser/material [g g^{-1}] applied is multiplied by its (daily) application rate [DIFAR, DOFAR[10], DHWAR respectively, in g m^{-2}].

The inputs of N as dry and wet deposition and as non-symbiotic fixation, and the outputs of N as gaseous losses are calculated according to the transfer functions derived from literature data by Stoorvogel and Smaling (1990) and by Smaling (1993). These equations consider the average annual rainfall of the site, and in the case of gaseous losses also the clay fraction [CLAY, kg kg^{-1}] and N content [the initialisation values for soil organic and inorganic N values, ISON and ISMN, g m^{-2}] of the soil plus the N fertilisation rate (Table 2.6.1). The amount of N applied as inorganic fertiliser was calculated in Table 2.6.1 as the product of the fertiliser application rate [IFAR, kg ha^{-1}] times its N content [NCIF, kg kg^{-1}].

As stated in the previous section these flows are of minor importance, which can be corroborated in Table 2.6.1, except to some extent for N lost as gas, which seems quite high. Anthofer and Kroschel (2002) estimated annual gaseous losses of 14 kg N ha^{-1} for *Mucuna*/maize rotations in the savannah-forest transitional zone of Ghana, whereas Millar (2002) measured NO_2-N emissions of only ca. 2 kg ha^{-1} during 84 days after incorporation of improved fallow species residues in western Kenya. The transfer functions for their estimation were developed from a large number of experimental data -considering annual means for different sites- with their validity defined for the range of values originally used. Their 'transformation' to a daily time step assumes an even distribution of the process over long time periods (i.e. processes taking place in seconds, when they are calculated from daily average data such as rainfall), which is mostly not the case. Moreover, since they are functions of 'site-scale' parameters (i.e. rainfall, clay), they will not show important differences for the different fields within a farm. Therefore, these flows will not be included in the dynamic simulation, so the terms DNDEP, DNFIX and DNLG were removed from the balance equation, which then reads:

```
DNBAL = (DNIF + DNOF + DNHW) - (DNREM + DNLEA + DNLE)
```

and only the major flows were dynamically simulated. This partial balance calculation resembles the one used to analyse the results of the resource flow map (see Section 2.3.1) but adding erosion and leaching as outputs from the system.

The removal of N by harvests is considered as a daily rate because often farmers do not harvest all their produce in one day, especially in the case of plant parts other than grains (i.e. stover). The calculation of the rates of N removal by harvests, N leaching and N loss by soil erosion are shown below in the crop growth, water balance and soil erosion modules, respectively. An important omission of this balance calculation is the input of N by sedimentation, for which the model cannot be applied under conditions such as those of valley bottomlands. If soil losses are simulated for fields that are higher in a topographic sequence they could be used, in principle, as rough estimations for the amount of sediments transferred to the valley bottom. Moreover, areas of soil loss and sedimentation can be also

[10] In the model listing (Appendix 2.6.2) these parameters (DIFAR and DOFAR) are expressed in kg ha^{-1} because it is easier for the user to enter them this way. However, a factor 0.1 is used to transform them into g m^{-2} when the rates of inputs are calculated.

identified in a single field, for which the proportion of soil lost from a soil/crop unit is normally higher than for the whole soil/crop system (field).

Table 2.6.1: Partial N balance considering three minor N flows calculated according to transfer functions for a seasonal time span

N flow	Transfer function*	Seasonal magnitude** (kg ha^{-1})
N gaseous loss	*NLG = (Soil N + Fertiliser N) * (-9.4 + 0.13 * CLAY + 0.01 * R)*	13.9
N deposition	*NDEP = 0.14 * R*$^{1/2}$	2.63
Non symbiotic N fix	*NFIX = 2 + (R – 1350) * 0.005*	0.83
Partial balance	*NDEP + NFIX - NLG*	-10.4

The example considers a 0.3 m deep topsoil with 25% clay, 1.5 % SOC (C:N = 15) and 46 kg N ha^{-1} applied as fertilisers; N deposition includes both dry and wet; N denitrification is a function of clay and rainfall and gives extremely low values of N loss (not shown); R = annual rainfall (mm); CLAY = soil clay content (25% in the example) ; Soil N = ISON + ISMN; Fertiliser N = IFAR * NCIF
*Stoorvogel and Smaling, 1990; Smaling *et al.*, 1993
**Long rain season (Feb – Aug) with weather data from Kisumu – Kenya, 1986

2.6.1.1 N balance in the soil

The amount of mineral N[11] in the upper 0.3 m of the soil [SOILMN, g N m^{-2}] results from the integration of the net rate of change in soil mineral N [NRSMN, g N m^{-2} d^{-1}]. This rate represents the daily balance of inputs and outputs of mineral N to and from the soil solution. Inputs to the soil solution that are considered in the balance are N from inorganic fertilisers [DNIF] and the N released by decomposition of the different organic pools through their N mineralisation rates [RSON, RYON, ROFON, g m^{-2} d^{-1}], which are explained in the organic matter module. The outputs are represented by N uptake by the crop [DNUPT, g m^{-2} d^{-1}, see below], N leaching [DNLEA, g m^{-2} d^{-1}, see below] and mineral N loss by soil erosion [DMNLE, g m^{-2} d^{-1}, see below].
The total amount of soil N [TOTSN, g m^{-2} for the upper 0.3 m of the soil] is calculated as the sum of the amount of mineral N [SOILMN] plus the N contained in the different pools of soil organic matter [SON and YON, g m^{-2}]. To calculate the soil contents of total and mineral N [SOILNC and SLMNC, respectively, in g N per kg of soil] the following expressions are used in the FST program:

```
SOILNC = TOTSN / (BULKD *  (TKLT / 1000.))
SLMNC = SOILMN / (BULKD *  (TKLT / 1000.))
```

where BULKD [kg m^{-3}] is the soil bulk density and TKLT [mm] is the depth of the topsoil layer. Though the status of mineral and/or organic N in the soil at a certain time are not part of the calculation of the N balance for the soil/crop unit (in the sense that they are not N *flows* as they were defined in the previous chapter, see Table 1.3), they are very important in determining the magnitude of other processes affecting it. For instance, the rate of N lost by leaching [DNLEA, g m^{-2} d^{-1}] is calculated from the rate of water percolation to the subsoil layer and the amount of mineral N in the soil solution (see Section 2.6.1.5).

[11] No distinction is made between $N\text{-}NO_3$ and $N\text{-}NH_4$

2.6.1.2 Crop growth with the expo-linear function (LINTUL type approach)

Crop growth is simulated following the expo-linear growth function, introducing an artificial truncation in leaf area development by means of a maximum LAI, which in turn leads to a maximum fraction absorbed from the incoming radiation (Goudriaan, 1994).

(i) $$W = Cm / Rm * Fm * \ln \{1+\exp(Rm * (t - tb))\}$$

(ii) $$dW/dt = \frac{Cm * Fm * \exp\{Rm * (t - tb)\}}{1 + \exp\{Rm * (t - tb)\}}$$

(iii) $$L = 1/k * \ln\{ [1 + \exp(Rm * (t - tb)] / [1 + \exp(Rm * (t - tb) - k*Lm)] \}$$

(iv) $$dL/dt = pl * s * dW/dt * \frac{1 - \exp[-k*(Lm - L)]}{1 - \exp[-k*Lm]}$$

Where,
W: crop biomass at time t [g m^{-2}]
Cm: maximum absolute growth rate in the linear phase [g m^{-2} d^{-1}]
Rm: is the maximum relative growth rate in the exponential phase [d^{-1}]
tb: is a timing parameter (the projection of the linear growth curve to the x- axis) [d]
L, Lm: leaf area index [-], and maximum LAI [-]
pl: partitioning to leaf dry weight [-]
s: specific leaf area [m^2 g^{-1}]
k: extinction coefficient [-]
Fm: maximum fraction of radiation absorbed $\{1 - \exp[-k * Lm]\}$ [-]

Using this approach implies, in principle, three main assumptions:

- exponential extinction of radiation with leaf area and a constant extinction coefficient k, according to the expression:

$$F = 1 - \exp[-k * L]$$

- a direct proportionality between this fraction (F or FRABS in the model listing) and actual growth rate of biomass (dW/dt):

$$dW/dt = Cm * F$$

- a constant ratio between leaf area and plant dry matter, defined by the partitioning to leaves (pl) and the specific leaf area (s):

$$dL/dt = pl * s * dW/dt$$

where dL/dt (or GLAI in the listing, m^2 m^{-2} d^{-1}) is the rate of increase of the leaf area index. Two functions are used to account for changes in pl and s [PTL and SLA in the model listing], according to the development stage [functions PTLTB and SLATB]. Coefficients of partitioning towards leaves in maize crops have been calculated by Boons-Prins *et al.* (1993). The net rate of change in the leaf area is calculated by considering the death rate of the leaves as well [NLAI = GLAI – DLAI], which is explained below.

The maximum leaf area index to be achieved by the crop [Lm or LAIM in the model listing, $m^2 m^{-2}$] can be introduced as a parameter for well-known crops growing under fairly controlled conditions (e.g. no defoliation by pests). Here, the maximum leaf area index is defined by plant density [plants m^{-2}] and by a maximum leaf area per plant [m^2]. Leaf area per plant in maize crops increases with decreasing plant densities up to a certain point (De Vos and Sinke, 1973), which is considered the upper limit for LAIM. This approach allows for the simulation of plant density, another management factor affecting crop performance. A function was fitted relating maximum leaf area per plant [LAPL, m^2 $plant^{-1}$] with plant density, using field data from one of the allometric calibration experiments (local variety *Nyamulu*, see section 2.4) at the experimental fields of TSBF in Nyabeda, western Kenya. The following polynomial relationship was obtained: $y = 0.0005x^2 - 0.031x + 0.6823$ (R^2 = 0.81; n = 18) in which y represents the maximum leaf area achieved per plant [LAPL, m^2 $plant^{-1}$] and x is plant density [plants m^{-2}]. The experimental units where the measurements were taken showed a high degree of variability (due to crop failure and to the differences between N and P nutrition treatments), since it was not meant as a trial to study plant density/ leaf area relationships.

The highest values of LAPL were achieved in the range of plant densities from 4 to 7 plants m^{-2}. This relationship, however, was obtained from a wide range of plant densities (from c. 4 to 22 plants m^{-2}) of pure maize stands, and the plant density was measured almost at the end of the crop growth period (plants could have been lost after the critical phases of inter-plant competition). On the other hand, this was not an experiment designed to determine leaf area per plant as a function of plant density and many other factors, such as N availability, may have been affecting LAPL even in the less dense plots. Under farmers' conditions maize is normally grown intercropped with other species (e.g. beans and cowpea) and at much lower densities (ca. 2 to 10 plants m^{-2} in most cases). This means that the LAPL will always be around the higher range (low inter-plant competition effect). Thus, the average measured LAPL corresponding only to plant densities <10 plants m^{-2} (n = 9) was calculated (0.53 m^2 $plant^{-1}$) and adopted as a model parameter to simulate maize growth under the given conditions. However, if higher plant densities were to be simulated, i.e. above 10 plants m^{-2}, then the empirical relationship presented above could be used to estimate LAPL. Considering a plant density of 5 plants m^{-2} and the estimated LAPL the maximum leaf area index of the canopy reaches 2.65 $m^2 m^{-2}$, a low but more realistic value under the given conditions than the one often used (ca. 5 $m^2 m^{-2}$) for pure stands of maize growing under potential growth conditions.

To allow for the use of weather variables from the site, particularly global radiation, the expression in the second assumption (growth rate, CGR in the model listing, in g $m^{-2} d^{-1}$) can be replaced by:

$$dW/dt = IR * RUE$$

In which IR [MJ_{PAR} $m^{-2}d^{-1}$] is the amount of global radiation absorbed by the canopy, converted into photosynthetically active radiation (PAR) by assuming that it represents half of the total global radiation [RAD, MJ m^{-2} d^{-1}]:

$$IR = RAD * 0.5 * F$$

RUE is the radiation use efficiency [g MJ_{PAR}^{-1}] of the crop, that can be defined as a function of development stage, and is affected by N nutrition and water status (see below). The effect of these environmental conditions on RUE can be subsequently introduced as functions or multipliers, thereby adjusting growth to actual site conditions (and their dynamics). The value of RUE is derived from literature on experiments in tropical (African) conditions in which it was measured for maize intercropped with beans growing under ample N and water supply (Tsubo and Walker, 2002), and it is then affected by the above mentioned factors. Since the required functions relating N and water status with growth reduction coefficients are not available for the given agroecological conditions, these effects are simulated by calculating two multipliers (NEFGR and WEFGR, respectively, see below):

$$CGR = IR * RUE * NEFGR * WEFGR$$

By adopting a RUE value the effect of the rate of maintenance respiration on the gross crop growth rate is, at the same time, accounted for and there is no need to simulate it separately.
To control the onset of the different processes, an arbitrary development stage scale was defined, in which maturity (mat) is reached at stage 1 [DVS = T_{sum} / T_{mat}]. Tsum [°C d] represents the thermal accumulation of daily mean temperatures above a certain base temperature (e.g., for tropical maize 10°C). Thermal times to flowering (silking) and to maturity (end of grain filling) are to be defined for each crop [T_{flo} and T_{mat}, respectively, in °C d]. The development stage of flowering (flo) is defined by T_{flo} / T_{mat} (e.g., for maize 693 / 1479 = 0.47).
The growth rates of the different above-ground plant parts [i.e. leaves, stems and grains, LGR, SGR and GFILL, respectively, in g m^{-2} d^{-1}] are calculated by multiplying the crop growth rate [CGR] by the corresponding partitioning coefficients [PTL, PTS and PTG]. These coefficients change during the growth period [functions PTLTB, PTSTB and PTGTB, depending on DVS] according to the functions derived by Boons-Prins *et al.* (1993). The death rates of the vegetative biomass [LDR and SDR, for leaves and stems, respectively, in g m^{-2} d^{-1}] are calculated with the leaves/stems biomass times their relative death rates. The relative death rate of the leaves is the inverse of the life span of the leaves [SPAN, in d], whereas the relative death rate of the stems [RDRS, in d^{-1}] is defined as a function of the development stage [function RDRSTB] according to Boons-Prins *et al.* (1993). The net rates of change (i.e. growth minus death) in the vegetative biomass plus the growth rate of the grains are integrated to obtain the total amount of biomass in the different crop parts, and summed to obtain the total crop biomass [TDW, g m^{-2}]. These calculations in the FST programme read:

```
TDW = SDW + GLDW + GDW
GDW  = INTGRL (ZERO, GFILL)
GLDW = INTGRL (ILDW, NLGR)
DLDW = INTGRL (ZERO, LDR)
SDW  = INTGRL (ISDW, NSGR)
```

where GLDW and DLDW are the quantities of green and dead leaves, respectively. The rates that are integrated in the equations above are calculated as:

```
*Leaves
NLGR = LGR - LDR
LGR  = PTL * CGR
PTL  = AFGEN (PTLTB, DVS)
LDR  = INSW (TSUM - TFLO, 0., GLDW * (1./SPAN))
```

```
*Stems
NSGR = SGR - SDR
SGR  = PTS * CGR
PTS  = AFGEN (PTSTB, DVS)
SDR  = SDW * RDRS
RDRS = AFGEN (RDRSTB, DVS)

*Grains
GFILL = CGR * PTG
PTG = INSW (TFLO - TSUM, AFGEN (PTGTB, DVS), 0.)
```

The rate of grain growth is switched on after flowering and is represented by the net growth rate for a determinate crop such as maize. It is assumed therefore that basically all the net dry matter accumulated during the reproductive phase is allocated exclusively to grains. The growth rate of grains is integrated over time between DVS ~ 0.5 and 1 to obtain the total grain biomass (GDW, g m^{-2}). At the end of the growth period, a harvest index is calculated relating grain to total aboveground biomass [HI = GDW / TDW].

2.6.1.3 N uptake by the crop and growth limitation by N (Goudriaan, 1994)

N taken up by the crop [NCROP, g N, referring to 1 m^{-2} soil] is calculated by adding the amounts of N accumulated in the vegetative and grain biomass [NVEGE + NGRAIN, g N m^{-2}]. The daily N uptake rate [DNUPT, g N d^{-1}, referring to 1 m^2 soil] results from the sum of the N uptake rates during vegetative [DNURV] and reproductive [DNURG] development, along the growth period.

The N uptake rate during vegetative stages [DNURV] is the result of the rate of leaf area expansion [GLAI, m^2 leaves m^{-2} soil d^{-1}] times the N concentration (on leaf area basis) in the leaves [g N m^{-2} leaves]. Since the N concentration is distributed across the canopy according to the assimilation rate of the different layers (Werger and Hirose, 1991), the extinction coefficient of light may also be applied here, as proposed by Goudriaan (1994). Thus, the mean N concentration in the leaves is equal to the concentration of the upper leaves [NUPPER, g N m^{-2} leaves] times the fraction of radiation absorbed [FRABS]. Due to the limitation imposed by a maximum leaf area, the N uptake rate during vegetative stages will show a peak value when that maximum is achieved, and will stop afterwards. The death rate of leaves imposes a reduction in the amount of N in the vegetative pool, which is calculated by considering a minimum N concentration in the dead leaves (most of the leaf N is assumed to be reallocated within the plant). During the last stages of crop development (from mid grain filling period onwards) a remobilization term (REMOB) is calculated, which will eventually add to the grain N pool in case the supply of N from the soil is less than the crop demand (see below).

During grain filling the rate of N allocated to grains is defined by their growth rate [GFILL, g m^{-2} d^{-1}] and by their characteristic N content [NCG, g N g^{-1} grains], the N uptake rate for grains [DNURG, g N m^{-2} d^{-1}]. When N availability in the soil [DNSUP] is not enough to match the demand of the grains, N is re-mobilised from leaves. Therefore the net rate of N accumulation in leaves becomes negative and the amount of N accumulated in vegetative structures will go down until a crop-specific, minimum N content is reached (e.g. for maize 0.002 g N g^{-1} dry matter). Below such limit no more N is allocated to grains and, indeed, dry matter accumulation in grains is also reduced (or stopped) by means of a multiplier in the model growth rate calculation equation [NEFGR, see below]. In this way, the minimum N content in the grains is always achieved and a down-regulation of yield can be mimicked when N is not available.

The upper limit for N uptake rate is the amount of mineral N in the soil [SOILMN, g mineral N m^{-2} soil for a 0.3 m soil depth], which is defined in other modules by native mineralisation, fertiliser application, leaching and erosion. When this mineral pool is emptied, no N uptake occurs until it is replenished. The effect on crop growth in such situations [NEFGR] is calculated by a simple ratio between the (simulated) actual N status of the crop [NCROP] and a target N uptake [NTARG], which is defined by total biomass accumulated [TDW] and its characteristic N content at each time. Since the N status of most maize crops is very low for the given production situation, the N content adopted to define the target N is on the lower side of the range found in literature (Boons-Prins *et al.*, 1993). This N effect coefficient [NEFGR] is limited between 0 and 1, and used as a multiplier of the gross crop growth rate to simulate biomass production under N limitation (Appendix 2.6.2, model listing).

The N removal by harvests [DNREM, g N m^{-2} d^{-1}] is calculated as the sum of the N removed in grains and in maize stover [DNREM = DNHARV + DNSTOV]. The expressions for the calculation of these rates in the FST program, considering an example in which the grains and the stover are totally harvested in one day (harvesting date, HDATE), are the following:

```
DNHARV = (NGRAIN / DELT) * GHVEFF * PUSHF
DNSTOV = ((NCROP - NGRAIN) / DELT) * STVHRV * PUSHF
PUSHF  = INSW (TIME - HDATE, 0., 1.)
```

where NGRAIN [g N m^{-2}] results from the integration of the rate DNURG over the grain filling period as explained above, GHVEFF is the grain harvest efficiency [0 – 1] accounting for grain losses during harvest, and STVHRV is the proportion [0 – 1] of the stover biomass that is removed from the field (see Section 2.3.1 Resource flow maps). PUSHF is an auxiliary variable used to control the onset of the removal event through a harvest date [HDATE].

2.6.1.4 Organic matter dynamics and N release (NDICEA)

The approach to organic matter dynamics used in this module is similar to that used in NDICEA (Habets and Oomen, 1994), a dynamic, process-based simulation model that calculates N and C balances during a crop rotation with a time step of one week. The complete model description can be found in Woli (2000) who derived NDICEA from the original theoretical equations into a simulation program with a FST coding. Three different pools of organic matter are considered in this module. The soil organic matter is split into young and old organic matter (Janssen, 1984), with residence times in the soil longer than 1 and 20 years, respectively. The third organic matter pool corresponds to the applied or fresh organic matter, as cattle manure, compost, etc. To avoid confusion with other nomenclatures existing in literature or by using suffixes, these pools will be called SOM ['old' soil organic matter], YOM [young soil organic matter] and OFOM [organic fertiliser organic matter]. These state variables have the unit g m^{-2}, corresponding to the upper 0.3 m of the soil.

The amount of organic matter in each pool at any time is calculated from the initial amount at the beginning of the season [ISOM, IYOM and IOFOM, g m^{-2}] plus the integration of the daily rates of change (decomposition) of each pool [RSOM, RYOM and ROFOM, g m^{-2} d^{-1}]. The rate of change of the OFOM pool considers also the organic fertiliser application rate [OFAR, g m^{-2} d^{-1}]. When organic fertilisers are applied in one single day, OFAR is controlled by an auxiliary variable [PUSHOF] that takes the values 0 or 1, as a function of the organic fertilisation date [OFDATE]:

```
PUSHOF = INSW (TIME - OFDATE, 1., 0.)
```

The rates of decomposition of the different organic pools are calculated based on Janssen's formula (Janssen, 1984), which estimates annual mineralisation (dissimilation) rate of organic carbon (dC/dt) as a function of time (t):

$$dC/dt = - 2.82 * C * (a + t)^{-1.6}$$

where 'a' is the 'apparent initial age' [years] of the substrate, an index for the resistance of the substrate to mineralisation. Since a is the *initial* apparent age, a + t can be considered as *age*, increasing linearly with time (Woli, 2000). Then, the dynamic rate of ageing can be written as:

$$dC/dt(age/dt) = -2.82 * C * age^{-1.6}$$

A correction factor [F] was introduced to account for the effects of temperature, moisture, texture and pH. Since F affects the ageing of the substrate, it can be considered as a rate of ageing [F = dage/dt, year $year^{-1}$] and incorporated in the above written equation as:

$$dC/dt = -2.82 * C * F * age^{-1.6}$$

Or, adapted for organic matter decomposition with day as units:

$$dOM/dt = (-2.82 * OM * F * age^{-1.6}) / 365$$

where OM represents any of the organic matter pools defined earlier. The age of the substrate is traced over the season by integrating their rate of ageing [(dage/dt) / 365, in year d^{-1}] over time (see below). The expressions used to calculate the rates of change of the different organic fraction in the FST program are the following:

```
RSOM = ((-2.82 * SOM * F * (AGESL)**POT1)/365.)* 0.1
RYOM = ((-2.82 * YOM * F * (AGEY)**POT1)/365.)* 0.1
ROFOM = ((-2.82 * OFOM * F * (AGEOF)**POT1)/365.)* 0.1 * NLIMIT
```

where POT1 is –1.6 and 0.1 converts the units from kg ha^{-1} to g m^{-2}. The age of the substrates [AGESL, AGEY, AGEOF, year] results from the integration of the rate of ageing, starting from the apparent initial age of each substrate [ASL, AY and AOF, years], which are the parameters to be defined by the user. Janssen (2000) proposed a method to estimate the apparent initial ages of different substrates from experimental data on organic matter decomposition. The rates of ageing of the different substrates are calculated from the correction factor F (see below) and integrated using the expressions:

```
AGESL = INTGRL (ASL, DASLDT)
AGEY  = INTGRL (AY, DAYDT)
AGEOF = INTGRL (AOF, DAOFDT)

DASLDT = F / 365.
DAYDT  = F / 365.
DAOFDT = F / 365.
```

since, according to the derivation of the original equations (Leffelaar, P.; personal communication), it holds: $age = a + \int F\, dt$. The rate of ageing is obtained on a daily basis by dividing F by 365. Since due to the often high C:N ratio of the organic resources applied to the fields there is a net 'capture' of mineral N from the soil by the decomposing substrate, this process will not take place when no N is available in the soil. That effect is introduced by a switch in the model [NLIMIT] that takes the value zero when the soil mineral N falls below a minimum.
The correction factor F is the sum of the correction factors for temperature [FTEMP], moisture [FMOIST], texture [FTXT] and pH [FPH]. A detailed description of the theoretical background for the calculation of each of those can be found in Woli (2000), or in their original sources (Yang, 1996; Rijtema, 1980). The temperature correction factor [FTEMP] was derived by Yang (1996) from literature data on decomposition experiments under tropical, subtropical and temperate conditions. This factor varies for different temperature [T, °C] ranges:

Below 0 C:	FTEMP = 0
From 1 to 9 C:	FTEMP = 0.1 * (T + 1)
From 9 to 27 C:	FTEMP = $2^{(T-9)/9}$
Above 27 C:	FTEMP = 4

Considering the temperature range for which the model will be used, the implementation of this factor in the FST program is as follows:

```
FTEMP = INSW (TMEAN - 27., 2.**((TMEAN - 9.)/9.), 4.)
```

The moisture correction factor [FMOIST] according to Rijtema (1980) assumes a linear relation with the water tension in the soil [pF], decreasing from 1 to 0 between pF 2.7 and 4.2. The pF of the layer is estimated from the characteristic water constants of the soil layer [WLWPT, WLFCT, WLSTT, see below: Water balance module]. The estimation of this factor as a function of soil water content [WCLT, m^3 water m^{-3}soil] varies for soils of different texture, defined here as FMCLAY and FMSAND when the clay content of the soil is above or below 20%, respectively:

```
FMOIST = INSW(CLAY - 0.2, FMSAND, FMCLAY)

FMCLAY = INSW(WCLT - WCFCT,  AFGEN(FMTB1, WCLT), 1.)
FUNCTION FMTB1 = 0., 0., 0.2, 0., 0.35, 1., 1., 1.
```

```
FMSAND = INSW(WCLT - WCFCT,  AFGEN(FMTB2, WCLT), 1.)
FUNCTION FMTB2 = 0.,0., 0.05,0.,0.15, 1., 1.,1.
```

where the points 0.2 and 0.35, and the points 0.05 and 0.15 are indicating the volumetric water contents (m^3 m^{-3}) at permanent wilting point [WCPWPT] and at field capacity [WCFCT] of a clay and sandy topsoil, respectively.
The texture correction factor [FTXT] is included as a parameter for the model depending on clay content of the soil layer considered. For fine clay soils it is taken around 0.6 while for coarser soils it approaches 1 (Woli, 2000). The pH correction factor[12] [FPH] assumes a logistic relation with soil pH, which is implemented in the FST program as follows:

```
FPH = 1./(1.+ EXP(-1.5 * (PH - 4.)))
```

Except for the temperature correction factor that was derived from mineralisation data including tropical and temperate environments, the different components of F were originally derived to study and estimate nitrogen emissions from grassland dairy farms in western Europe (Rijtema, 1980). Further research efforts should be focused on establishing the relationship between the correction factors for OM decomposition and the texture, moisture and pH characteristics of tropical soils.
N mineralisation is considered as the difference between N turnover (C turnover times the C:N ratio of the substrate) and assimilation of nitrogen (C assimilation times C:N ratio of the soil micro-organisms). Woli (2000) shows the derivation of the mathematical relationship used to calculate the rates of N mineralisation [RSON, RYON and ROFON, g N m^{-2} d^{-1}] from the rate of organic matter decomposition of each organic pool. The expression of these formulas in the FST program is as follows:

```
RSON = ((1.+ADM)/(SOM/SON) - (0.58*ADM)/CNM) * RSOM
RYON = ((1.+ADM)/(YOM/YON) - (0.58*ADM)/CNM) * RYOM
ROFON = ((1.+ADM)/(OFOM/OFON) - (0.58*ADM)/CNM)* ROFOM
```

where the parameters ADM and CNM are the assimilation/dissimilation rate and the C:N ratio of the soil micro-organisms, respectively. The coefficient 0.58 indicates the C content of the organic matter. These rates are integrated over time to calculate the amount of N remaining in each organic pool [SON, YON and OFON, g N m^{-2}]. The initial amount of N in each organic pool is determined by their C:N ratio. The rates of N release RSON, RYON and ROFON are used as daily inputs of mineral N into the soil mineral pool [NRELEA, g N m^{-2} d^{-1}].

2.6.1.5 Water balance and N leaching, the tipping-bucket approach (van Keulen, 1975)

The main assumption in this module is that the soil presents only two compartments, topsoil and subsoil, both with homogeneous internal characteristics. The topsoil layer represents the portion of soil that is considered within the soil/crop unit, with depth TKLT [300 mm]. The

[12] Among the different correction factors that were initially developed for western European conditions, the pH correction factor is perhaps the one that requires the strongest adaptation (i.e. decomposition takes place in tropical soils at very low pH values – Giller, K., personal communication).

water balance in the topsoil layer [WLT, mm or kg m^{-2}] and hence its water content [WCLT = WLT / TKLT, in mm water mm^{-1} soil or m^3 water m^{-3} soil] are the result of infiltration, uptake, evaporation, capillary rise and percolation to deeper layers. These processes determine the daily rate of change in topsoil water [mm d^{-1} or kg m^{-2} d^{-1}]:

```
RWLT = WLFLT - WLFLS - TRANSP - EVAPO + CPRISE
```

Where,
WLFLT: inflow of water (infiltration) into the topsoil layer [mm d^{-1} or kg m^{-2} d^{-1}]
WLFLS: inflow of water (percolation) into the subsoil layer [mm d^{-1} or kg m^{-2} d^{-1}]
TRANSP: transpiration losses from the topsoil layer [mm d^{-1} or kg m^{-2} d^{-1}]
EVAPO: evaporation losses from the topsoil layer [mm d^{-1} or kg m^{-2} d^{-1}]
CPRISE: capillary rise from the subsoil to the topsoil layer [mm d^{-1} or kg m^{-2} d^{-1}]

Since only the topsoil layer (0.3 m) is being considered, the water balance might fall below wilting point in certain simulated situations (e.g. when late planted crops are in their last phases, growing on sandy soils). To avoid this problem the lower limit for soil water is then artificially set at the amount of water corresponding to permanent wilting point [WLWPT] by means of the CPRISE rate (see below). Crop growth will be reduced by water availability though, but in the range from field capacity to permanent wilting point (WEFGR – see later). This assumption can be made on the basis that intense water stress (drought) is not commonly observed in the area. On the other hand, such a simulated stress originates from the soil depth considered for the soil/crop system, allowing small water storage (i.e. small buffer capacity) in the topsoil, and does not reflect reality.
During a rain event water that is not intercepted by the canopy or lost as runoff infiltrates into the topsoil layer:

```
WLFLT = RAIN - AINTC - RNOFF
```

The amount of rainfall intercepted by the canopy equals the interception capacity per layer of leaves [parameter INTC, mm d^{-1}] times the leaf area index [LAI]. This process only takes place under sufficiently heavy rains, so it cannot be larger than RAIN [mm d^{-1}]. When the rate of water supply to the soil surface exceeds infiltration capacity and the excess water accumulated at the soil surface exceeds the topsoil water capacity [WCSTT, water content at saturation] runoff of water takes place. An empirical relation between runoff and rainfall that was developed from Sahelian experimental conditions is adopted in the model (van Keulen, 1975), which is truncated to avoid negative values:

```
RNOFF = MAX (0., 0.15 * (RAIN - AINTC - 10.),...
        RAIN -AINTC- (WCSTT * TKLT - WLT)/ (2.* DELT))
```

The inflow of water into the subsoil layer [WLFLS] is considered as percolation and used to calculate N leaching in the N balance module. The model expression for this flow is as follows:

```
WLFLS = MAX(0., MIN ((WLT - WCFCT*TKLT) / (DRAICO * DELT), MDRATE))

LEACH = WLFLS
```

WCFCT is the water content of the topsoil at field capacity. A parameter DRAICO = 2 is used to set a drainage coefficient of 0.5, which means that each day half the surplus of water in excess of field capacity is drained from the upper to the lower layer. Drainage is limited by the maximum drainage rate of the subsoil [MDRATE, mm d^{-1}], which under the conditions for which the model is used here it is set at a high value (200 mm d^{-1}), implying no drainage limitation.

Water uptake and direct evaporation from the topsoil layer are considered as 'actual' evapo-transpiration losses [ACTETP = EVAPO + TRANSP, in mm d^{-1}]. Both the evaporation and transpiration rates for potential conditions [POTETP = PEVAP + PTRAN, in mm d^{-1}] are calculated with the Penman combination equation, using a subroutine written in the original LINTUL 2 program (Subroutine PENMAN, see Appendix 2.6.2 Model listing), from actual weather data. A transpiration reduction [RED] factor is switched on when the water content in the soil [WCLT] falls below a critical water content [WCCRIT] that corresponds to 80% of the available water that can be stored at field capacity:

```
WCCRIT = WCWPT + (WCFCT - WCWPT) * 0.8
```

where WCWPT is the water content at permanent wilting point for the topsoil. When the water content in the soil is below this threshold, the reduction factor RED is proportional to the fraction of water stored:

```
RED =INSW(WCLT - WCCRIT, LIMIT (0.,1., (WCLT - WCWPT) /(WCFCT - WCWPT)),
1.)
```

The 'actual' transpiration rate [TRANSP] is then calculated by multiplying the potential rate [PTRAN] times the reduction factor RED:

```
TRANSP = PTRAN * RED * AVAILF
```

The 'actual' evaporation rate [EVAPO] is proportional to the potential evaporation rate [PEVAP] and to the water content, in the range between field capacity [WCFCT] and air-dry point [WCADT], according to the following expression:

```
EVAPO  = (PEVAP * LIMIT (0., 1., (WCLT-WCAD)/(WCFCT-WCADT))) * AVAILF
```

Both TRANSP and EVAPO are limited by a minimum available amount of water determined by the air-dry point water content, calculating a reduction factor [AVAILF] that ranges between 0 and 1 when the (daily) amount of water in the soil is smaller than the potential (daily) evapo-transpiration demand:

```
AVAILF = MIN( 1., ((WLT-WLADT)/DELT)/NOTNUL(POTETP) )
```

When the water demand is not satisfied and the water content in the topsoil is exhausted (i.e. it falls below permanent wilting point), a capillary flow of water [CPRISE, mm d^{-1}] from the subsoil layer is allowed at the same rate at which it is required (ACTETP, mm d^{-1}), without simulating the water status of the subsoil layer. This assumption is made on the basis that water availability is mostly not an issue under the conditions for which the model is used and thus the uptake of water from lower layers is simulated in such a simple way. Moreover, under the referred conditions the value of CPRISE rarely exceeds zero. If it was normally larger than zero, the flow of mineral N from the subsoil to the topsoil (0.3 m) by capillary rise should also be considered in the N balance.

The only limitation to crop performance by water availability is introduced as a multiplier in the calculation of crop growth rate [WEFGR], to simulate the effect of increased water retention when the soil dries out. This 'transpiration reduction factor' or 'water effect on growth rate' is calculated by relating the actual to the potential transpiration rates:

```
WEFGR = TRANSP / NOTNUL (PTRAN)
```

The main assumption at this point is the linearity of the water retention factor between WCCRIT and WCWPT, which differs significantly from a characteristic pF curve. The WCCRIT represents the lower limit of the easily available water storage, and varies from soil to soil according to texture and organic matter content. An often-used water storage of 80% of the field capacity is assumed here, corresponding to a retention potential of ca. 1 bar for the range of soil textures considered (Jaetzold and Schmidt, 1982). Since the actual transpiration rate equals the potential one above this critical water content, the WEFGR becomes 1 and the crop growth rate is not affected by water availability beyond this point (no waterlogged conditions are simulated).

The main reason for introducing a water balance in the simulation model was to estimate N losses by leaching in a mechanistic manner, instead of using the transfer function adopted in NUTMON. The daily rate of N loss by leaching [DNLEA, g N m^{-2} d^{-1}] is calculated as the amount of water flowing from the topsoil to the subsoil layer [LEACH = WLFLS, mm d^{-1}] times the content of mineral N in the topsoil relative to the amount of soil water present [SOILMN / WLT, g N m^{-2} mm^{-1} for the upper 0.3 m]. The assumptions are made that all mineral N is dissolved in the (moving) soil water, and that no inflow of N to the topsoil by capillary rise occurs.

2.6.1.6 N losses by soil erosion, the universal soil loss equation (USLE)

Erosion by water is simulated by adapting the empirical universal equation USLE to a daily basis, which allows for the use of actual weather data. The mathematical expression of the USLE in its original form is:

$$\text{Annual soil loss } [t\ ha^{-1}] = R * K * C * LS * P$$

Where,
R: factor for rainfall erosivity
K: factor for soil erodibility
C: factor for the effect of soil cover by crops or vegetation
LS: factor for length [m] and inclination [%] of the field slope
P: factor for soil conservation practices

The approach followed here calculates a daily rate of soil loss [DLOSS, t ha^{-1} d^{-1}] that is integrated over the growing season to obtain the total loss [ERLOSS, t ha^{-1}], which is then expressed in kg of soil per m^2 [SLOSS].

The factor R is estimated as half of the annual rainfall [RNFALL, mm] times a factor 1.73 according to the procedure proposed by Roose (1975) while assessing soil losses by erosion in western Africa. Since this is an empirical relation with annual rainfall, the model expression, adapted to a daily basis, is as follows:

```
FACR = 0.5 * RAIN * 1.73
```

RNFALL is the integral of RAIN over time. Integrating FACR over time for the whole year gives the annual value obtained by the original equation [R]. Factor K for soil erodibility [FACK], depends on soil texture and organic matter content, and can be obtained in literature from the nomograph developed by Whitmore and Burnham (1969).
Factor C [FACC] represents the effect of soil cover by crop canopies and is related to leaf area index [L], by means of a function developed by Roose (1975) for maize, millet and sorghum crops (FACCTB in the model). This effect of soil cover by the crop is switched-off after harvest. FACC is also affected by a coefficient [MF] that represents the effect of the mulch if present on the soil surface. This expression according to Colvin *et al.* (1981) is:

$$MF = \exp(-A * RC)$$

where A is a coefficient varying between 0.02 and 0.09, being 0.05 generally used, and RC [%] is the soil cover by the residues left in the field, which can be estimated from their total amount in kg of residues per ha by means of a function [RCTB in the model] proposed by the author (e.g. 5 t ha^{-1} represents 70 – 75% of soil cover). The amount of mulch on the soil surface [MULCH, g m^{-2}] tends to decrease as its decomposition by micro-organisms proceeds, affecting the effective soil cover. To account for this effect a decay rate of this material is adopted in the model, with a relative decay rate[13] of 0.01 d^{-1} [DECAY = - MULCH * 0.01]. Thus, the main components of soil cover (i.e. leaf area and mulching) can be traced over the season and the effect of management practices on soil cover can be accounted for.
Factor LS [FACLS] results from the combination of the length [m] and inclination [%] of the field slope according to the original equation:

$$LS = (LENGTH / 22)^{0.5} * (0.065 + 0.045 * SLOPE + 0.0065 * SLOPE^2)$$

Factor P [FACP] represents the effect of soil conservation structures and management practices oriented to control soil losses by erosion. This empirical factor varies with the slope of the field and the type of practice adopted. Some reference values for African conditions that are used in NUTMON are presented in Table 2.6.2.
Daily nitrogen losses by erosion [DNLE, g N m^{-2} d^{-1}] are calculated by multiplying the daily soil loss in kg of soil per m^{-2} [DLOSS * 0.1] times the total soil N content [SOILNC, g N kg^{-1} soil]. In the same way, daily losses of mineral N can be calculated by means of the soil mineral N content [SLMNC].

[13] This yields an average residence time of the residues in the field, on the soil surface, of about 100 days.

Table 2.6.2: Determination of USLE P-factor (conservation practices)

Slope (%)	Contour cultivation	Strip cropping
0	1.0	1.00
1 – 2	0.6	0.30
3 – 8	0.5	0.25
9 – 12	0.6	0.30
13 –16	0.7	0.35
17 – 20	0.8	0.40
21 – 25	0.9	0.45

Source: Roose, 1987

2.6.2 Selecting case studies and developing scenarios

The selection of case studies was done according to the results of the resource flow maps and considering the available data to generate the simulation scenarios. The analysis focused on those parameters that showed the largest variation within a soil fertility gradient, as well as for farms of different classes. For a certain site selected according to the available data (e.g. weather data) two farms belonging to contrasting classes were chosen as case studies. These farms should be representative enough of the site as well as of the class to which they belong, with production activities and socio-economic characteristics that were commonly observed. Other major requirements were the completeness, sensibility and accuracy of the resource flow map drawn at those farms, since that was the main source of data on management practices. The next requirement was to find a clearly differential management pattern of the various fields included in the simulation scenario, again with the aid of the resource flow maps and with the information gathered during the interviews. Most of the soil and landscape parameters were derived from own measurement at the case study farms (e.g. slope, soil carbon, pH, etc.). Others, such as the soil water characteristics, were derived from secondary sources. A detailed description of the assumptions and considerations taken during the scenario development is given in Chapter 5.

2.6.3 Sensitivity analysis

A sensitivity analysis was carried out to study the relative variation in model outputs in response to changes in model parameters. Since the scope of simulating nutrient balances along a soil fertility gradient implies the inclusion of differences in both field attributes and resource allocation, the analysis was performed by varying the values of the main land quality and management parameters. The relevant model outputs studied included the crop performance and the N flows that affect the overall N balance. They were for the crop: (1) total crop biomass; (2) grain yield and (3) the average value of the crop growth reduction factor due to N shortage (NEFGR). For the N dynamics: (1) N losses by soil erosion; (2) N losses by leaching; (3) N uptake by the crop and (4) N mineralised from the organic fraction; (5) N balance at plot scale and (6) mineral N balance in the soil.
The effects of a change in model input or parameters were investigated by calculating the relative partial sensitivity of the model output:

$$(dO / O) / (dI / I)$$

where dO/O is the relative change in model output (final values), and dI / I is the relative change in the value of a parameter or input data. Sensitivity was calculated as the average sensitivity to changes in the value of the parameters that were set according to the information from the field biophysical characterisation and from the resource flow maps (see Sections 2.2 and 2.3 on this chapter), but not systematically (e.g. 10 or 20% + or – for all parameters). This is for instance the case of the sowing date, for which early, optimal and late dates for a certain site were tested. Table 2.6.3 gives the list of parameters included in the sensitivity analysis and their range of values. Some of these ranges are wide (e.g. slope) while others are quite narrow (e.g. organic fertiliser applications). However, what was important to determine is the sensitivity of the model to the conditions for which it was developed and eventually used.

Table 2.6.3: Group of parameters selected for sensitivity analysis and their range of variation

Parameter	Unit	Range*		
		High	Normal	Low
Land quality				
Field slope	%	15	3	0.5
Clay content	%	54	44	28
Soil organic carbon	g kg^{-1}soil	18	10	6
C:N ratio of soil organic matter	-	17	13	9.2
Management practices				
Sowing date	Julian day	92	72	52
Plant density	plants m^{-2}	6.8	4.5	2.3
N applied as inorganic fertiliser	kg ha^{-1}	80	20	0
Organic fertiliser applied (2.5% N)	kg ha^{-1}	600	300	20

*Since real data is used to set the ranges the names high, normal and low seem more appropriate to characterise them, though they are defined only in relative terms. For planting date they should be interpreted as late, normal and early, respectively.

This partial sensitivity, of course, does not account for the synergism of more than two parameters varying at the same time. For instance, the effect of the soil C content on N losses by erosion would be different for fields with different slopes. These types of combined effects are indeed included in the simulation scenarios.

2.6.4 Model parameterisation, initialisation and weather data

A set of (fixed) model parameters were derived from secondary sources including diverse literature on previous work in the region and elsewhere (Appendix 2.6.3). Crop parameters were tuned for maize growth and development, considering those for a tropical variety when possible (Tsubo and Walker, 2002; Boons-Prins *et al.*, 1993; van Heemst, 1986). Since they were *fixed*, no simulation of different varieties or of crops other than maize were performed. Though in none of the working sites maize is grown in pure stands but intercropped with beans or cowpeas (see Chapter 3), the simulation of an intercrop canopy is not considered. It is assumed that maize is grown in pure stands but with low plan densities (this had also an effect in the N balance, due the amount of N removed from the field with the harvest of

beans and other pulses). Available data to contrast the results of the simulation was only on maize (and not e.g. maize + beans) yield. The radiation extinction coefficient was adapted for a maize crop growing in an intercrop according to Tsubo and Walker (2002). The same authors presented values of radiation use efficiency for maize crops growing under African conditions. The leaf area ratio was derived from field data as explained above (Section 2.6.1 Model description). The empirical coefficient for mulch effect was proposed by Colvin *et al.* (1981). The 'organic matter' parameters were derived from different studies referring to the original source (Janssen, 2002; Woli, 2000; Yang, 1986). The parameters used for the calculation of the water balance (drainage and canopy interception coefficients) were taken from van Keulen (1975). The maximum drainage rate was set at an extremely high value to reflect the characteristics of the soils in the region, for which no limitations to internal drainage were ever reported (deep ferric Nitisols and humic Ferralsols). The system parameters (Appendix 2.6.3) refer to those that set the physical limits of the soil/crop unit used for simulation. The initial values for crop dry matter and leaf area index were set arbitrarily to simulate the values of a just emerged crop. The initial amount of water in the topsoil layer corresponds to a water content close to field capacity, assuming that farmers normally plant their crops after the onset of the rainy season.
The only set of weather data available in a format that could be operated in a FST program corresponds to the year 1986 for the meteorological station at Kisumu (Ahero, 0° 9'S : 34° 36'E, 1200 m) western Kenya (Appendix 2.6.4 Weather data). This station is located at 52 km S of Shinyalu, at 39 km SE of Emuhaia and at more that 80 km from Aludeka. For that reason, the latter site was not included in the development of scenarios. The topographic characteristics of the region create considerable differences in the amount of rainfall received by these localities. The bi-modal distribution pattern of the rainfall (long and short rain season), however, remains almost similar for all of them. The duration of the long rains is somewhat longer in the higher areas, and the temperatures are cooler. This implies that the results of the simulations will not reflect the real climatic situation. Comparisons between sites are, therefore, not relevant. Since the objective of this work is to investigate the potential use of a dynamic model to study the effects of management decisions on the development of soil fertility gradients, using the available weather data still allows for it.

2.6.5 Model validation

Since no experiment was conducted to gather data for the model validation, it was carried out by simple comparison of the *trends* shown by the model outputs with the results of the resource flow maps and with partial results reported in previous studies in the region (i.e. soil losses by erosion, N balances at field level, grain yield of maize in different trials, etc.). No formal statistical method was applied in this analysis.

3 Describing and categorising farm heterogeneity

Introduction

This chapter describes the variability found at the regional, site and farm scales and presents a methodology for its categorisation. Initially, the samples of farms from each of the three working sites (i.e. localities) are characterised and relevant differences between them affecting soil fertility management are indicated (the between sites variability). Secondly, a farm typology is presented in order to categorise the variability found within each site (the between farms variability), the farm types are socio-economically characterised and the differences in soil fertility management are derived from the results of the resource flow maps. Finally the variability in management practices, nutrient balances and soil properties found within the farms is described by means of a proposed field typology.

Three sites (i.e. Emuhaia, Shinyalu and Aludeka) were selected in order to include contrasting biophysical and socio-economic conditions. However, due to the large amount of data gathered most numerical examples and figures in the main text as well as in the appendices will be presented for one of the three sites (when comparisons among sites are not relevant). And for the sake of consistency they will be presented always for the same site.

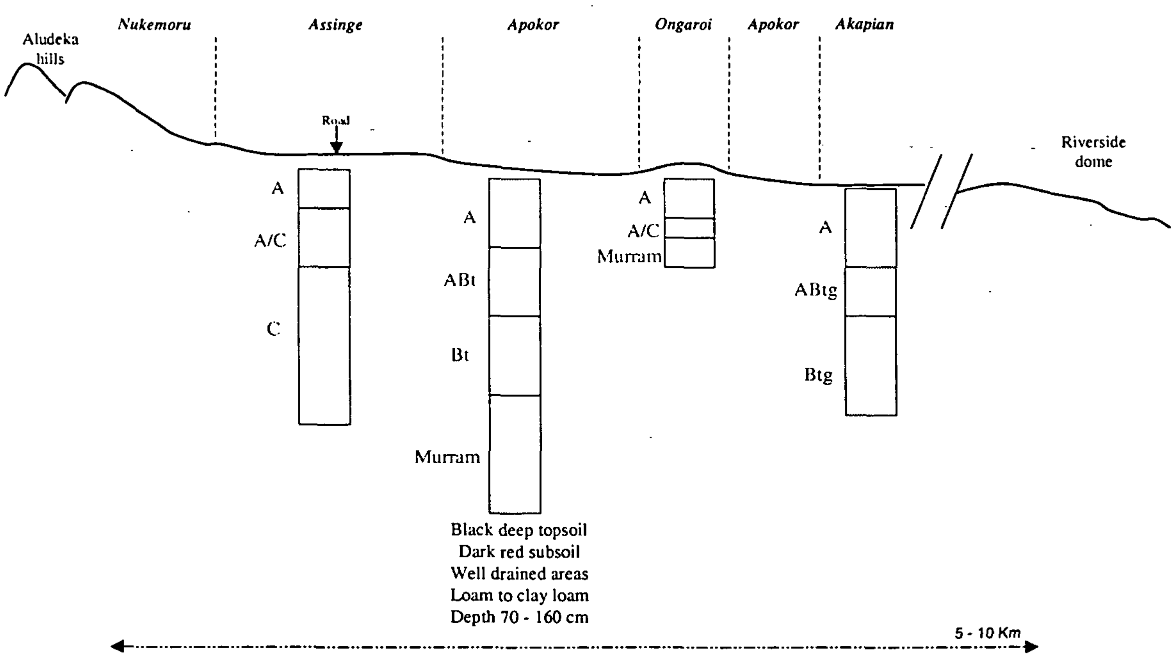
Emuhaia (Vihiga district) is an area of much higher population pressure than any other highland area in Africa (Soule and Shepherd, 2000) and its proximity to urban centres introduces some distortions in terms of outputs, inputs and labour markets. On the other hand, Aludeka (Teso district) shows biophysical conditions that are closer to those observed in the midland humid areas of eastern Uganda, and a livestock production system that shows distortions due to Tse-tse fly problems. Shinyalu (Kakamega district) presents biophysical and socio-economic characteristics that are more representative of the situation often found in the tropical highlands of different African countries. Thus, most numerical examples and illustrations will be presented for Shinyalu.

3.1 Characteristics of the sites and the farm samples

3.1.1 Site biophysical variability

This source of variability was described through what is known as soilscape delineation, relating inherent soil properties to their position in the landscape, along a topographic section representative for the area covered by the selected group of villages in each of the sites (Box 3.1.1). To reduce the effect of including different soil types on the magnitude of the soil fertility gradients, farms for soil sampling were concentrated as best as possible within the main soilscape unit in terms of occurrence in the area as well as land use. For example, swampy areas used for rice production in Aludeka were avoided as they are not evenly spread (see Appendix 3.1.1 a and b, Distribution of farms along the soilscape).

Box 3.1.1 A schematic representation of a soilscape delineation for Aludeka site, illustrating soil profile development of the main units. Names in Italics on top of the figure indicate local soil names.



At Shinyalu and Emuhaia, most farms where concentrated on the locally-termed *Ingusi* soils (Nitosols and Ferralsols) whereas in Aludeka, with a larger farm size and a more uneven soil distribution, farms were selected that had *Apokor* soils (ferralo-orthic Acrisols) in most of their land. In all sites it was also attempted to have all farm types (see later Farm typology) represented in the selected soilscape unit. However, larger farms belonging to the wealthier class tended to include more than a single soilscape unit within their boundaries. Certain soilscape units showing a particular land use and/or resource allocation and widely distributed among the sample of farms where considered as 'special niches' for the field typology (see later Field typology), e.g. valley bottoms used for yam (*Dioscorea* spp.) production.

3.1.2 Socio-economic variability

The sample farms showed characteristics in terms of land size, family structure, labour availability, income sources and general wealth indicators that make them representative for each of the sites, comparing adequately with the data from the official annual surveys (Kenya Ministry of Agriculture and Rural Development, 2001 Annual Reports for Vihiga, Kakamega and Teso Districts, West Kenya). Some characteristics of the household heads in terms of gender, marital status and education for the samples of farms from each site are shown in Appendix 3.1.2a. The percentage of female household heads was higher in Emuhaia and Shinyalu, as well as the number of widows. The percentage of people that achieved a secondary education level in Emuhaia was almost twice as high as those from Shinyalu and Aludeka, probably due to the proximity and easier access to urban areas.
Although the average farm size in Aludeka is almost two times larger than that of the other sites, the percentage of annually cropped land and the farm sub-division were about the same (Table 3.1.1). About 20 to 25% of the farms in the three sites had an annexed[1] -owned or permanently hired- piece of land. Again, the average size of such units was much larger in Aludeka. In spite of the differences in land availability, the number of family members and of those working on the farm was just slightly higher in Aludeka (Table 3.1.1), often leading to labour shortage during critical periods (see later: land availability per labour unit, Farm typology).
Most farms in all working sites hired casual labour, but hiring of permanent labour was more often seen in Emuhaia. Farmers from the poorer classes often derive some income by working as land labourers during the onset of the rainy seasons (planting time), before (land preparation, when oxen are not used) or even later (especially for first and second maize weeding, maize harvesting). Others are hired for all kind of farming activities by those farmers that are permanently employed outside and earning a fixed salary (see Appendix 3.1.2 b, Activities for which casual labour is hired). These and other off-farm opportunities, as well as the smaller land size, is reflected in the lower percentage of the total household income generated by farming in Emuhaia (Table 3.1.1). Almost 80% of the farmers in the sample from this site earn part of their income outside their farm (see also Appendix 3.1.2 c, Relative importance of on-farm income). Cash flows generated by the alternative sources of income have a decisive impact on the extent of input use, particularly inorganic fertilisers, as will be shown later.
Livestock (i.e. cattle, goats, sheep and pigs) ownership is more common in Emuhaia, distributed more evenly among the farms and apparently less related to differences in wealth than for the other sites (Table 3.1.1). However, the number of animals per farm was lower than in the other sites, partly due to differences in land availability and to the lack of communal rangeland. When only cattle are considered among livestock, the effect of the lasting epidemic disease Tripanosomiasis spread in the area of Aludeka shows up clearly in the smaller percentage of farms owning cattle and in the amount of animal heads per farm (data not shown).

[1] Annexed land is defined here as an area of land that is not physically attached to the main farm land (where the homestead is placed), but it contributes to the household food or cash income. Farmers often own or hire land in particular niches in the area, like in fertile swamps, either for the production of a specific cash crop, like cotton, or just to increase the available land for food crops.

The smaller average farm size in Emuhaia was also reflected in the fact that 40% of the households had no source of fuel wood on their land, covering their needs by purchasing it on the market and up to a certain extent by using crop residues as fuel. Self-sufficiency in maize production was achieved by less than 40% of farmers in all three sites. The production of the two rainy seasons was consumed by the household in half a year except in Shinyalu, as a consequence of having more land allocated to maize production and better agro-ecological conditions for maize growing. However, maize sufficiency is not a clear wealth indicator for Aludeka, where food habits include a larger share of cassava, sorghum and finger millet in the daily diet (see also Appendix 3.1.3, Production activities).

Table 3.1.1: Selected socio-economic indicators for the three farm samples (n = 20 at each location)

Indicator	Site		
	Emuhaia	Shinyalu	Aludeka
Farm structure			
Average farm size (ha)	0.77	1.04	1.83
Annually cropped land (%)	85	81	77
Number of units*	5	6	7
% of farms having annexed land	25	21	25
Average area annexed (ha)**	0.70	0.72	1.23
Labour and income			
Household members	5.6	6.4	6.9
Living and working on the farm	3.3	3.4	3.7
%that use own labour	95	100	100
%that hire casual labour	65	90	79
%that hire permanent labour	15	0	0
%that work for other farmers	10	11	16
Income generated by farming (%)	56	76	72
%that have a permanent off-farm income$^{\Psi}$	76	63	43
Wealth indicators$^{\varphi}$			
% that have livestock$^{\varphi\varphi}$	85	75	65
Number of animals	2.8	3.2	3.6
% that have a woodlot	60	95	75
% that grow cash crops	70	90	75
% that is self sufficient in maize	20	35	15
Number of months that maize lasts	6.7	9.4	5.4

(*) indicating main identifiable sub-divisions, permanent or semi-permanent, within the farm
(**) owned or permanently hired
(Ψ) including salaries, pensions, bussinesses and submissions from family members living outside
(φ) according to the definition given by Crowley and Carter (2000).
($\varphi\varphi$) including cows, goats, sheep and pigs.

3.1.3 Land use and management practices

As a consequence of the preceding characteristics, particularly land size, off-farm income and livestock ownership, some management practices varied widely from one site to the other. The most common production activities at the three sites and their distribution among farms are shown in Appendix 3.1.3. In Emuhaia and Shinyalu, which are ethnically and ecologically closer, almost the same pattern in terms of crop choices can be observed. Maize is grown in all farms in the samples from the three sites. Beans tend to be replaced by groundnuts in the more sandy soils of Aludeka. Certain cash crops (e.g. kale and cabbage) are more related to factors such as access to markets, while others (e.g. tea or cotton) are more related to agro-ecological factors. Napier grass is extensively planted for feeding cattle or as a cash crop where grasslands are scarce.

Cattle are kept for milk production, draught power (especially in Sinyalu and Aludeka) and as a quick source of cash to cover household investments and/or (un)expected expenditures. While in Emuhaia cattle are normally tethered and fed by cut grass or other residues, in Aludeka they are taken to graze on fallow land and crop residues by herders. In Shinyalu, an intermediate situation was found: during the second rainy season, when some fields were left for fallow, grazing was practised as in free ranging systems.

Table 3.1.2: Percentage of farms within the farm samples from the three sites that adopt different management practices (n = 20 at each location)

Management Indicators	Site		
	Emuhaia	Shinyalu	Aludeka
% that fallow some land	30	30	55
%that rotate fallow	35	15	40
% that rotate crops	35	40	90
% that prepare compost	90	65	30
% that use cattle manure	35	80	35
% that use inorganic fertilisers	70	85	20
% that grow legumes in general*	75	65	50
% that use improved maize seeds**	65	40	30

(*) as green manure, improved fallow and cash or food crops, excluding beans and groundnuts.
(**) to distinguish hybrids and selected populations from local varieties.

The practice of fallow (Table 3.1.2) was constrained by land size in Emuhaia and was the result of lack of labour in Aludeka, where larger fields require oxen ploughing (which are normally scarce due to the sleeping sickness, see Chapter 2). The effect of land availability is also reflected by the adoption of crop rotation in the three sites. In Shinyalu maize crops during the first rains season have a longer development cycle and therefore are harvested later, often at the onset of the second rains. In addition, a higher risk of crop failure exists during the second rains. Thus, many farmers decide not to grow maize and to leave the land under fallow vegetation until the end of the year, and the practice of fallow is not always meant as a way of recovering soil fertility. This is also the reason why the *rotation* of the area of land under fallow is not widely adopted in this site (Table 3.1.2).

Cattle manure can be applied pure or composted together with other organic resources (e.g. crop residues). The latter method is widely used in Emuhaia and therefore only few farmers apply manure directly (Table 3.1.2). The opposite happens in Shinyalu where crop residues are mainly left on the field and sometimes grazed by free-ranging cattle. Both practices are less widely practised in Aludeka due to the lower cattle population, the lack of experience with composting and the fact that manure collection is less efficient due to the free grazing of cattle.

Inorganic fertilisers are widely used in Emuhaia and Shinyalu (Table 3.1.2), where farm sizes are smaller and soil depletion is generally recognised by the farmers as one of the main problems for farming (see later, Farmers' land quality classification). In Aludeka, increasing the area under crops compensates for lower yields and the land is used more extensively, with less use of inputs in general. A moderate range of legumes is known and used as green manure, improved fallow or for biomass transfer in Emuhaia and Shinyalu due to the longer period of contact with researchers and/or with extension services by the farmers interviewed. The use of hybrid maize seeds is more common in the relatively more intensive production system of Emuhaia and less common under the more extensive conditions of Aludeka. In Shinyalu farmers were reluctant to use them because of their poor performance in the area. Crop lodging was commonly seen on the sloping fields exposed to valley winds, and hybrids used in the area are particularly susceptible according to farmers' opinion.

3.1.4 Farm transects

This way of assessing both between-farms and within-farm variability yielded much valuable information in terms of biophysical aspects, farm assets and infrastructure, crops distribution and performance, and general management practices. An example of a farm transect for Emuhaia is shown in Box 3.1.2. In most cases in Emuhaia and Shinyalu the homestead was built in the uppermost part of the farm, near the road (roads run along the top of the ridges). The homestead was surrounded by living fences delimiting a compound often used as grazing place for tethered cattle with scattered trees for shade, fruits, fuel and/or construction wood (see Appendix 3.1.4, picture of a compound site in Emuhaia). Bananas and (local) vegetables were grown around the house, together with maize for roasting[2]. The most remote fields, especially in larger farms, were those occupying the extreme slopes or the valley bottoms. In some farms (mainly in Shinyalu) the homestead is moved to a different place within the farm after about 10 to 15 years, in order to make use of the fertility accumulated around it by growing crops. In Aludeka it was also possible to identify a compound although it was not used as grazing place, and often shows no fencing around. In many cases the homestead is placed in the centre of the land and surrounded by banana plants and fruit trees. Due to the relatively plain landscape no association exists between slope and distance from the homestead (except for swampy areas where no houses are built). Main biophysical differences within the farm were given by soil depth and texture. Because of theft, crops like maize and groundnuts tended to be grown nearer the house while others like cassava and finger millet tended to be grown in remote fields. Many farms had remote fields with a permanent fallow of grass (*Hyparrhenia* spp.) used for roofing (see Appendix 3.1.4 b, picture of roofing grass). In the few farms with cattle, they were kept in a *kraal*[3] during the night.

3.1.5 Range of soil properties at the three sites

The distribution of most relevant indicators of inherent and actual soil fertility, and land quality are presented for the three sites in Appendices 3.1.5 – I, II and III (Figures a - f), highlighting the variability found between sites.

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[2] Basically early maturing local varieties. Cobs are harvested from late milky stage onwards and roasted.

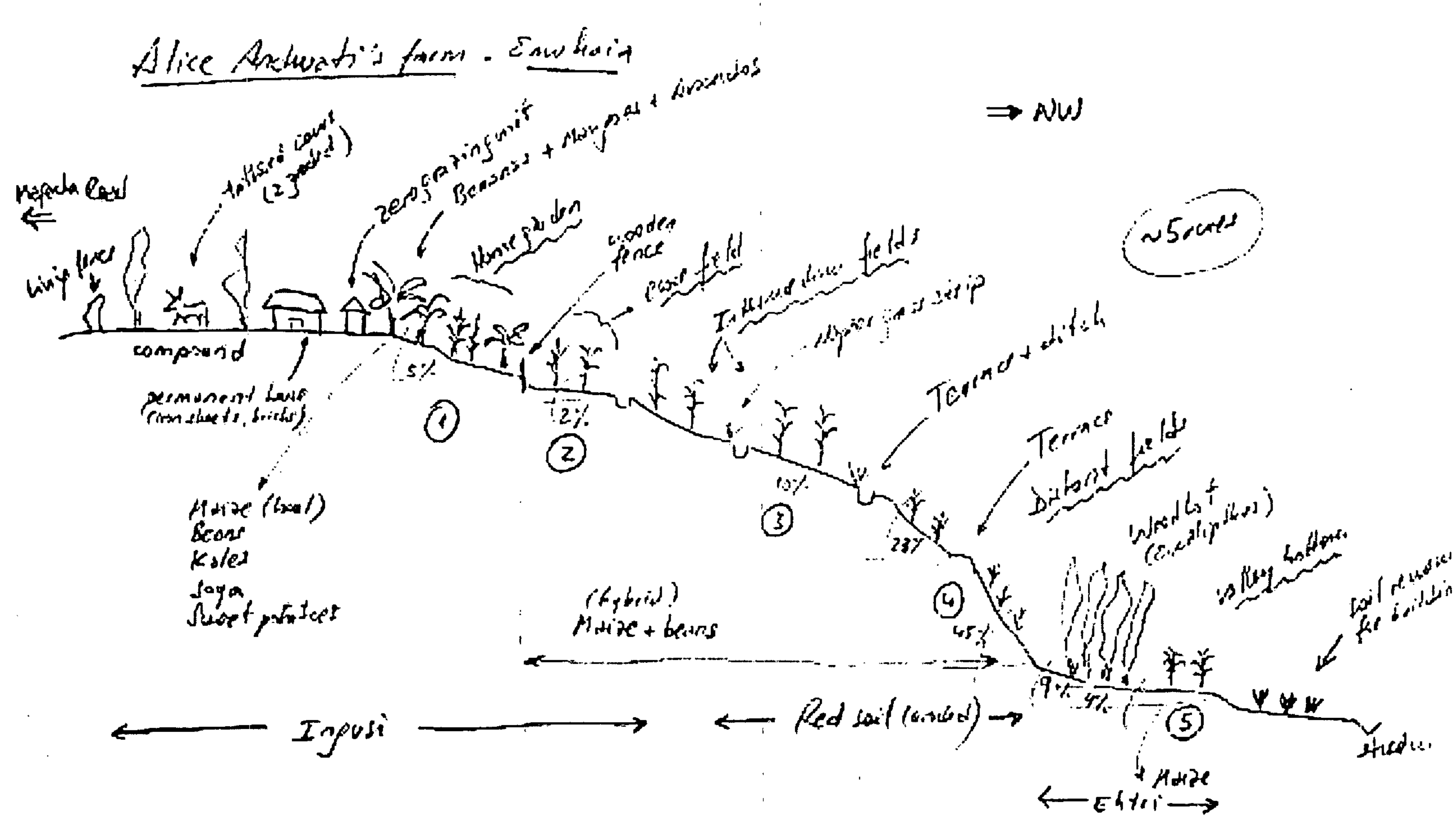
[3] As it is locally termed

The hilly characteristics of Emuhaia and Shinyalu become evident when the slope of all fields measured and sampled for this study are compared in Appendix 3.1.5 - I Fig. a. In spite of the extreme values found in Emuhaia the landscape generally is less undulating than in Shinyalu. A clear gradient of clay content in the soil is found from Aludeka to Shinyalu (Eastwards) due to the inherent soil types dominating at each site (Appendix 3.1.5 - I Fig. b). Moreover, some sampling points in the former site fell into the sandy, flat soilscape units occupied by the locally known as *Assinge* soils surrounding the hills. In Emuhaia, many production units can be found on the sandy *Oluyekhe* soils in shallow valleys or surrounding rocky outcrops. In Shinyalu, production units on these sandy soilscape units are less frequent since due to a steeper topography they are less accessible and therefore kept as grazing places.

Fields sampled at Shinyalu had a much higher C content in their topsoil than those at the other sites (Appendix 3.1.5 - II Fig. c). At this scale of analysis the inherent properties at each site seem to explain most of the differences, since the C contents are in line with the trend observed for clay contents (C saturation potential – Feller and Beare, 1997; see Chapter 4 Section 4.1.1). Differences in the original vegetation between Aludeka and the other sites could also be brought about. A higher pressure on the land due to denser population seems to be responsible for widening the differences between the ecologically closer Emuhaia and Shinyalu sites (compare also differences in clay content). A similar trend is found for the C:N ratio (data not shown) which shows the lowest values for Shinyalu and the highest for Aludeka. These differences in clay and C contents are reflected in the trend of the (effective) cation exchange capacity (ECEC) across the three sites (Appendix 3.1.5 - II Fig. d).

The topsoil of the fields sampled in Shinyalu and Emuhaia was more acid than that in Aludeka due to the bio-physical background: low-saturated red soils under heavy rainfall, developed under forest vegetation vs. brown and reddish soils developed from mineral-carrying fluvial sediments, respectively (Appendix 3.1.5 - III Fig. e). However, soil management and in general land use aspects must also be considered in explaining these differences. The same was true for extractable P concentrations that, in spite of the inherent aspects of soil types, were lowest in the more depleted soils of Emuhaia (Appendix 3.1.5 - III Fig. f). For the acid soils of Emuhaia and Shinyalu total P values (data not shown) gave the same trend, confirming the effect of land use overwhelming the inherent properties.

Box 3.1.2: An example of a farm transect drawn at Alice Andwati's farm (type 2), Emuhaia – Western Kenya



3.2 Between-farm variability

3.2.1 Categorising the variability found within sites: Farm typology

Five relevant farm types were identified using the proposed methodology (see in Chapter 2: Developing a farm typology according to the objectives), which considered wealth (socio-economic) indicators as well as farmers' objectives (production orientation) and limitations (production constraints). They were numbered from 1 to 5 reflecting approximately their position in a wealth ranking (from high or rich to low or poor resource endowment). This relation to wealth class is not strict. For instance, some farms of type 1 (see below) could fall in the category of medium resource endowment (MRE) as well. However, most farms in type 1 and 2 fell into the wealthiest class (high resource endowment, HRE), farms of type 3 in to the middle class and farms type 5 into the poorest (low resource endowment, LRE). Farms of type 4 fell into both MRE and LRE although mainly in the latter, showing a different distribution for all three sites. Although largely consistent, each farm type model might show slight differences across sites due to socio-cultural particularities and to differences in the production system. For illustrative purposes Figures 3.2.1 and 3.2.2 show the graphic models of the five farm types for Shinyalu.

Farms of type 1 are land-limited and the household head and/or any other family member/s work outside the farm earning a fixed salary or have a shop or another sort of off-farm income. This source of income is much higher than that generated by farming and therefore the main income for the household (Figure 3.2.1). Labour requirements are covered by hiring casual and sometimes permanent workers. Although family sizes tend to be small (see later Tables 3.2.1 and 3.2.2), such farms are normally not self-sufficient in food production and therefore obtain most of it from outside or by cropping hired land.

Type 2 farms are typically the large, wealthy farms with many family members and self-sufficient in terms of food production[4]. Household heads of this type of farms tend to be older and getting to or already dividing their land for their sons. Plantations of a perennial cash crop like tea are seen more frequently in this type of farms (Figure 3.2.1). Although farming represents the main source of income, off-farm income[5] sources are often observed as well. In spite of their large families, labour is hired to replace that of children who are studying and to deal with highly labour-demanding activities like tea picking or harvesting finger millet.

Farms of type 3 are self-sufficient in food production, normally having surpluses for the market, and almost all their income is generated by farming. Activities that demand investments, like purchasing inputs required for growing cash crops (e.g. planting materials) are not widely adopted due to financial limitations. Instead, often most of the food crops (e.g. maize, beans) production is sold[6] (Figure 3.2.2).

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[4] Certain food items like sugar are always purchased on the market.

[5] Income generated from selling cash crops, milk or wood on the market is *not* considered as off-farm income.

[6] There is an important difference between growing cash crops like tea, sugar cane or cotton and growing maize with low inputs and sell most of it on the market.

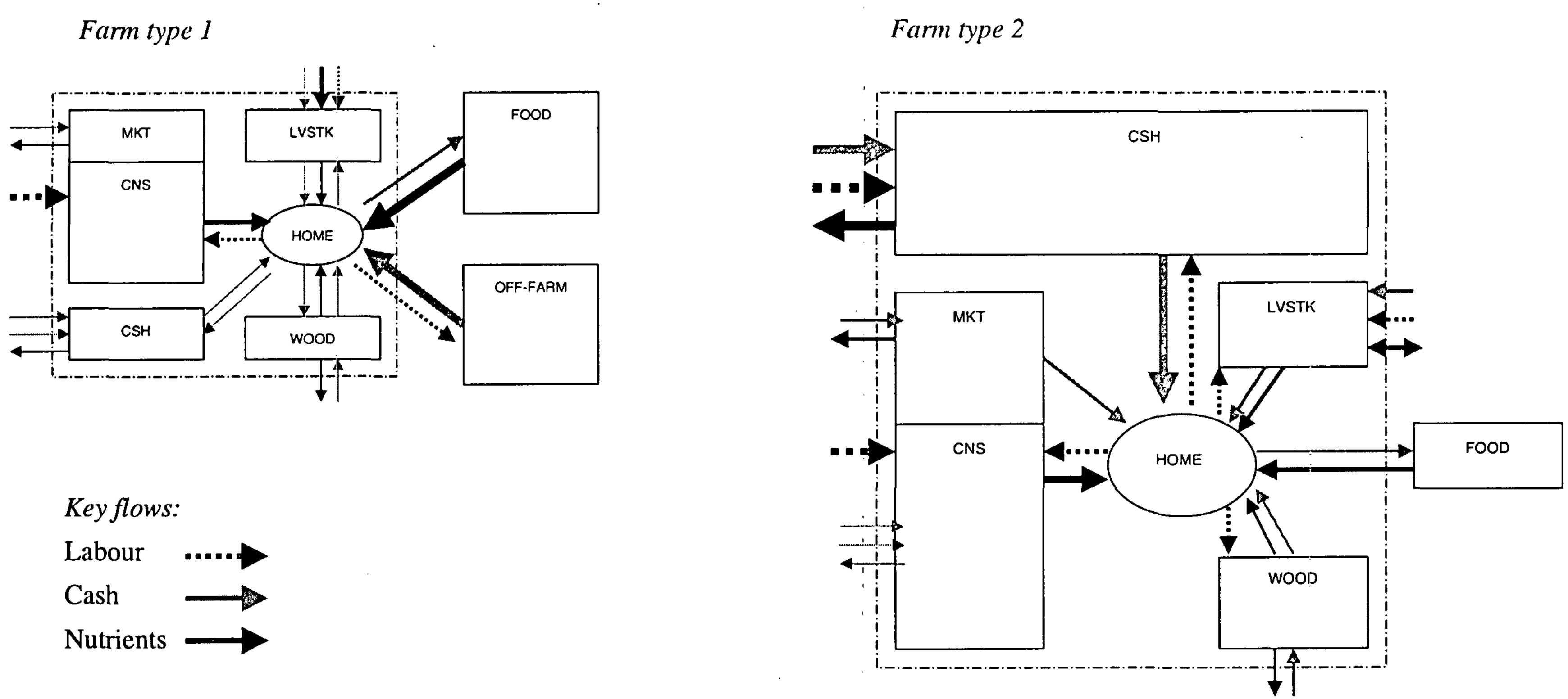

Figure 3.2.1: Graphic models of farms of types 1 and 2 at Shinyalu. The sizes of the components as well as of the system boundaries indicate their relative size and/or importance in reality (e.g. the size of the homestead indicates family size; the size of the boundaries indicates land size). The weight of the arrows indicates the relative importance of the flows they symbolise. For the sake of 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.

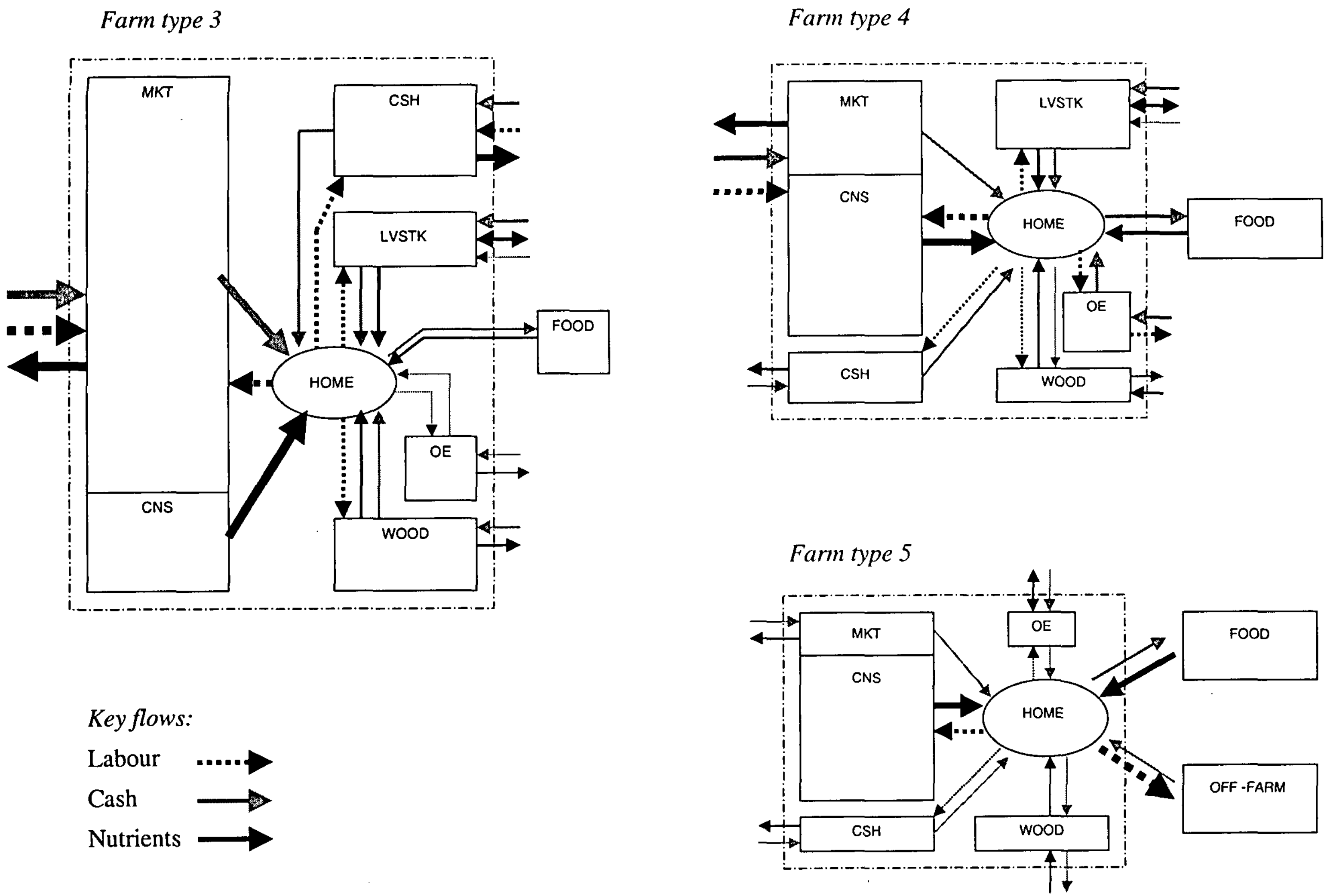

Figure 3.2.2: Graphic models of farms of the types 3, 4 and 5 at Shinyalu. For references and explanation see Fig. 3.2.1. OE: other enterprises, which comprise income-generating activities that involve on-farm production factors (e.g. honey bees, oxen-ploughing services, etc.).

Fodder crops like Napier grass are also partly sold on the market, but do not receive any special management or additional inputs. Annual vegetables like kale, cabbage or tomatoes are grown as cash crops in small proportion due to competition for labour with main food crops. They require some degree of investment and are normally assigned to good quality land, and near the homestead (due to theft). Household heads in this type of farms tend to be young to middle-aged and family size is normally in expansion. Sources of off-farm income are practically nil[7]. Instead, other enterprises (OE in Fig. 3.2.2) such as honey production are seen as alternative income generating activities.

Type 4 farms are not self-sufficient in food production, normally land-limited and with low financial capacity to grow cash crops. Although it is the most heterogeneous group, a common denominator is that livestock keeping is one of the most relatively important farm activities in terms of labour allocation[8] (Figure 3.2.2). Many farmers in this group lease oxen services during land preparation times. They purchase food from the market and have a variable source of off-farm income by doing temporary businesses (e.g. women buy maize grown in other areas and retail it at the farm gate) or leasing labour. However, as for Type 3 farms, off-farm income is rather intermittent. Characteristics of the household heads and family structure are also similar to that of farm type 3. Land limitation is, among others, the main difference between farm types 3 and 4.

Table 3.2.1: Main criteria considered for the categorisation of farms

Farm type	Wealth class	Production orientation	Main constraints	Position on farm cycle, family structure	Main source of income
1	Mainly HRE, few MRE	Mainly self-consumption	Land, (labour)	Variable age of HH, small family	Salary, pension, etc.
2	HRE	Market-oriented	(labour)	Old HH head, big family, start dividing land	Cash crops and other farm produce
3	MRE	Self consumption and (low-input) market-oriented	Capital, sometimes labour	Young to mid-aged HH head, small family, in expansion phase	Farm produce, surpluses, other enterprises
4	Mainly LRE, some MRE	Self-subsistence	Land and capital	Young to mid-aged HH, variable family size	Services, little farm produce
5	LRE	Self-subsistence	Land, capital and labour	Variable age of HH, big family, often women-headed farms	Selling labour

HH: household head; HRE, MRE and LRE: high, medium and low resource endowment, respectively; (labour) indicates that the initial limitation was removed by hiring in labour.

Farms of type 5 are typically those land-limited farms in which more than one family member works for other farmers as casual labourers. This intermittent, low-skilled source of employment generates low wages for the household and creates an important labour shortage on their own farm. Such farms are not self-sufficient in food production. Few of them have livestock, which are generally in a very poor condition. They normally grow only food crops (except for some fruit bananas or avocados that can be sold on the market). Although most of their income comes from off-farm sources, they differ clearly from the

[7] A certain proportion of off-farm income is present in most farms (form Type 1 to 5), specially in land-scarce areas.

[8] Livestock activities could also be of importance in farm types 1 to 3, specially dairy production.

farm type 1 in terms of the relative importance of the cash and labour flows (i.e. labour:income ratios), as shown in Figure 3.2.2. Most households headed by widows are found within this farm type.
Table 3.2.1 summarises the main criteria considered for this typology, and the following section provides socio-economic data (gathered during the interviews with the farmers) for each of the farm types. As stated in Chapter 2, farms in the sample were initially grouped according to wealth class (resource endowment). Such classification proved not entirely satisfactory for the objectives of this work. To illustrate this point comparisons between both classification criteria (i.e. farm types and wealth classes) are made throughout the rest of this chapter.

3.2.2 Socio-economic, land use and management factors: farm types vs. wealth classes

Indicators of family structure and labour availability, source of income and wealth for the different farm types in each working site are presented in Table 3.2.2. In Appendix 3.2.2 - I a, such indicators are shown for the same samples of farms grouped according to wealth classes. In all sites the number of family members and of those working on farm tend to be higher for farm types 2 and 3[9] (Table 3.2.2). Although all farm types from 1 to 4 hire some labour during the season, types 1 and 2 are those that effectively cover their labour demands by hiring in labour. Classification by wealth (Appendix 3.2.2 - I a) does not show clear differences for these indicators except for hired labour, which is significantly higher among the farms of high and medium resource endowment.
Larger farms are found within types 2 and 3 for all working sites as well as the largest areas under crops (Table 3.2.3). The area under crops is extended by annexing/hiring land, a practice that is more frequently seen among the low-input, food-sufficient farms of type 3. Although LRE farms had smaller total and cropped areas than MRE and HRE, classifying the farm samples by wealth (Appendix 3.2.2 - I b) does not show consistent differences in land tenure and use intensity across sites. The number of easily identified production units within the farm was meant as a rough indicator of diversification in production activities and in management practices. However, it does not appear as a good indicator of diversification due to its association with land size (Table 3.2.3 and Appendix 3.2.2 - I b).
When land availability per capita was calculated on the basis of family size and of family labour (i.e. the number of family members living and effectively working on the farm) no significant differences were found between farm types except for Emuhaia, due to the smaller farm sizes (Table 3.2.3). When hired labour was included in the calculations, in spite of the absolute differences across sites, it becomes clear that Type 5 farms were more labour-limited whereas type 1 farms were more land-limited. No significant differences were found between the food-sufficient farm types 2 and 3, nor between types 3 and 4 (both family-expanding types). Larger figures for Aludeka partly explain why in most farms an area of uncultivated land was often seen during the growing seasons. Classification by wealth did not discriminate for these indicators as consistently as the proposed typology (Appendix 3.2.2 - I b).

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[9] Figures concerning family labour and their relation to family size vary considerably due to the age of the children. During the interviews farmers were asked how many family members worked in the farm (c.f. Appendix 2.2.2, First approach questionnaires). Duties assigned to very young children were either considered or not as labour by different farmers.

As an illustration, in Appendices 3.2.2 - II and III the production structure and management practices adopted by farms of different types and wealth classes, respectively, is presented for the farm samples from the three working sites. The sample size for the number of households per site was not large enough to conduct a statistical analysis that could reveal reliable discriminations on these figures. Though certain trends on the adoption of management practices across farm types and wealth classes could be observed, such as fallow and crop rotation, differences between sites tended to be more important than between farms at each site (cf. Appendix 3.2.2). The interviews conducted during the first approach to the farms were meant to record whether a farmer uses inorganic fertilisers or not, for example, but not how much and on which crops as will be revealed by the results of the resource flow maps.

Table 3.2.2: Labour, income and wealth indicators for the different farm types at the three working sites

Site	Farm type	Family size	Family members working		Hired labour	Income from farming	Self-sufficiency of maize	Livestock ownership*
			On farm	Off farm	(man-days year^{-1})	(%)	(months)	(heads)
Emuhaia	1	4.8	3.2	1.7	4.2	38	6.2	3.0
	2	7.1	3.3	1.2	7.0	50	11.0	4.0
	3	7.6	4.2	0.8	1.4	71	8.0	3.2
	4	5.7	4.0	0.3	0.7	73	5.7	2.7
	5	5.3	1.5	1.3	0.0	53	1.5	0.8
	SED	*2.5*	*1.1*	*0.4*	*0.6*	*16*	*2.8*	*3.1*
Shinyalu	1	5.0	2.7	0.9	5.0	50	8.7	1.7
	2	8.3	5.0	0.7	8.7	77	11.0	5.0
	3	8.0	4.2	0.6	4.4	80	9.6	2.8
	4	4.8	2.5	0.3	2.0	95	9.1	6.3
	5	5.5	2.8	1.0	0.5	73	6.3	0.3
	SED	*2.3*	*1.4*	*0.6*	*0.8*	*9.2*	*1.6*	*1.4*
Aludeka	1	5.7	3.7	1.0	6.7	58	5.7	2.7
	2	8.3	5.5	0.3	6.8	84	6.8	2.3
	3	8.4	3.6	0.4	4.8	78	8.4	7.0
	4	6.0	2.9	0.2	1.2	84	4.6	2.4
	5	6.3	3.3	0.7	0.0	53	3.3	1.7
	SED	*2.4*	*1.1*	*0.4*	*1.4*	*15*	*3.1*	*2.8*

SED: Standard error of the differences
*Including cattle, sheep, goats and pigs

3.2.3 Food production and resource allocation by the different farm types

The results of the resource flow map exercise at case study farms (one per farm type and per site) are presented in this section, showing trends at farm scale. Many data from secondary calculations are presented in the Appendices, whereas the attention in the main text is focused on the most relevant indicators in terms of food production, land use and resource allocation at farm level.

Table 3.2.3: Land distribution and land:labour ratios for the different farm types at the three working sites

Site	Farm type	Land distribution			Land availability (ha)		
		Farm size (ha)	Cropped area (ha)	Production units	Per family member	Per family labour	Per labour unit**
Emuhaia	1	0.6	0.7	5.0	0.19	0.22	0.07
	2	2.1	2.1	6.3	0.39	0.63	0.20
	3	0.7	0.8	5.0	0.15	0.22	0.13
	4	0.3	0.3	5.0	0.06	0.10	0.07
	5	0.5	0.4	2.8	0.08	0.27	0.27
	SED	*0.15*	*0.14*	*0.7*	*0.06*	*0.07*	*0.08*
Shinyalu	1	0.6	0.6	4.3	0.15	0.30	0.08
	2	1.6	1.3	7.7	0.19	0.35	0.11
	3	1.3	1.3	8.0	0.21	0.43	0.15
	4	0.7	0.6	5.3	0.19	0.32	0.17
	5	1.0	0.8	6.3	0.23	0.42	0.35
	SED	*0.25*	*0.15*	*1.1*	*0.06*	*0.11*	*0.04*
Aludeka	1	1.4	1.1	7.7	0.28	0.39	0.12
	2	3.8	2.6	6.5	0.46	0.68	0.30
	3	1.8	2.2	8.6	0.38	0.68	0.24
	4	1.2	0.9	6.0	0.21	0.39	0.26
	5	1.2	1.0	6.3	0.26	0.40	0.40
	SED	*0.75*	*0.6*	*2.3*	*0.21*	*0.24*	*0.08*

SED: standard error of the differences
**Including hired labour in the calculations

Food production and grain yields

Gross food production including grain, tuber, leaf and fruit crops by the different farm types showed a similar trend across sites (Fig. 3.2.3 A). No livestock product (e.g. milk, chickens, eggs, piglets) was included in the calculation. Higher values for Aludeka are indicative of a larger land size, but also resulted from the higher contribution of cassava and sweet potato to the total food figure. Farms type 3 showed the highest values in all working sites. This farm type was characterised by extensive but commercial production of food crops under a low-input situation, selling most of their food produce on the market (Fig. 3.2.2 B). The non self-sufficient farm types 1, 4 and 5 produced less than 2 t of food in all working sites (Appendix 3.2.3 - I a).

Food production per capita was below 0.1 t for farms of type 5 in all sites (Fig. 3.2.3 C). Type 1 farms, with almost the same average land area than type 5, produce two to four times more food due to their capacity to intensify production in terms of labour and inputs, as reflected by their higher yields (Fig. 3.2.3 D). However, each farm type allocates resources to the various crop types in a different way, which makes comparisons of gross food yields difficult to interpret. Appendix 3.2.3 - II gives some indicators of resource allocation to several production activities for the five farm types at Shinyalu. These results clearly show the correspondence between the adopted farm typology and the patterns of the resource flows.

Grain production by type 4 and type 5 farms (Appendix 3.2.3 - I b) was for all sites lower than the often assumed annual requirement of 170 kg per person (Shepherd *et al.*, 1997). For

Emuhaia, Shinyalu and Aludeka, respectively, grain yields were slightly above, at the same level and just below the reference yield of 1 t ha^{-1} indicated for sub-Saharan Africa (e.g. FURP, 1994). Higher yields in all three sites were attained by farm types 1 to 3. The magnitude of the absolute difference in maize yield between the best and the worst fields within each farm (an evident on-farm estimator of the magnitude of the soil fertility gradients at first glance) tended to be the largest in those farms where the yields were highest. However, spots of high maize yields in the field could be found in all farm types - especially in those farms where cattle are kept.

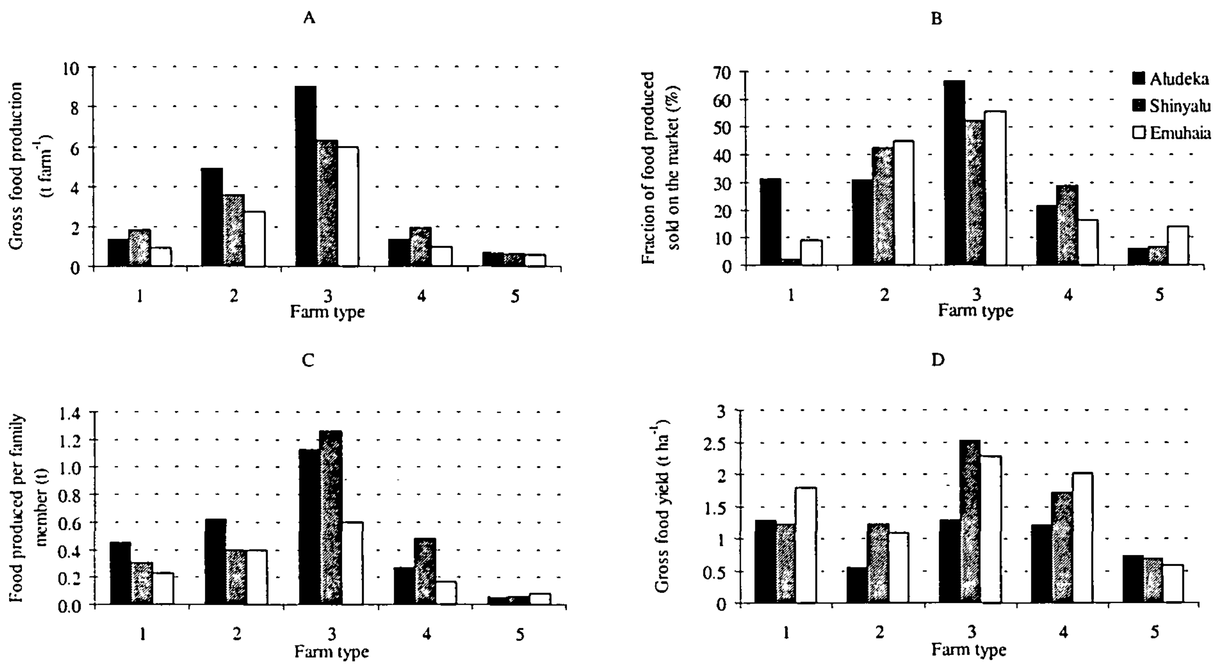

Figure 3.2.3: Estimations from the resource flow map exercise at Emuhaia (Vihiga District), Shinyalu (Kakamega district) and Aludeka (Teso District) in Western Kenya. A, gross farm food production; B, proportion that is sold on the market; C, food production per capita; D, average gross yield in food production at farm level. Estimates are given in fresh weight.

Fertiliser use

There were large differences in the use of organic and inorganic fertilisers across sites as well as between the different farm types within each site (Table 3.2.4). Practically all farmers in Emuhaia used small amounts of inorganic fertilisers and due to the smaller farm size the application rates (amount of fertiliser applied to a certain field over its area) were higher than for the other sites. The highest average fertiliser use and use intensity (total amount used over total cropped land) was found in Shinyalu. In Aludeka fertiliser use was restricted only to the wealthier farms. The use of organic fertiliser was the highest in Emuhaia, where most farmers prepared compost (cf. Table 3.1.2), lower in Shinyalu, where cattle could be seen free ranging during certain periods of the year (cf. Section 3.1, Management practices) and nil in Aludeka where manure was not collected. The application rates of organic fertilisers should be considered with care, specially those calculated for

Emuhaia (the smallest land sizes). They resulted from farmers' estimations expressed in local units (e.g. *debes*, baskets or wheelbarrows) and from GPS-aided measurements of the area of the plots. Farmers normally indicated application rates as "between 20 and 30 wheelbarrows", which introduces a high variability when the calculations are expressed in kg ha^{-1}, particularly when the average area of the fields is as small as in Emuhaia.

Table 3.2.4: Estimates of fertiliser use from the resource flow map exercise for different farm types

Site	Farm type	Inorganic fertilisers: Total use (kg)	Inorganic fertilisers: Use intensity (kg ha^{-1})	Inorganic fertilisers: Application rate (kg ha^{-1})	Organic fertilisers*: Total use (kg)	Organic fertilisers*: Use intensity (kg ha^{-1})	Organic fertilisers*: Application rate (kg ha^{-1})
Emuhaia	1	13	48	92	2200	8000	9800
	2	29	16	66	900	500	1100
	3	15	26	17	2300	4000	7000
	4	3	6	43	700	1300	4100
	5	7	12	16	300	500	6160
Shinyalu	1	40	51	25	780	990	1480
	2	93	32	82	200	70	320
	3	19	9	14	360	170	1170
	4	25	22	18	240	210	720
	5	5	5	7	0	0	0
Aludeka	1	2	2	14	0	0	0
	2	19	6	33	0	0	0
	3	0	0	0	0	0	0
	4	0	0	0	0	0	0
	5	0	0	0	0	0	0

Total use: total amount of fertiliser used per farm; Use intensity: total amount used (total use) divided by the total cropped area per farm; Application rate: amount of fertiliser applied to a certain field divided by its area (dose).
*Figures were rounded off to nearest 100 multiple.

A certain degree of substitution of organic resources by inorganic fertilisers could be observed for the largest and wealthier farms of type 2, where labour requirements for distribution of manure in the different fields play an important role (Table 3.2.4). Moreover, in type 1 farms cattle are often kept tethered in the compound or confined to zero grazing units, making the collection of manure much easier. Nevertheless, when C, N, P and K application rates are calculated from the amount and type of organic and inorganic fertilisers used (Appendix 3.2.3 - III a), it is clear that farms of type 1, with the smallest outputs of biomass to the market, are those concentrating more nutrients in their land for all sites.

Crop residue management

Four main ways of managing residues were identified and defined: residues used as fodder, burnt, composted and incorporated (Table 3.2.5). The first three are *assumed* to extract the residues from the field after harvest. Crop residues used as fodder are mainly transported to grazing sites where the animals are tethered. Grazing of standing crop residues on the field is not widely practised in Emuhaia due to the intensive double cropping (all fields are planted in both rainy seasons due to land scarcity). It can be seen in Shinyalu during the second rains only in those fields that are left as fallow - a practice mainly adopted by the large sized farms of type 2 and to a less extent by type 3 farms. In Aludeka, where land is available and where only few farmers own cattle, grazing takes place mainly in natural grasslands.

Table 3.2.5: Four ways of managing crop residues in the different farm types at the three working sites, derived from the results of the resource flow maps. These figures do not include organic fertilisers but only the residues of the crops grown in each field.

Site	Farm type	Crop residues management*			
		Fodder (%)	Burnt** (%)	Incorporated (%)	Composted (%)
Emuhaia	1	15	42	32	11
	2	19	38	34	9
	3	25	52	7	17
	4	28	37	11	24
	5	13	43	43	0
Shinyalu	1	10	49	29	13
	2	17	36	37	9
	3	19	44	38	0
	4	65	18	14	3
	5	33	39	29	0
Aludeka	1	2	8	85	6
	2	8	33	59	0
	3	24	3	73	0
	4	10	14	76	0
	5	0	12	88	0

* Since maize is the main crop in all farm types, the pattern of residue management applies mainly to maize residues
** Including both residues burnt to clear the fields for the next planting and residues used as fuel in the kitchen

Burning of crop residues is practised to cover fuel requirements for cooking, as a way of clearing the fields before planting and, in the case of beans residues, to produce salt[10]. Only in the second case, which is the least used in all three sites, some of the nutrients held in the residues are left in the field. In Emuhaia and to a less extent in Shinyalu, crop residues are taken from the field to a compost pile or compost pit, where they are mixed with animal manure, ashes and kitchen wastes and used as organic fertilisers into planting holes. This biomass transfer implies that residues harvested from a certain field may be used to fertilise other fields. Residues incorporation is the most common practice in Aludeka as well as in certain fields within the farm in Emuhaia and Shinyalu (see later Section 3.3.3, Resource allocation to different field types). In many cases, however, residues are not evenly incorporated on the fields but accumulated as trash lines along their boundaries (they are often used to demarcate field boundaries).

Labour demands:

Labour requirements through the season for the different activities concerning a maize/beans intercrop were estimated from the information collected during the resource flow map exercise (Appendix 3.2.3 – IIIb). A concentration of activities occurs during planting times

[10] Beans and other legumes residues are burnt and the ashes are suspended in water, filtered and left to crystalise as a salt.

in late February, March and early April, with slight differences across sites. Additionally, farmers were asked not only about the timing of their activities along the season but also about the number of man-days required to carry them out (e.g. how many people do you need to weed this plot of maize and for how many days?). Again, the number of households interviewed is too small and the answers given by farmers too variable to show clear figures. For illustrative purposes, Appendix 3.2.3 - IV gives the distribution of labour requirements by different farm activities during the long rains season. Consistently, most farmers considered land preparation and weeding as the most labour-consuming activities.

3.3 Within-farm variability

3.3.1 Common field types appearing in all farms: Field typology

Fields within a farm were classified in two main groups: those fields that are clearly identified in all farms, home gardens, grazing sites, close, mid-distance and remote fields; and those that only appear in some of them and that result from biophysical discontinuities or history of use (valley bottoms, swamps, old bomas, etc.), the '*special niches*' (see Chapter 2: Field typology).

The home gardens (HG) are typically the small fields around the homestead that are used for a variety of crops sharing small pieces of land or intercropped between each other. They can be found in practically all farms in Emuhaia and Shinyalu whereas in Aludeka they are either more difficult to identify or absent, especially in larger farms (Table 3.3.1). Typical crops for the HG include fruit trees, bananas, local vegetables, sugar cane (eating type), cowpea, common beans and maize for roasting. The HG receive the kitchen wastes and the sweepings from the house (that often include chicken manure). From 4 to more than 9 crops can be seen growing at the same time in the HG in all sites (see below, Table 3.3.2 and related text). The HG are normally managed by women and often the first fields to be planted and weeded. Since they are located around the homestead, farmers tend to keep them neat, well managed and productive.

Table 3.3.1: Common field types and their frequency of occurrence in the different working sites

Site	Field Types (% of farms in which they appear)				
	Home gardens	Close fields	Mid-dist. Fields	Remote fields	Grazing sites
Emuhaia	93	100	80	67	93
Shinyalu	87	100	93	60	73
Aludeka	73	93	79	93	20

The grazing sites (GS) are fields that for some reason are not cropped and therefore used as natural grasslands. This heterogeneous group includes areas not suitable for crops (e.g. shallow soils), areas within the compound where the house is placed or remote fields where crops are not grown due to risk of theft. The GS are often not large enough to support the grazing animals with fodder. Animals are tethered and are fed with cut grass or crop residues. Manure is collected from the GS when they are near the homestead. The GS are common in Emuhaia and Shinyalu but not in Aludeka (Table 3.3.1).

Table 3.3.2: Average area and crops grown most frequently for the different field types, averaged over all farm types at Shinyalu.

	Field type			
	Home Gardens	Close fields	Mid-distance fields	Remote fields
Average area (ha)	0.07	0.18	0.23	0.23
Most frequently grown crops (frequency %)				
Maize/beans	37	82	73	53
Maize	4	3	4	14
Beans	12	3	4	0
Cowpeas*	12	17	8	5
Sweet potatoes	8	0	8	16
Cassava	4	3	0	0
Kales	4	3	0	0
Sugar cane**	4	0	0	0
Banana	19	0	0	0
Napier grass	0	3	4	6
Others	8	3	8	5

*Normally inter-cropped
**Eating type

The close, mid-distance and remote fields (CF, MF and RF, respectively) are those in which the more extensive crops are grown (e.g. maize and beans inter-crops) but their definition and identification vary across wealth classes. The CF can be found in almost all farms in the three sites (Table 3.3.1) and are typically those in which most inputs are used (e.g. fertilisers, improved seeds) and where higher yields are attained. Farmers normally regard them as good quality land (see later, Farmers' land quality classifications). The RF are those fields that are distant and/or difficult to access (especially in areas of steep slopes), and where crop produce is more prone to be stolen. Quite often this type of field is associated with poor quality land, receives almost no inputs and produces low yields. Some farmers plant their woodlots in these fields. The RF are clearly seen in Aludeka and to a less extent in Emuhaia and Shinyalu[11] (Table 3.3.1). In the MF an intermediate situation is found, strongly affected by farm wealth. In wealthy farms they are managed almost in the same way as the CF, though input use might be less intense. In poor farms they receive little or almost no inputs - as the RF do - and crop growth gradients can be clearly seen along these fields from their closer to their farther extremes. Farmers, again depending on wealth, can regard them as either good or poor quality land.

Table 3.3.2 shows the average area of the different fields and the crops that are mostly grown in each of them for Shinyalu. The home gardens are much smaller but no differences can be seen between the others. Though maize/beans intercrops can be found predominating in all field types, they are more common in the close and mid-distance fields (Table 3.3.2). The home gardens show the highest variety in terms of crops with a notorious patchy

[11] In Emuhaia and in Shinyalu due to topography remote fields are often in valley bottoms, which in this typology and according to the allocation of production activities and resources are considered as special niches.

distribution. The remote fields tend to receive crops that are known to withstand poor soil fertility, like sweet potatoes or Napier grass, or that are not easy to steal.

Table 3.3.3: Special niches and their frequency of occurrence at the different working sites

Site	Special niches (% of farms in which they appear)				
	Valley bottoms	Permanent fallow*	Swamps	Ex-*boma*	Ex-*kraal*
Emuhaia	33	33	7	0	0
Shinyalu	40	47	13	13	7
Aludeka	0	33	21	40	20

*waste land

The field types grouped within 'special niches' and their frequency for the three working sites are shown in Table 3.3.3. The valley bottom fields (VB) are found in Emuhaia and Shinyalu due to the hilly landscape characteristics. These are regarded as naturally fertile areas and are managed without fertilisers. The permanent fallow fields (PF) are associated with rocky outcrops, steep slopes or 'murrams'[12] in Emuhaia and Shinyalu. In Aludeka, due to labour shortage and land availability, poor but potentially cultivable land is left permanently as fallow and sporadically used for cattle grazing (low quality grasslands) or for cutting roofing grass.

The swamps (SW) are the preferred niches for cash crops (e.g. cotton, rice, and tobacco) for most farmers in Aludeka due to their dark, fertile soils and are seasonally rented for that purpose. Ex-boma sites (EB) are the places where the homestead has been for some time (about 10 - 15 years) before moving it to another part within the farm, accumulating fertility from animal droppings and kitchen wastes. They are not found in Emuhaia due to the land scarcity. In Aludeka, where even wealthy families have semi-permanent houses, this type of niche is more common. For the same reason, they are found only among the poorest farms in Shinyalu. Land availability and grazing management result in a higher frequency of the fertile Ex-Kraal[13] sites (EK) in Aludeka as well, where they rotate after about 4 years.

3.3.2 Within-farm variability in land quality from the farmers perspective

Farmers classified as fertile[14] between 40 and 50% of their land in Emuhaia and Shinyalu and about 30% in Aludeka (Figure 3.3.1). This implies, for the average farm size at each site, between 0.4 and 0.7 ha of good quality land per farm (Appendix 3.3.2 a). Between 26 and 36% of the land was classified as poor, though the reasons behind this classification vary widely from site to site as well as among farmers.

[12] *Murram* is the name given to a layer of laterite concretions that are found at different soil depths. Where this layer is found on the soil surface, farmers use the term *murram* to refer to those fields as well.

[13] Terms such as *Kraal* and *Boma* seem to have variable meanings in eastern and southern Africa. In western Kenya, farmers use the term *Boma* to refer to the homestead, where often a cattle confinement unit can be seen next to it, and *Kraal* to a precariously fenced area where the cattle are kept during night time

[14] Fertile was a name given by farmers to indicate good quality land, which they associate with obtaining good yields either with or without fertilisers. See Methodology: Farmers' land quality classification.

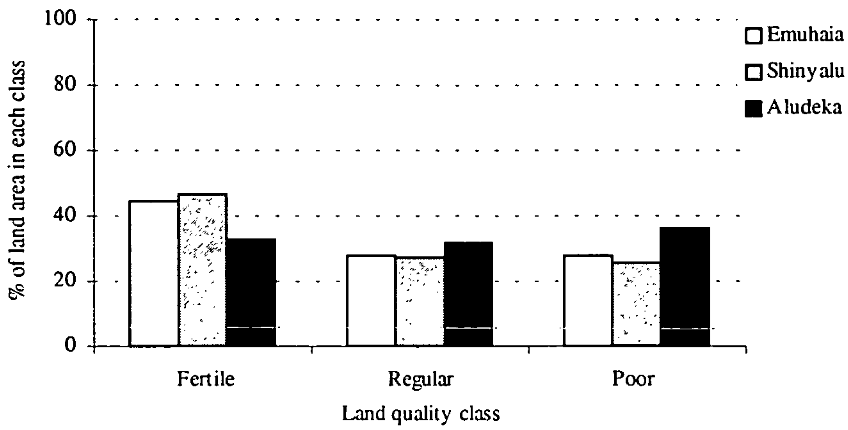

Figure 3.3.1: Farmers' classification of their farm area according to land quality into Fertile, Average and Poor at Emuhaia, Shinyalu and Aludeka, Western Kenya. Classification criteria varied from farm to farm.

Appendix 3.3.2b shows the frequency of different reasons given by farmers to explain differences in land quality classes. In Emuhaia and Shinyalu soil erosion is the main reason for poor yields given by farmers, followed by soil depletion and input use. In Aludeka, soil texture and shallow soils are referred as the main causes of poor yields.
Cross-checking the adopted field typology with the land quality classes yields the trend shown in Table 3.3.4. The home garden and the close fields were classified as Fertile in more than 60 and 50% of the cases, respectively, whereas the remote fields fell in the Poor class in most cases at the three working sites. For the mid-distance fields the results are more variable and no clear trend is observed across sites. Such trends, however, must not be given too much credence since land quality was defined by each farmer under his/her own criterion and in relative terms.

Table 3.3.4 : Land quality class given by farmers to the different field types at the three working sites.

Site	Field quality class	Field Types (frequency in each quality class %)			
		Home garden	Close fields	Mid-dist. Fields	Remote fields
Emuhaia	Fertile	76	52	39	19
	Average	14	29	36	25
	Poor	10	19	25	56
Shinyalu	Fertile	62	75	5	7
	Average	31	17	53	36
	Poor	8	8	42	57
Aludeka	Fertile	62	67	29	13
	Average	23	27	42	9
	Poor	15	7	29	78

3.3.3 Resource allocation and management practices in the different field types (Resource flow map results at field scale)

Biomass production

The dry matter yield of the crops and crop mixes grown in the different field types within the farm varied widely and followed different patterns for different farm types, as indicated for Shinyalu in Figure 3.3.2 A. However, differences between farm types for a certain field type were larger than those found between fields in a farm type. This is partly due to the fact that all crops were considered, from bananas to sweet potatoes, with a range of plant morphological features (i.e. dry matter partitioning) and dry matter contents (for calculation procedures see Chapter 2, Section 2.3.1). For the wealthier type 2 farms there seemed to be a different pattern: good yields could be obtained from the remote fields (Fig. 3.3.2 A). In the type 2 farms at Shinyalu cash crops like tea or perennial crops like fodder grasses were normally grown in the steep slope subject to erosion, producing good biomass yields in the remote fields.

In general, most of the farm produce was obtained form the close and mid-distance fields (Figure 3.3.2 B). While the mid-distance fields sustained mainly maize/beans intercrops, crops produced in the close fields were normally those of the highest value, like kale and cabbage, with a low dry matter content. The home gardens showed the highest yields among the poorer farm types 4 and 5 (Fig. 3.3.2 A), though their contribution to total biomass produced by the household was often the smallest for all types of farms except for type 5 (Fig. 3.3.2 B).

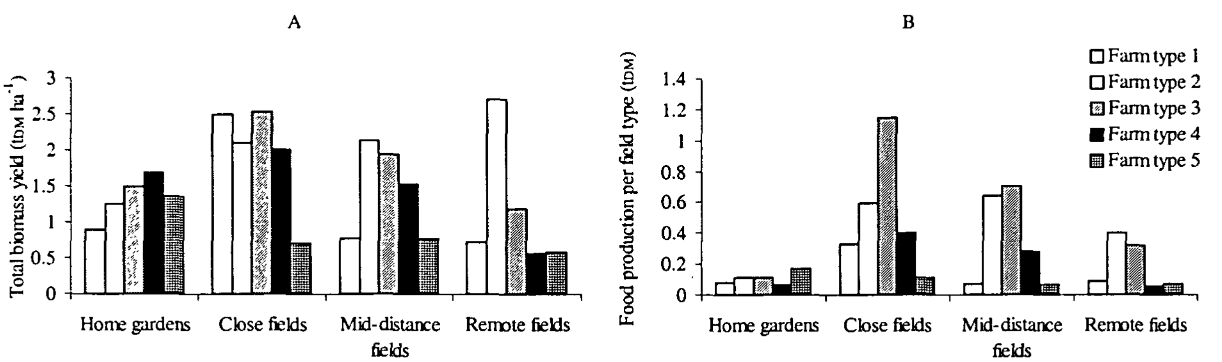

Figure 3.3.2: Biomass production in the different fields of the case study farm types 1 to 5 at Shinyalu, western Kenya. A: dry matter yield of the outputs from each field (t_{DM} ha^{-1}), and B: total food production per field (t_{DM}); estimated from the results of the resource flow maps. Outputs from a field included all biomass harvested/removed from a certain field, including for instance Napier grass or Tea, whereas 'food' production from a field included only the edible produce, such as grains or vegetable leaves.

Fertiliser use

Inorganic fertilisers were used with different intensities in the different field types within a farm, as illustrated for Shinyalu in Figure 3.3.3 A. The wealthiest farm types 1 and 2 applied them everywhere within the farm and, as shown by these case study farms, relatively high rates were used in the poor quality land of the remote fields. For the other farm types application rates were very small or nil in the remote fields and, in general, almost no application was done at rates higher than 20 kg ha^{-1}. At the other working sites (data not shown) inorganic fertilisers were almost not used in the home gardens (in Aludeka, fertiliser use was extremely restricted and only by farm types 1 and 2, cf. Section 3.2.3, resource flow map results at farm scale). The main type of inorganic fertiliser used in all three sites was diammonium phosphate (18:46:0) at planting, followed by calcium-ammonium nitrate and urea (46:0:0) for top dressing. Rock phosphate and triple super phosphate were less widely used. Tea growers used a compound fertiliser (25:5:15) provided by the tea processing industry.

The use of organic fertilisers varied clearly for the different field types and was strongly affected by the distance from the homestead and/or grazing sites and by the type of crop (Figure 3.3.3 B). The vegetable crops grown in the home gardens received most of the organic resources, followed by the cash and/or grain crops grown in the close and mid-distance fields, and virtually nothing was applied to the remote fields. This distribution was obviously affected by the labour requirement involved in transporting coarse materials to distant parts of the farms (organic resources are transported with baskets and, in the few farms where they are available, by wheelbarrows). Organic resources included animal manure, compost (mostly cow dung plus crop residues) and kitchen wastes.

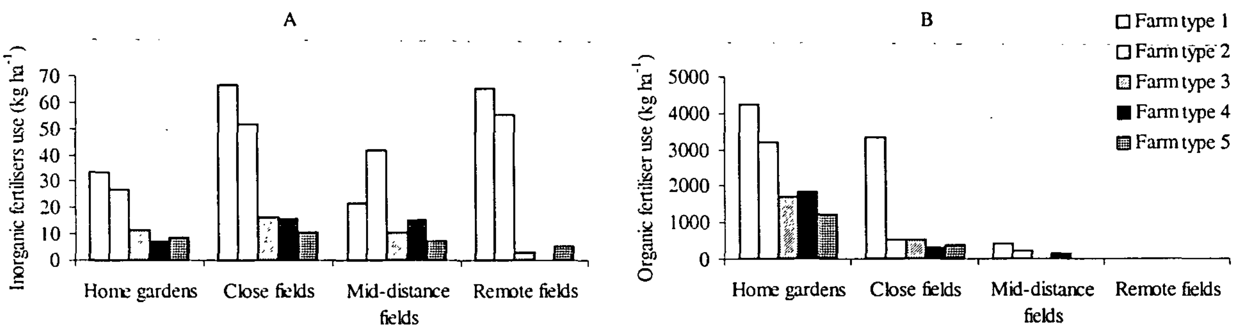

Figure 3.3.3: Fertiliser use (kg ha^{-1}) in the different fields of the case study farm types 1 to 5 at Shinyalu, Western Kenya. A: inorganic fertilisers in general; B: organic fertilisers in general. Estimations from the results of the resource-flow maps.

Crop residue management

The four ways of managing crop residues previously identified (cf. Section 3.2.3) were adopted to a different extent for different field types, as illustrated for the case study farms at Shinyalu in Figure 3.3.4, in which only incorporation was considered. Besides clear differences among farm types residue incorporation took place mainly in the home gardens followed by the close fields, when considered in relative terms (Fig. 3.3.4). The wealthiest farm types 1 and 2 incorporated most of the crop residues in all fields. In farm types 4 and 5 crop residues were mainly used as fodder and fuel, respectively. Additionally, crop residues have different quality. Most residues from vegetables or banana leaves were incorporated in the home gardens or composted rather than fed to animals or burnt.

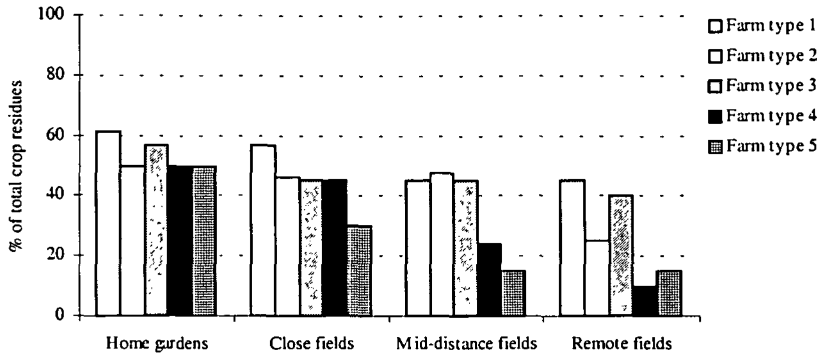

Figure 3.3.4: Crop residue management in the different fields of the case study farm types 1 to 5 at Shinyalu, Western Kenya. Estimation of the percentage of total crop residues that are incorporated in each field type according to the results of the resource flow maps.

Partial Carbon[15] *and Nitrogen balances in the different field types*

As a result of the various inputs and outputs in terms of fertilisers and crop biomass (animals are not considered due to the dominant grazing management adopted in the region, see Chapter 2: Partial nutrient balances at field level) and their quality, clear differences in C and N balances could be observed between farm and field types. Inputs of C and N were much higher in the home gardens and in the close fields than in the other field types (Fig. 3.3.5, A and B). The big difference in the absolute amounts of C and N applied indicates the predominantly poor quality of the organic resources used, with a wide C:N ratio.

Figure 3.3.5: C (A) and N (B) inputs in the different fields of the case study farm types 1 to 5 at Shinyalu, Western Kenya. Estimations considering organic and inorganic fertilisers and residues incorporated in each field type according to the results of the resource flow maps. Note the important differences in the scales of the y-axes.

Differentiating the inorganic from the organic sources of N inputs (Figure 3.3.6 A and B, respectively. Note the wide difference in the scale of the y-axes), it is clear that the pattern of N allocation in Fig. 3.3.5 B (from home gardens to remote fields) was mostly explained

[15] What was calculated here is literally *not* a carbon balance, which should include the C inflows from the atmosphere, and that is the reason why it was called partial C balance. As stated in Chapter 2 the objective of calculating this was to detect areas of accumulation of C (already fixed in the biomass) within the farm that could reflect the trends in soil organic carbon observed from the results of the soil analyses.

by the pattern of organic resource allocation. The distribution of N from inorganic fertilisers was mainly affected by farm type: in the type 1 and type 2 case-study farms the remote fields received as much fertiliser N as the close fields. On the other hand, the N application rates were low for all field types in the case-study farms of types 3, 4 and 5 (Fig. 3.3.6 A). The main type of inorganic fertiliser used by the farmers was diammonium phosphate (18: 46: 0), with a relatively low N content, and only few farmers practised top dressings with urea (46: 0: 0).

Instead, the distribution of N added through organic inputs was chiefly affected by field type (Fig. 3.3.6 B), reflecting the effect of 'distance from the homestead' that is dealt with in Chapter 4. However, the definition of field types may affect the interpretation of the results: apparently, the application rate of N in the organic inputs in the close fields was much higher for type 1 farms than for the other types. In spite of differences in the quality of the organic resources applied in terms of their C:N ratio, the area of the fields and the distance from the homestead are not homogeneous across farm types, leading to wide differences in N application rates (Fig. 3.3.6 B). In other words, due to the smaller land size the close fields of the type 1 farms were much closer to the homestead and had a smaller area than in the type 2 farms, affecting the N application rates estimated for those fields.

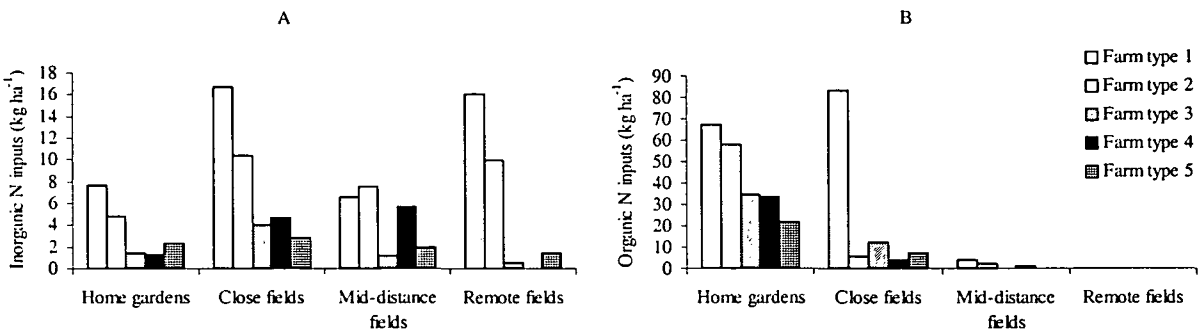

Figure 3.3.6: N inputs in the different fields of the case study farm types 1 to 5 at Shinyalu, western Kenya. A: N applied as inorganic fertilisers; B: N applied as organic fertilisers. Estimations considering organic and inorganic fertilisers in each field type according to the results of the resource-flow maps. Note the important differences in the scales of the y-axes.

According to the results of the resource flow maps from the case study farms at Shinyalu, the partial C balances were 'negative' (in the sense that the amount of C incorporated by crop residues and organic fertilisers was much less than the amount of C harvested with the biomass removed) for most fields in all farm types except for the home gardens where a net 'C accumulation' occurred (Fig. 3.3.7 A). The same general trend could be observed in the other working sites. The partial character of these calculations does not consider, for instance, C fixation by weeds which is a C source incorporated *in situ* or soil C lost by erosion. These partial balances do not give definite values but show trends in nutrient depletion and accumulation.

The partial N balance was negative in most fields of all farm types (Fig. 3.3.7 B). Only in the home gardens of the wealthiest type 1 and type 2 farms the partial N balance was positive. As illustrated for Shinyalu, the N balance tended to be more negative in those fields where the highest yields were attained, especially in the poorer farms (cf. Figure 3.3.2). In the close and mid-distance fields of type 3 and type 4 farms good yields were often attained with low inputs, since other management practices are adequately done (i.e. timely planting, weeding). This, in principle, leads to a higher N demand by those well growing crops that is covered by the mineral soil stocks and by the current decomposition of organic materials. Even when fertilisers were applied, the application rates adopted were not high enough to compensate crop demands in most cases. As for the case of partial C balances, these results were calculated from the resource flow map exercise in which farmers estimated amounts harvested and application rates, and they were only meant to show trends in nutrient balances as affected by management practices.

Figure 3.3.7: Partial C (A) and N (B) balances (kg ha^{-1}) in the different fields of the case study farm types 1 to 5 at Shinyalu, western Kenya. Estimations considering organic and inorganic fertilisers, residue management and harvests from each field type according to the results of the resource-flow maps. Note the important differences in the scales of the y-axes.

4 Explaining the variability in crop performance

Introduction

As stated in the introductory paragraphs, crop growth performance (and its variation in the field) is considered here as an integrator of all the sources of variability originated from the multiple SWIM factors (i.e. site, wealth, inherent properties and management, see Chapter 1). This chapter presents the results of the maize yield estimations performed with the allometric models previously calibrated (see Appendix 2.4.1) using field measurements of standing crops that were in late development stages (i.e. from milky stage onwards). Average yield estimates were in agreement with yields obtained under farmers' conditions in the region, fluctuating around 1 t ha^{-1} (Jaetzold and Schmidt, 1982; Stoorvogel and Smaling, 1990; FURP, 1994; Palm *et al.*, 1998). Yield variability is presented and analysed at different scales, showing the relative importance of the factors S, W, I and M at the various levels of analysis.

Weighted averaged yields at farm scale (t ha^{-1}) were compared between sites and between farm types and/or wealth classes. *Direct yield estimates* at field scale (t ha^{-1}) were validated against the results of the resource flow maps and used for comparisons between field types and across sites. In different farm types within each site spots of high and low yields were identified and deliberately chosen as measuring points, rather than randomly 'sampling' the fields to obtain a representative average maize yield. For example, high yields were measured in the home gardens of the poorest farms and extremely low yields in the remote fields of large, wealthy farms. In such a case wealth would not be a reasonable criterion to discriminate between high and low yields at *field* scale. For that reason, direct estimates at field scale were not used for between-farm type or between-wealth class comparisons but rather average farm yields, and therefore the triple (Site x Farm type x Field type) interactions for maize yield could not be considered (see later). Average values of inherent properties, actual soil fertility indicators and management factors are presented and compared for the different field types and land quality classes (see Chapter 3, Field typology and Farmers' land quality classification). Finally, multiple regression models were developed to explain maize yield variability at field scale using the above-mentioned groups of factors as explanatory variables. As in the previous chapters, the results are presented in the sequence Emuhaia – Shinyalu – Aludeka, in the direction of decreasing population pressure and increasing soil variability.

4.1 Maize yield variability at different scales

4.1.1 Yields at farm scale: structural differences within the region, the influences of wealth and production orientation

Maize yields at farm level varied significantly between sites and farm types (Table 4.1.1), but the interaction between these two factors was not significant. Average yields were significantly higher in Emuhaia and Shinyalu than in Aludeka (Table 4.1.1). The highland area around the Kakamega forest is normally recognised as a site of high yield potential for crops, particularly for maize (Niang *et al.*, 1997). The inherent and actual soil fertility status was also higher than for the other places (see Chapter 3, Range of soil properties). In spite of the severe soil fertility depletion caused by high population pressure in Emuhaia, yields were still above the average for sub-Saharan Africa. Input - especially fertiliser - use intensity in Emuhaia was higher than in the other sites and its agro-ecological conditions are close to those found in Shinyalu, near Kakamega forest.

Table 4.1.1: Average maize yields (t ha^{-1}) at farm scale (weighted averages) for different farm types across sites. The standard error of differences (SED) are indicated in *italics*

Site	Farm type					Mean	SED
	T1	T2	T3	T4	T5		
Emuhaia	2.3	1.6	2.5	1.8	1.0	1.9	
Shinyalu	2.5	2.0	2.2	1.6	0.7	1.8	*0.12*
Aludeka	1.1	1.2	1.3	0.8	0.6	1.0	
Mean	2.0	1.6	2.0	1.4	0.8		
SED			*0.16*				*0.28*

The lower yields measured in Aludeka are in line with expectations from trends shown by previous research (FURP, 1994), reflecting the effect of a lower rainfall regime, higher potential evapo-transpiration and a more heterogeneous soil quality (from sandy to clayey, from acid to basic and from deep to shallow soils). Additionally, and due also to ethnic characteristics (i.e. food habits), the staple food in Aludeka is not maize but cassava, which may also partly explain differences in resource allocation to maize crops at this site.
Clear differences in actual soil fertility between sites could be partly explained by inherent soil properties. The parent materials and the interaction of the soil forming factors during their genesis and evolution (plus the long term effect of the consequent land use and management) may explain between-sites differences in nutrient contents, especially for those held in the soil inorganic fraction. Plotting maize yields against clay plus silt content for the whole set of soil samples showed a narrowing in the range of yields as the amount of clay plus silt decreased (Figure 4.1.1 A). In spite of other factors controlling organic C contents in soils (i.e. climate, vegetation and long-term management) texture explained more than 70% of the variability in the soil organic faction across sites (Figure 4.1.1 B), which is in agreement with the principle of physicochemical C stabilisation in soils (Feller and Beare, 1997; Hassink, 1997; Ladd *et al.*, 1985). The effective cation exchange capacity

(ECEC) and the sum of exchangeable bases (Ca + Mg + K + Na) increased as the sum of the clay and silt fraction increased (Figure 4.1.1 C and D).

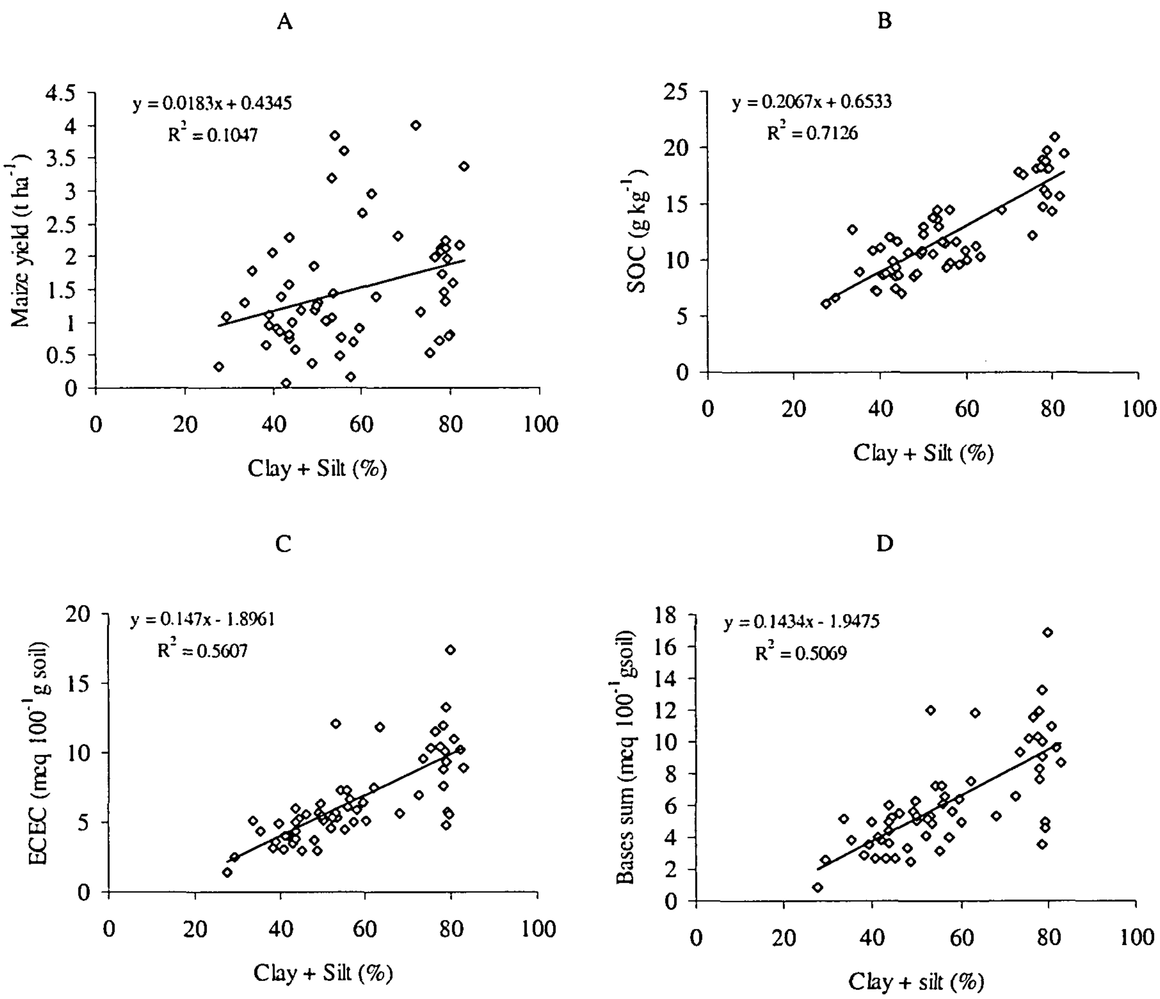

Figure 4.1.1: Yield variability and the range of some soil properties for soils of different texture (clay plus silt content) from three localities in western Kenya. A: the relationship between the clay + silt fraction in the topsoil and maize yield (t ha^{-1}). B, C and D: Soil organic carbon (SOC), effective cation exchange capacity (ECEC) and sum of bases (Ca, Mg, K and Na), respectively, for topsoils of different clay + silt content.

The relationship between soil organic carbon and maize yield was rather weak and, due to the covariance with texture, it showed a similar trend: while low yields (c. 0.5 t ha^{-1}) can be obtained under high or low soil C situations, high yields are mostly achieved on the higher side of the range of soil C, particularly above a threshold of ca. 10 g C kg^{-1}soil (Figure 4.1.2 A). This trend in maize yield is partly explained by the benefits in terms of soil physicochemical properties brought about by the organic matter, but also by higher N (note that C:N ~10 in Fig. 4.1.2 B) and P stocks and by a higher cation exchange capacity in soils with higher C (and clay) content (Figure 4.1.2 B-D). The topsoils from Aludeka showed higher values of extractable P by modified Olsen (see Chapter 2, Soil sampling and laboratory analysis, and Chapter 3, Range of soil properties at site level), reflecting a lower 'use intensity', than those from the other sites. However, total P values were higher in the samples from the other sites and followed the trends in organic matter contents (Fig. 4.1.2 C).

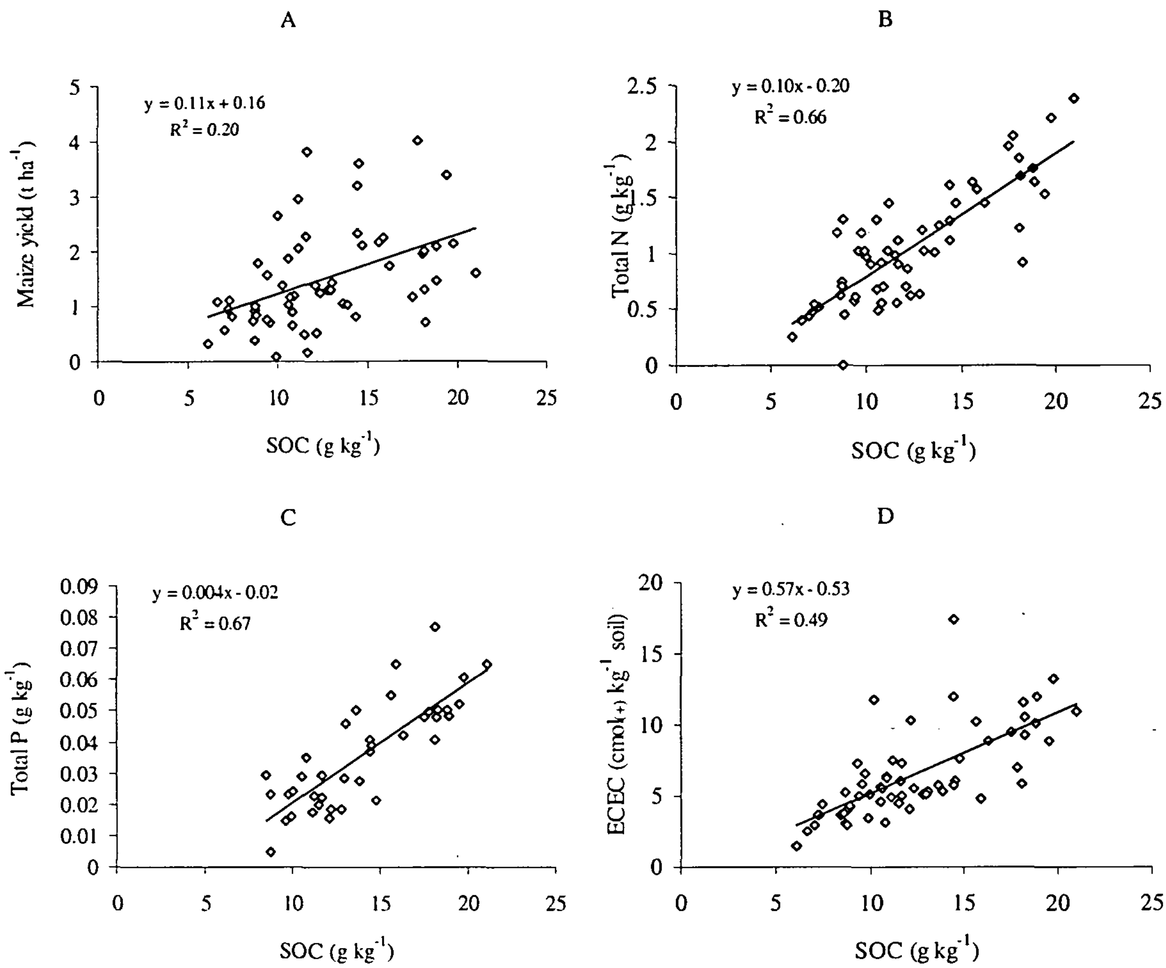

Figure 4.1.2: Yield variability and the range of some soil properties for soils of different organic matter content from three localities in western Kenya. A: the relationship between soil organic carbon (SOC) in the topsoil and maize yield (t ha^{-1}). B, C and D: Total nitrogen and phosphorus contents and effective cation exchange capacity (ECEC), respectively, for topsoils with different soil organic carbon (SOC) levels.

The effects of wealth and production orientation on maize yields at farm scale were quite consistent across sites. The highest average yields in all sites were achieved by the land-limited, high-input farms of type 1 and by the low input, self-sufficient farms of type 3 (Table 4.1.1). The wealthy farms of type 2 showed yield levels similar to those shown by type 4 farms. This way of averaging yields (i.e. weighted mean yields[1]) accounts for the variability found within farm. In the larger farms this implies that the low yields achieved in remote fields contributed to the average at farm scale, thereby reducing it. Moreover, due to land, cash and labour availability in wealthy farms good quality land tended to be allocated to cash crops or vegetables, while grain requirements were covered by the production from lower quality fields or by purchasing from the market. In farms of type 1 land limitation was

[1] Basically assigning a certain percentage of the total farm area under maize that was represented by each measuring point. See Chapter 2.

compensated by intensification (i.e. input use) and higher yields were achieved. The production of cash crops was limited by lack of resources in type 3 farms and therefore good quality land was allocated to grains. In these farm types maize surpluses constitute an important market item.

At all sites maize yields attained by type 4 farms were between those of type 3 and type 5 farms, while the land- and labour-limited farms of type 5 had the poorest yields. However, yield levels shown by farms type 5 in Emuhaia and Shinyalu were not significantly different from those from all farm types in Aludeka, presenting a widely different picture in terms of meeting food requirements. In farms of types 4 and 5 most land was allocated to maize production, except sometimes in Aludeka where cassava was widely grown by poor farmers. Clearly, different yields can be attained under a low input production situation, as reflected by the significant differences between farm types 3, 4 and 5. Here, land and (especially) labour availability play a major role.

Table 4.1.2: Maize yield (t ha^{-1}) at farm scale (weighted averages) for different wealth classes across sites. Standard error of the differences (SED) are indicated in *Italics*

Site	Resource endowment				
	High	Medium	Low	Mean	SED
Emuhaia	1.8	2.5	1.3	1.9	
Shinyalu	2.3	2.0	1.0	1.8	*0.15*
Aludeka	1.1	1.2	0.7	1.0	
Mean	1.7	1.9	1.0		
SED		*0.15*			*0.3*

When farms in the sample from each site were grouped exclusively according to wealth classes a significant interaction site x wealth class was observed (Table 4.1.2). Either no difference between the high and medium resource endowment classes (HRE and MRE, respectively) or higher yields for the MRE were observed at the different sites. In all cases the average yields of the MRE farms were about two times higher than those of the low resource endowment (LRE) farms. The MRE class included all farms type 3 and in some cases types 1 and 4. Farms of type 2 fell obviously within the HRE together with most farms of type 1. The LRE class included types 4 and 5. Maize yields at farm level were not well discriminated by the wealth class criteria between the medium and high resource endowment households. This is partly due to the fact that wealthy farms tended to allocate the best pieces of land to more valuable crops. On the other hand, as in Emuhaia, many farms of type 1 fell within the medium resource endowment class according to the classification criteria used (Crowley, 1997). This type of farms included those in which the household head has an off-farm employment and therefore a relatively important cash flow into the farm system that allows for higher input use.

Differences in land quality between farm types may also contribute to explain yield variability since it might be assumed that wealthier farms would have a larger share of quality land. However, no clear distinctions in land quality that would lead to differences in maize yields can be drawn from the farm stratification due to the high within-farm variability. As a consequence, larger farms show a wider range in soil types (texture, slope) that affects the range of other properties such as C content or P availability, and a potentially

wider range in maize yields. These ranges may be increased or decreased by the effect of management practices implemented in the different fields within a farm (see next section).
Due to the experimental design (including biophysically contrasting sites) and to the high within-farm variability (i.e. the variability that was to be 'captured' in this work) no clear trends could be derived when soil fertility indicators were analysed at this scale. That was illustrated for some soil fertility indicators (i.e. soil organic C, total N, extractable P, exchangeable K and cation exchange capacity) with the ANOVA tables presented in Appendix 4.1.1. The differences between sites were highly significant for C, N and the cation exchange capacity (inherently different soils, cf. Figs. 4.1.1, 4.1.2 and related text) but not for P and K, since they showed either a strong variation between farm types or, specially, between field types (*Farmty* and *Fieldty* in the ANOVA tables) as will be shown in the next section. Differences between farm types were seen for all these indicators but for P, again due to the high variability at the lowest scale (see below). Strong site x field type interactions were observed for certain indicators, which will be the core of the next section.
The significant site x farm type interactions would indicate that for instance certain farm types within each site had higher average values for a certain indicator. However, such a conclusion cannot be inferred from these results due to the experimental design: sampling points were deliberately chosen in order to include gradients in maize growth performance, which cannot be explained only by soil fertility indicators and management factors play a major role (see later). This can be illustrated as follows: in one farm (belonging to any farm type) 4 points were selected to determine maize yield and only one of those had 'poor' soil fertility indicators, the differences in yield between the others being explained by e.g. sowing dates. In another farm (probably from another type), the three points selected to measure yields showed important differences in soil fertility and a more homogeneous management. The average values for the soil fertility indicators would be higher for the first farm, which could even belong to e.g. a lower wealth class than the second one. A correct sampling to compare between farms (and then be able to consider the two- and three-way interactions) should account for the area of the farm that is represented by each sample by calculating a weighted average for each soil fertility indicator.

4.1.2 Yields at field scale: inherent properties, soil fertility, and short and long-term management effects

The figures presented in this section for maize yields, soil fertility and management variables corresponding to the different field types and land quality classes are average values, and should be considered as an indication. Large differences were seen between individual farms (even from the same farm category) in the magnitude of the soil fertility gradients, according to the results from the soil analysis. Moreover, large differences were observed *within* the fields of an individual farm. Averaging across a large number of farms masked certain differences that are important in terms of crop nutrition and that can partly explain crop yield variability within the farm (see next section). Therefore, the average values would show those gradients only when the differences are strongly marked, and lack of differences between the average values for different field types are not a definite indication that the within-farm soil fertility gradients were absent.
Yields obtained by means of the allometric models were in reasonable agreement with those calculated from the results of the resource flow maps, as illustrated in Appendix 4.1.2 - I.

Maize yields at field scale (t ha^{-1}) showed significant ($P < 0.001$) differences between sites as well as between field types (Table 4.1.3), with no significant interaction between these factors. As for the yield estimates at farm level, the effect of the biophysical background was reflected in the significantly higher yields measured in Emuhaia and Shinyalu compared with those from Aludeka. Within the farms, yields were roughly double in the home gardens (HG) and in the close fields (CF) than in the mid-distance (MF) and remote fields (RF). In Emuhaia, yields were greater in the home gardens than in the close fields, which in turn were greater than in the mid-distance and/or remote fields ($P < 0.05$). In Shinyalu yields measured in HG and CF were significantly ($P < 0.05$) larger than in MF and RF. In Aludeka the yields in the RF were less (P < 0.05) than in the HG and CF but similar to the MF. Yields measured in all field types in Aludeka were not significantly different from the yield levels attained in the RF of Emuhaia and Shinyalu.

Table 4.1.3: Average maize yields (t ha^{-1}) for different field types in the three working sites. Standard errors of the differences (SED) are indicated in *Italics*

Site	Field type					
	Home gardens	Close fields	Mid-dist. Fields	Remote fields	Mean	SED
Emuhaia	2.7	2.0	1.5	1.4	1.8	
Shinyalu	2.3	2.5	1.2	1.2	1.7	*0.14*
Aludeka	1.5	1.5	0.9	0.6	1.1	
Mean	2.2	2.0	1.2	1.0		
SED			*0.17*			*0.29*

The contribution of each field type to the average yield at farm level explains in part the differences shown for different farm types in the previous section (cf. Table 4.1.1). On the other hand, differences in average farm size affected the yield variability found within-farm. In Emuhaia, where farm sizes are smaller, the yield differences between close and remote fields (ca. 30 % lower) are less marked than in the other sites (between 50 to 60% lower). In the larger farms of Aludeka yields measured at the mid-distance and remote fields were below the regional average value of 1 t ha^{-1}, reflecting the effect of distance (i.e. longer distances than in the other sites) from the homestead previously observed in smallholder African farms (e.g Brouwer and Bouma, 1997; Scoones, 1997). Important within-field variation in maize yield was observed in all sites as well, which normally increased at further distances from the homestead, though no systematic method was followed to document this.

In spite of the high yields measured in the home gardens, the close fields contribute most in terms of grain and pulse production for the household due to their relative larger size. The home gardens are mainly managed by women, present a variety of crops growing at the same time on a small area and receive the daily kitchen wastes and other organic resources (e.g. crop residues, manure, compost) but few inorganic fertilisers. They are part of the compound where the house is placed and tend to be well maintained, with well-managed crops due to aesthetic reasons. In Aludeka, the home gardens are more difficult to identify, and are normally characterised by almost pure stands of banana and maize production is secondary. The close fields at all sites are allocated to maize intercropped with beans or groundnuts, have relatively good quality land and receive most inputs (see Chapter 3, Resource flow maps).

Maize yields for different land quality classes

Yields were different in the different fields classified by farmers according to land quality (i.e. Fertile, Average and Poor) at all sites (Table 4.1.4) and the interaction between site and land quality class was not significant. Approximately a 2.5-fold difference in maize yield was observed between fields classified as 'Poor' and 'Fertile' in all sites. In the 'Average' fields maize yields were either closer to the 'Poor' - as in Shinyalu - or to the 'Fertile' - as in Aludeka. Obviously, the reasons for defining a field as poor or as average were different across sites and even from farmer to farmer.

Table 4.1.4: Maize yields (t ha^{-1}) for different land quality classes according to farmers' perceptions. Standard errors of the differences (SED) are indicated in *Italics*

Site	Land quality class				
	Fertile	Average	Poor	Mean	SED
Emuhaia	2.4	1.8	0.9	1.8	
Shinyalu	2.5	1.5	1.0	1.7	*0.13*
Aludeka	1.5	1.1	0.5	1.1	
Mean	2.1	1.5	0.8		
SED		*0.13*			*0.23*

Most farmers in Emuhaia and Shinyalu pointed out the effects of slope of the fields (due to soil losses by erosion) as the main reason. In Aludeka soil depth and texture (the latter also in Emuhaia) played the major role. However, these results are not surprising since, in spite of the reasons behind it, the main criteria to classify fields were the average crop yields[2] that are normally attained. Thus, these measurements simply confirmed farmers' land quality classification.

Inherent and actual soil fertility across field types and land quality classes

As expected, wider differences in the range of inherent soil properties as well as for some current soil fertility indicators were found between sites than between field types in each site (Table 4.1.5). A clear exception is the field slope that varies between both sites and field types, showing a significant interaction between factors. As described in the previous chapter (3.1.4 Farm transects) there was an important association between distance from the homestead and topographic slope in Shinyalu and to a less extent in Emuhaia, which is clearly revealed in Table 4.1.5. Soil texture and the quantity and quality of the soil organic fraction varied significantly ($P < 0.01$) between sites, but did not appear to be good

[2] Although the interpreters used the Swahili term *rotuba* to refer to it, the concept of soil fertility is difficult to translate. Therefore a 'Fertile' condition in this case refers mostly to a good land quality in general than to simply nutrient capacity and intensity in the soil.

indicators to represent the variations in soil fertility found within the farms. Nevertheless, they become very important when comparisons are made between sites, reflecting regional differences in soil fertility as influenced by inherent properties (cf. Figures 4.1.1 and 4.1.2). Values for the C:N ratio were highly variable for all farms and field types at Shinyalu and Aludeka. The values for the home gardens, particularly, seem to indicate that 'fresh' organic materials were present in the samples.

Table 4.1.5: Inherent and actual soil and landscape properties for different field types (n = 141) in the three working sites

Site	Field type	Field slope (%)	Clay + Silt (%)	SOC ($g\ kg^{-1}$)	C:N ratio	ECEC ($cmol_{(+)}\ kg^{-1}$)	pH in water (1: 2.5)
Emuhaia	HG	1.8	53.1	12.9	11.1	5.2	6.1
	CF	3.1	50.9	11.7	10.3	6.0	5.6
	MF	4.6	51.1	12.1	10.5	4.7	5.3
	RF	8.4	49.8	10.5	10.5	4.1	5.1
Shinyalu	HG	4.4	76.4	18.1	15.4	9.6	5.7
	CF	7.0	78.8	18.1	9.9	8.8	5.3
	MF	14.8	78.3	17.3	11.3	8.7	5.3
	RF	19.1	76.2	17.2	16.4	8.8	5.2
Aludeka	HG	1.4	36.1	6.9	24.3	1.8	5.4
	CF	1.3	42.9	8.8	15.9	3.1	5.8
	MF	1.1	44.3	8.6	16.9	3.5	5.4
	RF	1.1	39.4	7.9	16.7	3.4	5.2
Site * Field type (P value)		0.01	ns	ns	ns	ns	ns
SED (general)		2.74	3.36	1.03	7.20	1.21	0.24
SED (field types)		1.58	1.95	0.60	4.18	0.71	0.14
SED (sites)		1.31	1.46	0.45	3.12	0.47	0.10

HG: home gardens; CF, MF and RF: close, mid-distance and remote fields; SOC: soil organic carbon; ECEC: effective cation exchange capacity; SED: standard errors of the differences

The effective cation exchange capacity (ECEC) and the soil pH are closely associated to the soil clay and organic fractions, reflecting their amount and their influence on soil functions such as buffer capacity. Though more sensitive than the other soil properties, the ECEC did not show clear differences between field types in all cases. For pH, a significant ($P < 0.05$) decrease was observed from the close towards the remote fields in Emuhaia and Aludeka, whereas in Shinyalu only the home gardens showed significantly higher pH values. However, values for both ECEC and pH presented are averages that can vary widely within an individual farm. Therefore they may become very important in explaining within-farm yield variability, as will be discussed later.

Total soil N was on average very low in Aludeka (0.5 $g\ kg^{-1}$), low in Emuhaia (1.2 $g\ kg^{-1}$) and on the lower limit of the range of sufficiency given for maize crops (1.5 $g\ kg^{-1}$, FURP, 1994)[3] in Shinyalu, reflecting the effect of the inherent soil texture. Across field types, the close fields showed significantly ($P < 0.05$) higher total N values than the rest, though this pattern of variation changed from site to site (Table 4.1.6). In all sites the grazing places (data not shown) had total N contents that were the same or higher than the site average (1.5,

[3] Total soil N is generally seen as a poor indicator of soil N supply for crop growth

1.6 and 0.5 g kg^{-1} for Emuhaia, Shinyalu and Aludeka, respectively). This is not surprising since, besides the effect of the lack of tillage in these type of fields, there is also a concentration of nutrients in the places where cattle are tethered and fed (see Chapter 3, Resource flow maps); this is less frequent in Aludeka due to the availability of rangeland.

Table 4.1.6: Actual soil fertility properties for different field types (n = 141) in the three working sites

Site	Field type	Total N (g kg^{-1})	Extractable P (mg kg^{-1})	Exchangeable cations (cmol$_{(+)}$ kg^{-1}) K$^+$	Ca^{++}	Mg^{++}	H$^+$
Emuhaia	HG	1.3	19.8	0.54	5.5	1.7	0.13
	CF	1.1	3.5	0.31	4.2	1.4	0.42
	MF	1.2	2.0	0.22	3.6	1.3	0.39
	RF	1.0	2.1	0.14	2.6	1.1	0.55
Shinyalu	HG	1.2	14.0	0.53	8.0	2.7	0.49
	CF	1.9	6.6	0.32	6.4	2.1	0.29
	MF	1.6	4.0	0.35	6.5	2.0	0.39
	RF	1.3	2.7	0.28	6.1	2.6	0.44
Aludeka	HG	0.3	2.5	0.28	2.4	0.7	0.18
	CF	0.6	5.6	0.44	3.9	0.8	0.25
	MF	0.6	2.9	0.25	2.9	0.9	0.26
	RF	0.5	2.3	0.15	2.3	0.7	0.28
Site * Field type (P value)		0.073	ns	0.007	ns	ns	ns
SED (general)		0.2	7.1	0.15	0.8	0.4	0.18
SED (field types)		0.1	4.1	0.09	0.5	0.2	0.11
SED (sites)		0.1	3.1	0.07	0.3	0.2	0.07

HG: home gardens; CF, MF and RF: close, mid-distance and remote fields; SED: standard errors of the differences

In Emuhaia, N content decreased from the home gardens towards the remote fields, though the close and mid-distant fields did not differ significantly ($P < 0.05$) from each other (Table 4.1.6). The home gardens in Shinyalu had similar total N contents as in Emuhaia, but in contrast, they had the smallest N contents when compared with other field types, and a significant ($P < 0.05$) decrease was found from the close to the remote fields. A similar trend was also observed for Aludeka, which would be due the fact that ash is the major nutrient input for the home gardens in these sites (see below). Distance from the homestead and accessibility seem to play a major role in N distribution within the farm in Shinyalu, where the topography is steeper, and in Aludeka, where farms are larger. In Emuhaia, the home gardens are more intensively managed than in the other sites (most nutrient resources are applied to them) and have a more important contribution to the household needs (see Chapter 3, Resource flow maps).

No significant ($P < 0.05$) differences were found between sites for the average extractable P values (Table 4.1.6). The concentration effect within the farm and near the homestead referred to for total N was clearer in the case of extractable P since, in spite of being present in ash inputs, this nutrient is more prone to be accumulated in the soil as a result of management. Nutrients from the farther fields are brought to the home gardens through crop residues and cattle manure, creating concentration areas within the farm. Differences in soil pH may also explain this variation especially for the highly weathered soils of Emuhaia and Shinyalu, where the highest amounts of P where extracted from topsoil samples that showed average pH values > 5.5. On the other hand, the values of extractable P together with those for pH and cations, are also indicating the effect of ash inputs in the home gardens, as revealed by the resource flow maps.

Only the home gardens of Emuhaia and Shinyalu showed soil P availability values that, in spite of being outstanding from the rest, are similar to or just above the threshold level for response to P fertilisation of 15 mg kg^{-1} (FURP, 1994). In general, P concentrations decreased from the close towards the remote fields although in all cases they were very to extremely low (Table 4.1.6). As reflected by the resource flow maps (Chapter 3) composted crop residues and manure, together with ashes, kitchen wastes and house sweepings that normally contain chicken manure are applied to high value crops in the home gardens. In Aludeka, the home gardens are not managed as in the other sites, and nutrient demanding crops that are produced on the natural soil fertility are seasonally moved from one spot to another within the farm. The close fields (i.e. grain production fields that are next to the home garden) often receive P-containing fertilisers, particularly di-ammonium phosphate (18: 46: 0), though the soil P concentrations shown here do not seem to reflect that. However, the soil P concentration might not be a good indicator due to the P-fixing capacity of these soils.

Exchangeable K levels were not significantly ($P < 0.05$) different from site to site but varied across field types, showing a negative gradient from the home gardens towards the remote fields in most cases (Table 4.1.6). However, a highly significant ($P = 0.007$) interaction site* field type was observed. In Emuhaia, the home gardens showed significantly ($P < 0.05$) higher levels of exchangeable K than the other field types and, as in Aludeka, a gradual decrease was found from the close to the remote fields. Although the home gardens in Shinyalu showed the highest values, no significant differences were found between fields, and the remote fields showed values two times higher than in the other sites.

Both exchangeable Ca and Mg showed significant differences between sites although only the former varied significantly across field types (Table 4.1.6). Average Ca and Mg concentrations were between two and three times higher in Shinyalu than in Emuhaia and Aludeka, respectively, and the highest average values were shown for the home gardens and the close fields in all sites. However, this trend was not always as clear as for other nutrients and values shown by remote fields were similar to the close fields in certain cases. As the level of exchangeable cations decreased the charges provided by the clay and organic fractions were increasingly saturated with H+, as reflected in the higher exchangeable acidity found in the remote fields.

Soil fertility indicators and nutrient concentrations varied quite consistently between land quality classes in all sites, as indicated in Table 4.1.7 for the most relevant soil properties. Again, one of the most important criteria to distinguish between good and poor quality land in Shinyalu and Emuhaia was the topographic slope due to soil erosion. Texture was the main one in Aludeka though due to the large differences in the clay plus silt fraction between sites, the different land quality classes did not differ significantly ($P < 0.05$) in clay + silt content within each site.

Organic carbon content showed significant differences between sites and land quality classes, and a marginally significant interaction between factors (Table 4.1.7). Whereas in Emuhaia and Aludeka it decreased from 'Fertile' to 'Poor' fields, in Shinyalu it showed no differences between land quality classes. Soils of somewhat coarser texture would show more favourable physicochemical properties with a 20 – 30% increase in the organic carbon content – as the difference between Poor and Fertile in the former two sites – that is likely to explain why farmers regard them as different land quality. For the finer soils of Shinyalu, ranging around 1% of organic matter, the effect of small increases in soil C was not significant enough so as to generate differences in land quality that can be identified by farmers. Therefore, either relatively low or high values of soil C could be measured within each land quality class in this site. Due to similar though complementary reasons the slightly lower clay and organic C contents in the Poor fields of Aludeka explain the significantly ($P < 0.05$) lower effective cation exchange capacity they showed compared to that of the Fertile fields.

Table 4.1.7: Inherent and actual soil and landscape properties for different land quality classes according to farmers' criteria (n = 141) in the three working sites.

Site / Land quality	Field slope (%)	Clay + Silt (%)	SOC ($g\ kg^{-1}$)	ECEC ($cmol_{(+)}\ kg^{-1}$)	pH	Total N ($g\ kg^{-1}$)	Extr. P ($mg\ kg^{-1}$)	Exch. K ($cmol_{(+)}\ kg^{-1}$)
Emuhaia								
Fertile	3.7	50.8	12.5	5.1	6.0	1.3	13.7	0.53
Average	3.1	51.0	11.6	4.8	5.4	1.1	1.8	0.26
Poor	8.2	51.8	10.9	4.5	5.2	1.2	1.6	0.25
Shinyalu								
Fertile	5.9	78.1	17.8	9.3	5.4	1.5	9.7	0.42
Average	11.4	78.0	17.8	8.6	5.3	1.7	3.6	0.37
Poor	21.0	76.1	17.7	9.1	5.2	1.4	2.3	0.27
Aludeka								
Fertile	1.3	43.8	9.4	4.7	6.1	0.6	9.2	0.67
Average	1.2	42.2	8.7	3.3	5.6	0.5	3.3	0.34
Poor	1.1	38.3	7.3	2.9	5.1	0.4	1.4	0.13
SED (site)	1.27	1.47	0.45	0.48	0.1	0.08	3.09	0.07
SED (LQ)	1.27	1.48	0.45	0.52	0.1	0.08	3.08	0.07
Site * LQ interaction (p value)	0.001	ns	0.048	ns	0.043	ns	ns	ns

SOC: soil organic carbon; ECEC: effective cation exchange capacity; SED: standard errors of the differences; LQ: land quality

The pH of the topsoil reflected differences in soil fertility as recognised by farmers very consistently in Aludeka, to a lesser extent in Emuhaia, but not in Shinyalu (Table 4.1.7). Total N did not differ significantly ($P < 0.05$) whereas extractable P and exchangeable K showed highly significant ($P < 0.01$ and $P < 0.001$, respectively) differences between land quality classes in all sites. Fields classified as Fertile had much higher levels of extractable P than the Average and Poor in all sites, though in none of them the critical value of 15 $mg\ kg^{-1}$ was reached. Indeed, land quality classes showed differences in P depletion between the 'Fertile' fields and the rest. For exchangeable K, the differences between land quality classes were more important in Aludeka, followed by Emuhaia and almost no differences were found in Shinyalu. However, both P and K were, among the macronutrients, the most conspicuous in terms of differentiating land qualities.

Management factors affecting maize growth in the different fields

Significantly different values for the variables grouped within management factors (MF) were found across field types and land quality classes in all sites (Tables 4.1.8 and 4.1.9). Farmers tended to plant all fields of the farm at the same time in Shinyalu compared with the other sites. Plant densities used in Aludeka were significantly ($P < 0.05$) the least. Weed infestation levels did not differ across sites but rather across field types. Specifically for *Striga* spp. infestations, the highest levels were observed in Emuhaia, followed by Aludeka, and no infestation was observed in Shinyalu.

Table 4.1.8: Average values of the variables grouped as management factors for the different field types across sites (n= 177)

Site	Field type	Management factors				DHI
		PDI	PP (pl m^{-2})	Weed score	*Striga* score	
Emuhaia	HG	0.19	2.47	0.50	0.08	0.13
	CF	0.31	2.41	0.87	0.68	0.27
	MF	0.34	2.33	1.30	0.95	0.47
	RF	0.40	2.22	1.53	0.77	0.77
Shinyalu	HG	0.24	2.27	0.91	0	0.12
	CF	0.23	2.83	0.83	0	0.27
	MF	0.31	2.11	1.63	0	0.55
	RF	0.30	1.85	1.57	0	0.80
Aludeka	HG	0.19	1.61	0.40	0.00	0.11
	CF	0.27	1.91	1.25	0.19	0.24
	MF	0.39	1.58	1.25	0.25	0.46
	RF	0.69	1.60	1.90	0.82	0.67
Site * Field type (*P* value)		0.038	0.066	ns	0.062	ns
SED (general)		0.096	0.196	0.339	0.257	0/036
SED (field types)		0.055	0.114	0.196	0.149	0.021
SED (sites)		0.046	0.094	0.162	0.123	0.018

PDI: planting date index; PP: plant population; Weed and *Striga* scores: 0 = absent, 1 = low, 2 = medium, 3 = high; DHI: distance from homestead index; SED: standard error of the differences

The home gardens and the close fields tended to be planted earlier, with a higher plant density and showed lower incidence of weed and particularly of *Striga* spp. infestations than the mid-distance and remote fields (Table 4.1.8). Their proximity to the homestead is reflected in the values of the Distance from Homestead Index (DHI[4]) which ranged around 0.12 and 0.26, respectively, for all sites. The average DHI across sites for the mid-distance and remote fields were 0.49 and 0.75, respectively.

A significant interaction was observed for the relative delay in planting date, the planting date index [*PDI = (actual planting date – optimum planting date)/ optimum planting date*]. Maize was planted slightly earlier in the home gardens in Emuhaia and Aludeka than in Shinyalu, where almost all fields are planted at the same time and with a relative delay (PDI) between 0.3 and 0.4 with respect to the recommended optimum date. While in all sites fields were planted in the sequence HG - CF - MF - RF, the latter were planted relatively much

[4] The distance from the homestead index (DHI) relates the distance from the measuring point with the average maximum distance that can be measured within the farm, as explained in Chapter 2.

later in Aludeka than in the other sites. The relative delay in the planting date between CF and MF, which are the two main fields in terms of their contribution to the household grain production (see Chapter 3, Resource flow maps), was of only 0.03 in Emuhaia, of 0.08 in Shinyalu and of 0.12 in Aludeka. Such a pattern may result from the clear differences in land size and labour availability between sites.

Table 4.1.9: Average values of the variables grouped as management factors for the different land quality classes as recognised by farmers across sites (n= 184)

Site	Land quality class	Management factors				DHI
		PDI	PP (pl m^{-2})	Weed score	Striga score	
Emuhaia	Fertile	0.31	2.43	0.70	0.26	0.32
	Average	0.32	2.40	1.19	0.76	0.47
	Poor	0.47	2.16	1.65	1.24	0.60
Shinyalu	Fertile	0.24	2.62	0.85	0	0.23
	Average	0.26	2.09	1.45	0	0.53
	Poor	0.34	1.93	1.69	0	0.69
Aludeka	Fertile	0.30	1.73	0.91	0.14	0.28
	Average	0.36	1.76	1.38	0.19	0.40
	Poor	0.56	1.57	1.72	0.67	0.56
Interaction Site * Land quality (P value)		ns	0.06	ns	0.02	ns
SED (general)		0.08	0.16	0.28	0.20	0.06
SED (land quality)		0.05	0.09	0.16	0.12	0.04
SED (sites)		0.05	0.09	0.16	0.12	0.04

PDI: planting date index; PP: plant population; Weed and Striga scores: 0 = absent, 1 = low, 2 = medium, 3 = high; DHI: distance from homestead index; SED: standard error of the differences

When fields were grouped according to farmers' land quality criteria a clear association with management factors was identified (Table 4.1.9). Fields classified as 'Poor' were planted significantly ($P < 0.01$) later than 'Fertile' and 'Average' fields, had less dense stands[5], and higher weed and *Striga* spp. infestation levels (except for Shinyalu where no *Striga* infestation was observed). Weed type and weed infestation, however, may be considered either as a cause or as a consequence of poor quality land. The Fertile fields were normally those close to the homestead, the Average fields were at intermediate distances and the Poor fields were the furthest, with average DHI values of 0.28, 0.47 and 0.62, respectively. Moreover, distance from the homestead was often one of the reasons given by farmers to explain differences in crop performance in different fields. The reasons included, for example, the labour required to carry organic fertilisers to distant fields or their difficult access or workability when they have to be ploughed (in Shinyalu and to some extent in Emuhaia, furthest fields are also the steepest). These observations indicate that management factors are inextricably related to (farmer perceived) land quality in general, and to soil fertility in particular (cf. Tables 4.1.6 and 4.1.7).

[5] Plant density was measured at the end of the season and therefore less dense stands may also reflect failures during the establishment phase. However, farmers tended to adapt plant spacing to lower densities in poorer fields.

4.2 Statistical models to explain maize yield variability

4.2.1 The performance of individual factors[6] as explanatory variables

In general, maize yield variability was not satisfactorily explained by any individual factor but rather by combinations of factors. However, some exceptions appeared in which one factor could explain around 50% of the variance (e.g. extractable P in Aludeka). Among the inherent and actual soil and landscape properties, the topographic slope of the fields, the soil contents of C and N and the availability of P showed rather weak[7] but interesting relationships with maize yield estimates (Figure 4.2.1 A-D and Table 4.2.1).

The best models to explain the decrease of maize yield with increasing field slope were exponential declines, though with weak determination coefficients. A wide range in maize yields could be measured in the flatter fields of Emuhaia and a rapid decrease in the range of yields as well as in the absolute yields was found in fields with slopes higher than c. 10% (Fig. 4.2.1 A). This decline was less abrupt for Shinyalu where yields of almost 1 t ha^{-1} could be measured in fields with up to 30 – 40% slopes. Unlike in Emuhaia, practically no field with less than 5% slope showed yields below 1 t ha^{-1} in Shinyalu. There seems to be a lower threshold field slope for Emuhaia than for Shinyalu, from which yields start declining due to – as indicated by farmers – runoff, lower infiltration and/or soil losses by erosion. In principle, this threshold could be related to soil properties such as texture or C content, or to farmers' management strategies to control erosion at each site. However, these single-factor responses should be interpreted with caution due to the simultaneous effects of the many other factors affecting maize growth, and to the association between field slope and distance from the house (see later), which eventually affects crop management.

The relationship between maize yield and soil organic carbon was weak for Emuhaia and for Shinyalu but it explained about 30% of the variance in Aludeka (Fig. 4.2.1 B and Table 4.2.1). All regression lines (soil C vs. maize yield) intercepted the x-axis at C content values around 1 to 3 g kg^{-1}soil. The range of C content in soils of Emuhaia and Aludeka was narrower - around 10 g kg^{-1}soil - and between lower values compared with the soils of Shinyalu. However, when soil C increased the greatest increase of maize yields was observed for Emuhaia followed by Aludeka (Table 4.2.1). In the relatively more sandy soils of Aludeka and in the intensively cropped soils of Emuhaia these soil C ranges might still have an important effect on other soil properties (e.g. water holding capacity, soil compaction).

In Shinyalu soil C contents were always below 20 g kg^{-1}, a small value for soils of such clay content. This would imply that even by doubling the amount of C from the lower to the upper limit of the range found here (c. 10 – 20 g kg^{-1}) crop performance would not be significantly affected, since the absolute C content is still very low. Feller (1995) indicated a C saturation potential ranging between 20 and 40 g kg^{-1} for tropical soils with similar clay contents than those of Shinyalu, under several land use and management histories. However, the highest yields were always measured in the upper side of the soil C range, which might be due to the effect of soil C on other processes such as soil erosion. For instance, when the higher soil C points (approximately above 15 g kg^{-1} soil) were discarded from the data pool

[6] Maize yields are plotted here against single factors – variables – to visualise their distribution, using statistical models to show how much of the yield variability can be explained by several single factors.

[7] All regressions were statistically significant ($P < 0.01$)

the field slope explained up to about 40% of the variability in maize yield in Shinyalu (data not shown).

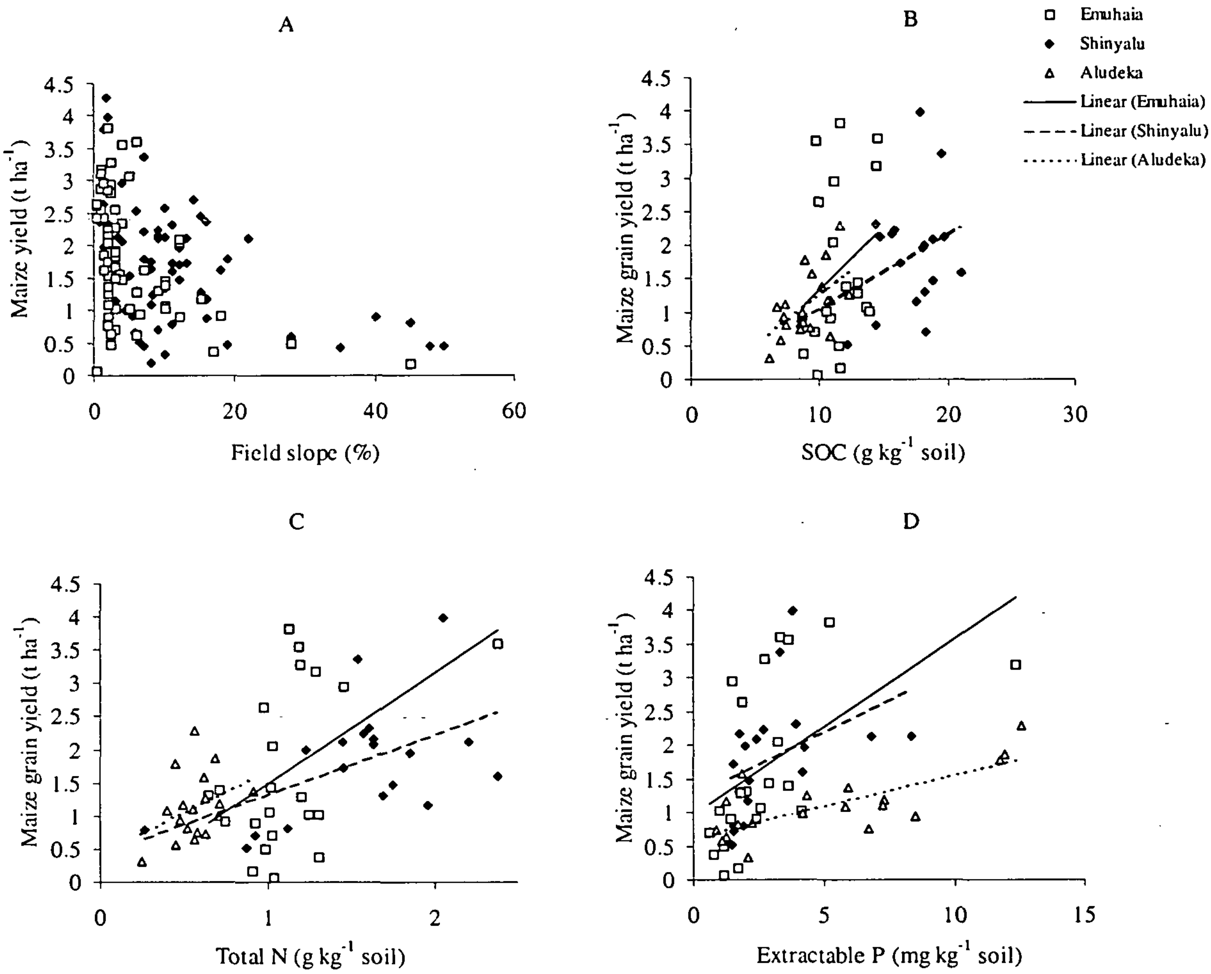

Figure 4.2.1: Individual soil and landscape properties used to explain maize yield variability at three working sites in western Kenya. A: maize yield vs. topographic slope of the fields from where samples and maize measurements where taken, data form Aludeka is not shown due to its narrow range; B, C and D: maize yields vs. soil organic carbon (SOC), total nitrogen and extractable phosphorus (modified Olsen), respectively. The equations of the regression lines (B, C and D) are given in Table 4.2.1.

The narrow soil C ranges that might be the result of both inherently lower clay content and more intense soil depletion imply that soil C would not be enough to explain the gradients in crop performance as affected by soil fertility. However, due to its co-variance with other soil properties, soil C remains as a key factor to explain yield variability through multiple term regression models, as will be shown later. The amplitude of soil C ranges was also reflected in that of total N (Fig. 4.2.1 C). In Emuhaia and Aludeka yields fluctuated widely between narrow ranges of soil N, respectively around 0.5 and 1 g kg^{-1} soil, whereas in Shinyalu yields were below 1 t ha^{-1} when total N was lower than 1 g kg^{-1} soil. Between 20 and 30% of the variability in maize yields was explained by total N in Emuhaia and Shinyalu and only 13% in Aludeka (Table 4.2.1). Again, the slope of the relationship between total N and maize yield was higher for Emuhaia and Aludeka compared with Shinyalu. As a factor to explain yield variability total N showed almost the same trends and response patterns as soil C. However, it appeared as more explanatory than soil C in Emuhaia.

Extractable P showed wider ranges for Shinyalu and Aludeka and, except for one point, narrower for Emuhaia (Fig. 4.2.1 D). The linear regression models explained between 20 and 50% of the variability in maize yield (Table 4.2.1) though the best equations to fit the points were polynomial of second (Emuhaia and Shinyalu) and of third (Aludeka) order, explaining 54, 43 and 69% of the variance, respectively (Appendix 4.2.1). However, due to the large amount of variability (from other sources) under these non-controlled experimental conditions, the interpretation of such polynomial equations might suggest misleading conclusions. For instance, for Emuhaia and Shinyalu the maximum yields according to the quadratic curves are attained at extractable P levels of 10 and 5 mg kg^{-1} soil, respectively, much below the generally accepted response threshold for maize. Considering again the linear regressions a much lower slope was found for the relationship between yield and extractable P for Aludeka, compared with the other sites (Table 4.2.1).

Table 4.2.1: Linear regression equations relating different soil properties to maize yield (t ha^{-1}). n = 60

Response variable	Explanatory variable	Site	Intercept	Slope	R^2
Maize yield	SOC	Emuhaia	-0.58	0.19	0.08
		Shinyalu	-0.10	0.11	0.15
		Aludeka	-0.23	0.15	0.31
	Total N	Emuhaia	-0.17	1.67	0.23
		Shinyalu	0.43	0.90	0.26
		Aludeka	0.42	1.27	0.13
	Extractable P	Emuhaia	0.75	0.28	0.37
		Shinyalu	1.22	0.20	0.18
		Aludeka	0.64	0.09	0.55

SOC: soil organic carbon

Crop growth limitation by N and P was recognised for Vihiga district (i.e. Emuhaia) in previous works (Crowley and Carter, 2000; FURP, 1994; Shepherd *et al.*, 1997). Strong responses to both N and P have been observed in multi-year experiments in Kakamega (25 km N of Shinyalu) and in Maragoli (Vihiga district, bordering Emuhaia to the North) on the same soil types (FURP, 1994). Rock phosphate applications together with cattle manure and compost improved crop performance when compared with applications of the organic resources alone at farmers' fields in Shinyalu (Rotich *et al.*, 1999) and under experimental conditions in Emuhaia (Palm *et al.*, 1997). For Aludeka, the little evidence available indicates more variable results. Strong responses to N and both strong and weak responses to P application to maize were reported at Alupe Experimental Station (40 km S of Aludeka) on a deep Ferralo-orthic Acrisol (FURP, 1994). In addition, the range of extractable P in the topsoils sampled here was much wider and with a higher median value for Aludeka than for the other sites, as was shown in Chapter 3 (Range of soil properties). This might also contribute to explain the less steep slope of the regression model for this site (Table 4.2.1).

Maize yields tended to decrease as the distance from the homestead increased. Therefore, the distance from the homestead index (DHI: relating the distance of a particular field to the maximum distance determined by farm size) explained part of the variation found in maize yields (Figure 4.2.2 A). In Emuhaia, where the average land size per farm was smaller this factor had less influence than in the other places, as reflected by the lower determination coefficients and regression slopes of the equations relating DHI with maize yield (Table 4.2.2).

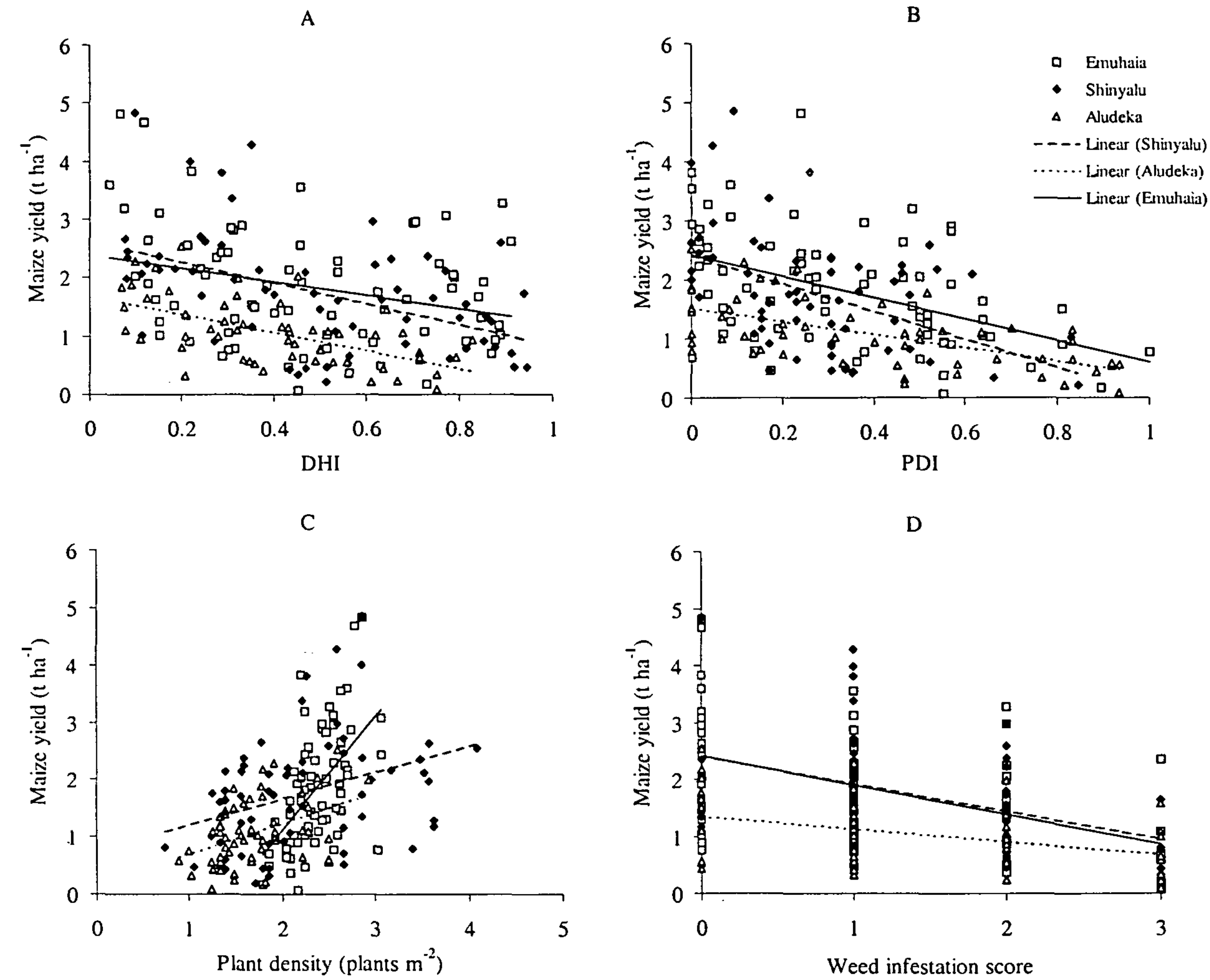

Figure 4.2.2: Individual management factors used to explain maize yield variability at three working sites in western Kenya. A: maize yield vs. distance from the homestead index (DHI); B: maize yield vs. planting date index (PDI): C: Maize yield vs. plant density and D: maize yields vs. weed infestation score. The equations of the regression lines are given in Table 4.2.2.

Among the management factors, planting date (PDI: planting date index) explained almost 40% of the variation under the drier conditions of Aludeka, and only 15 – 20% for the other sites (Fig. 4.2.2 B and Table 4.2.2). However, the highest rate of decrease in maize yield when the planting date was retarded was found at Shinyalu, where rainfall variability played a major role in yield security (FURP, 1994). Planting date appeared as an important management factor affecting maize yield, as can be seen in Figure 4.2.2 B where few yields fell below 1 t ha^{-1} when the crops were sown on time, with PDI lower than 0.2 (about 10 – 15 days of delay).

Table 4.2.2: Linear regression equations relating the distance from the homestead index (DHI) and different management factors to maize yield (t ha^{-1}) n = 193

Response variable	Explanatory variable	Site	Intercept	Slope	R^2
Maize yield	DHI	Emuhaia	2.39	-1.15	0.08
		Shinyalu	2.63	-1.78	0.23
		Aludeka	1.70	-1.55	0.34
	PDI	Emuhaia	2.42	-1.82	0.22
		Shinyalu	2.41	-2.36	0.21
		Aludeka	1.51	-1.12	0.37
	Plant density	Emuhaia	-2.91	2.01	0.31
		Shinyalu	0.74	0.46	0.13
		Aludeka	0.16	0.54	0.18
	Weeds	Emuhaia	2.42	-0.52	0.24
		Shinyalu	2.40	-0.48	0.13
		Aludeka	1.36	-0.22	0.16

PDI: planting date index

The range of plant densities observed in Emuhaia was much narrower (between 2 and 3 plants m^{-2}) than in the other sites (Figure 4.2.2 C). As for other factors, yields lower than 1 t ha^{-1} were found under the whole range of plant densities, but high yields (e.g. > 3 t ha^{-1}) were only found when the number of plants per m^{-2} was approximately above 2. Towards the end of the cropping season the number of maize plants per area may be the result of a low planting density, a higher proportion of pulses in the intercrop or crop failures due to several reasons. Plant density explained about 30% of the yield variability in Emuhaia and 20% in Aludeka (Table 4.2.2), but in the former it showed a much steeper relationship with maize yield than in the other sites. The stronger effect of plant density in Emuhaia could be related to the higher weed - and *Striga* spp. – infestation levels observed in this site compared with the others.

The degree of weed infestation measured through a score from 1 to 3 explained 24% of the yield variability in Emuhaia (Table 4.2.2). The effect of increasing weed infestation was the same as for Shinyalu but stronger than in Aludeka. *Striga* spp. infestation (data not shown) showed a similar pattern than weed infestation for Emuhaia and Aludeka (no *Striga* infestation was recorded in Shinyalu). In both cases, a wider range of yields could be attained as a result of other sources of variability when the infestation level was low, but under intense weed and/or *Striga* infestation yields always decreased, in all sites (Figure 4.2.2 D). However, the interaction between weed type and level and soil properties or other management factors makes it difficult to use weed infestation as an explanatory variable in a multiple term model, unless little co-variance with other factors is observed.

The distance from the homestead (normalised as an index, DHI) did not affect maize yields by itself but due to its association with other management factors (see Chapter 3, Resource flow maps and previous sections of the present Chapter), soil and landscape properties (Figure 4.2.3 A – D and Table 4.2.3). In Emuhaia and particularly in Shinyalu the steeper fields were those located at farther distances from the homestead (Figure 4.2.3 A). However, field slopes of around 10% were found at relatively close distances from the homestead in Shinyalu. The organic carbon and total nitrogen contents in the topsoil were higher near the homestead and tended to decrease at a higher rate with the distance in Emuhaia and Shinyalu than in Aludeka (Fig. 4.2.3 B and C). For extractable P the distance from the homestead explained 20% of the variability in Emuhaia but only 7 and 12% in Shinyalu and Aludeka, respectively, due to the large dispersion observed (Figure 4.2.3 D and Table 4.2.3). This dispersion was particularly important in Aludeka due to the high variability in soil types across short distances (See Chapter 2, Farm transects).

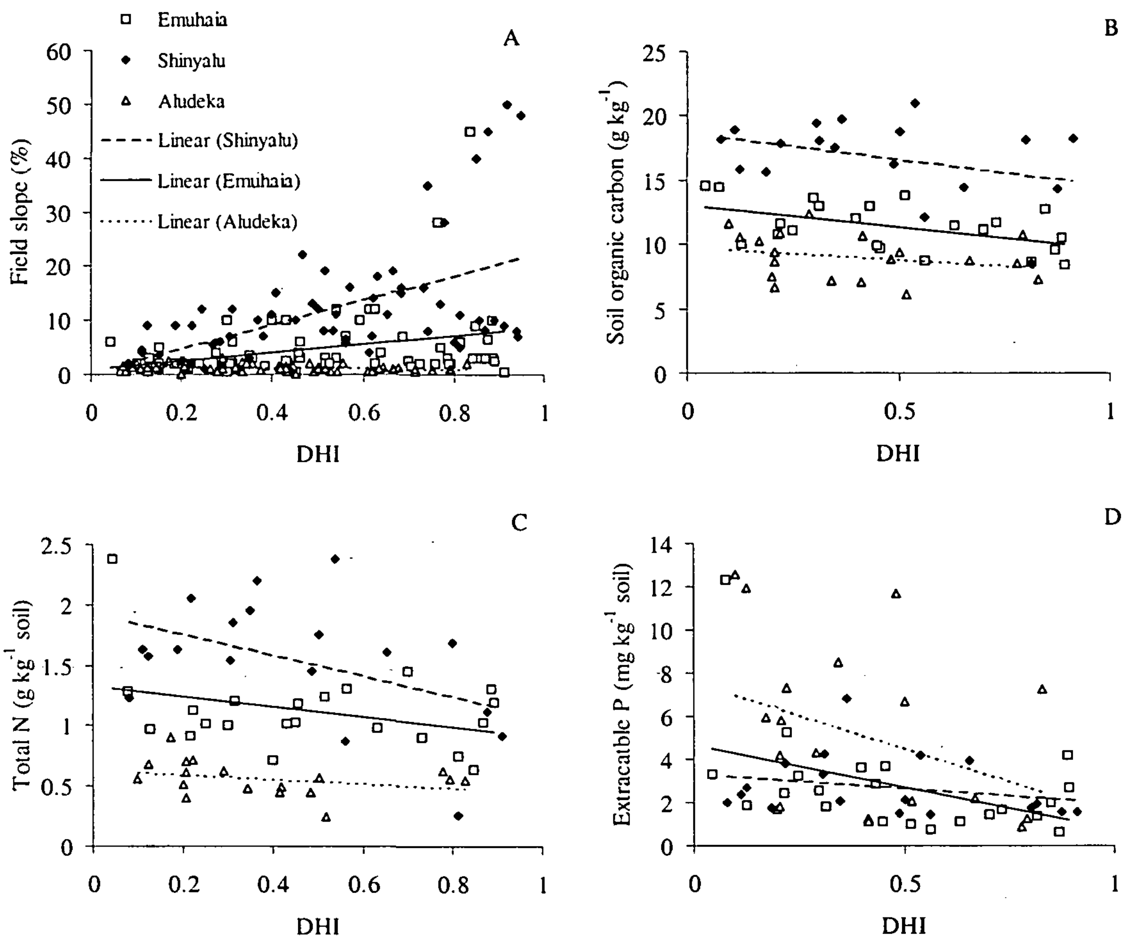

Figure 4.2.3: Selected soil and landscape properties at different distances from the homestead in small farms from three different sites in western Kenya. A: distance from the homestead index (DHI) and the slope of the fields from where the samples and maize measurement were taken; B, C and D: Soil organic carbon, Total N and extractable P vs DHI. The equations of the regression lines are given in Table 4.2.3.

Soil and management variables (some of them presented above) were used for the construction of multiple regression models to explain maize yield variability at site scale (see below). Using linear regression as the simplest method available - while keeping a good degree of accuracy - gave satisfactory relationships for different individual factors with maize yield. Though some relationships were better explained by non-linear regression models, the difference in the amount of variance explained was not substantially larger. Appendix 4.2.1 shows the determination coefficient of the best non-linear regression found for each factor. The multiple term explanatory models for maize yield variability were built as multiple linear regression models.

Table 4.2.3: Regression equations relating the distance from the homestead index (DHI) to different soil properties n = 60

Response variable	Explanatory variable	Site	Intercept	Slope	R^2
SOC	DHI	Emuhaia	13.0	-3.35	0.25
		Shinyalu	18.7	-4.29	0.15
		Aludeka	9.8	-1.89	0.06
Total N	DHI	Emuhaia	1.3	-0.41	0.11
		Shinyalu	1.9	-0.85	0.20
		Aludeka	0.6	-0.18	0.09
Extractable P	DHI	Emuhaia	4.7	-3.95	0.20
		Shinyalu	3.3	-1.34	0.07
		Aludeka	7.5	-5.78	0.12
Topographic slope	DHI	Emuhaia	1.1	7.43	0.10
		Shinyalu	0.6	22.10	0.31
		Aludeka	1.5	-0.76	0.06

SOC: soil organic carbon

So far, maize yield variability was explained to a different extent by a number of factors that were not the same from site to site. On the other hand, certain factors such as distance from the homestead and *Striga* spp. infestation are likely to vary across sites. As discussed in the previous section, the intercept of the regression equations shows that yields in Aludeka were lower than in the other sites even when the crop was planted near the homestead, around the optimal planting date and kept free of weeds (Table 4.2.2). These regional differences, which may have several other underlying reasons behind (e.g. rainfall, varieties, cultural practices), were too wide so as to consider the pooled data for the three sites in the construction of explanatory models (See Chapter 2, Statistical methods). Therefore, a site by site analytical approach was adopted in the following section.

4.2.2 Combination of soil fertility and management factors into multiple regression models

The best model to explain maize yield variability varied from site to site in terms of the explanatory variables involved and their relative weight (Tables 4.2.4, 4.2.5 and 4.2.6). The amount of maize yield variability explained by soil fertility variables was larger, smaller or the same than that explained by management factors for the different sites. The number of variables needed to build the models also varied from site to site. Appendix 4.2.2 – I shows the outcome of the analytical program with the complete set of variables included, their coefficients in each model, and the different steps of the model selection for each site. Appendix 4.2.2 – II gives the complete correlation matrixes for all the variables included in the analysis. Soil fertility and management variables to be included in the multiple regression models were selected by considering their correlation between each other, discarding those that were highly correlated (see below). For example, exchangeable Ca and exchangeable bases showed a high co-variance (a correlation coefficient > 0.9) between them and with the effective exchange capacity in all sites. Therefore, only the latter was included in the models.

Some interesting results from the correlation analysis are presented first, followed by the selected set of variables included in the best regression models to explain maize yield using soil fertility and management factors (and their combination). In the following section, an estimation of the resource use intensity (RUI) and a summarising soil fertility index (SFI) are discussed and included in the regression models.

Correlation between variables

Variables selected for explaining maize yield variability in the different sites were in general weakly correlated (Appendix 4.2.2 – II a, b and c). By using the *Best subset selection* option of GenStat 6th, variables that showed higher correlation with one another were automatically left out by the program. However, such correlation may, in certain cases, give valuable information about the interaction between the different factors affecting maize performance and its variability within a farm.
In Emuhaia *Striga* spp. infestation showed a moderately poor, negative correlation with all soil properties except for the C:N ratio, which was very low, and exchangeable acidity that was positive (Appendix 4.2.2 – II a). As expected, the latter showed a certain degree of negative correlation with pH, and with exchangeable Ca and bases that were in turn highly correlated between each other. Extractable P was positively correlated with pH, and therefore also with exchangeable bases and Ca. Extractable P showed also a moderate positive correlation with total P, which was also correlated positively with pH and exchangeable bases. Plant density and planting date were negatively correlated, indicating either that farmers chose for lower plant populations when the crop was delayed – in agreement with what they expressed - or that late crops were more prone to failures that could reduce the stand, or both. However, 70% of the variability in maize yield in Emuhaia could be explained with a model that included extractable P in combination with planting date and plant density (see later). These delayed crops had also higher *Striga* infestation, as seen in the field and indicated by the correlation coefficients.
Soil C was positively correlated with most soil variables in Shinyalu, which in this case included the macronutrients N, P K and Ca (Appendix 4.2.2 – II b). As for Emuhaia, the effective cation exchange capacity, the pH and the exchangeable Ca, acidity and bases were highly correlated. Planting date and distance from the homestead were negatively correlated with most soil variables but showed no correlation between them. Distance from the homestead showed also a positive correlation with the topographic slope, with the C:N ratio and with the weed infestation level and a negative correlation with total P. Weed infestation was moderately and negatively correlated with total N (and positively with the C:N and C:P ratios), and weakly but positively correlated with plant density and distance from the homestead. No *Striga* infestation was recorded in Shinyalu (score = 0).
The correlation between the variables selected for the explanatory models for Aludeka showed a similar pattern than for Emuhaia. Extractable P and the variables related to soil reaction and buffer capacity (i.e ECEC, exchangeable Ca, pH) were positively correlated between them (Appendix 4.2.2 – II c). As in Shinyalu, soil C showed a positive correlation with all soil variables, including macronutrients, effective cation exchange capacity and pH. The distance from the homestead was positively correlated with weed infestation level and negatively correlated with plant density in Aludeka (Appendix 4.2.2 – II c). Weed infestation was negatively correlated with most soil factors, which could be due to its association with distance from the homestead (DHI). However, weed infestation was more closely correlated with most soil variables than with DHI, suggesting that fields perceived to

be poor are weeded later or not weeded at all. *Striga* infestation showed no significant correlation with any of the other variables in this site.
Delayed planting and/or lower plant densities were generally associated with lower soil fertility and/or poor land quality, reinforcing the idea of concomitant 'management intensity gradients' along with the soil fertility gradients. This was revealed by the correlation between these variables with the C:N ratio, exchangeable bases and acidity and total P in Emuhaia, with soil C and total N in Shinyalu and with soil C, pH, ECEC, exchangeable K and Ca, extractable P and weeds in Aludeka. However, the distance from the homestead showed almost no correlation with planting date. This would suggest that farmers decide where to plant first according to perceived land quality rather than to the distance from the homestead.

Multiple regression models

The multiple regression models were built stepwise, by considering only soil fertility variables, only management factors and both of them combined (Tables 4.2.4, 4.2.5 and 4.2.6, respectively). Models including correlated variables were not considered since, in spite of slightly increasing the amount of variance explained, they were not meaningful.
When only soil properties were included as explanatory variables the best model was achieved with 6 terms[8] in Emuhaia, with 4 terms in Shinyalu and with only 2 in Aludeka (Table 4.2.4). Up to 75% of the variability in maize yields was explained by soil fertility variables in Emuhaia (Table 4.2.4) with a model that included a broad span of soil properties ranging from organic matter quality to exchangeable bases and P stocks and availability. However, exchangeable Ca and acidity showed a moderate degree of negative correlation between them. In Shinyalu, the best model explained only one third of the variation and included soil C and P availability, plus exchangeable K and Ca. However, a model including total N and the sum of exchangeable bases in addition to soil C and extractable P explained almost the same amount of the variability found in this site. In Aludeka, two thirds of the variation were explained by soil C and P availability and reasonably accurate models were obtained when also exchangeable bases like K and Ca were included.
The groups of variables included in these models show a clear predominance of C, N, P and K among the soil variables that better explained yield variability in all sites. In Emuhaia, the site with the highest population density (i.e the smallest average farm size), most of the crop variability was explained by soil fertility variables. Variables such as pH explained one fourth of the variation in maize yield in this site (Appendix 4.2.2 – I), though due to its correlation with exchangeable acidity and/or Ca, it did not appear in the multiple term models. Exchangeable acidity explained 35% of the variation and was moderately to highly correlated with other soil (e.g. Ca, ECEC) and management (e.g. PDI, plant density, weed infestation) variables (Appendix 4.2.2 – II a).
Total N and the C:N ratio were the soil properties that explained most of the maize yield variability as individual variables in Shinyalu (Appendix 4.2.2 – I). Both variables were correlated with each other and with soil C, total P and, to a lesser extent, with extractable P (see above). However, maize yield variability could not be satisfactorily explained with soil fertility variables for this site. Extractable P and soil organic C explained as individual variables more than 50 and 30% of the yield variation in Aludeka, respectively (cf. Table 4.2.1). A positive correlation has been indicated for extractable P with exchangeable bases

[8] The amount of variance explained in Emuhaia increased slightly when the sum of bases was included in a 7-term model (Appendix 4.2.2 – I). However, this variable is highly correlated with variables such as Ca.

and pH, and a negative correlation with the degree of weed infestation (see above). Soil C was positively correlated with the sum of the clay and silt fractions and with most soil properties, and negatively correlated with management factors such as planing date and plant density (see above and Appendix 4.4.2 – II c), as indicated before.

Table 4.2.4: Selected subsets of soil variables included in multiple regression models and the percentage of the variance explained by them. Up to 12-term models were developed but only the most significant are presented (for the number of points in each analysis see Table 2.6.2)

Site	Best subsets of explanatory variable/s	% of variance explained
Emuhaia	C:N ratio + K_{exch}	53.4
	C:N ratio + K_{exch} + H_{exch}	67.1
	C:N ratio + K_{exch} + H_{exch} + C:P ratio	72.9
	K_{exch} + H_{exch} + C:P ratio + Nt + SOC	73.7
	C:N ratio + C:P ratio + Ca_{exch} + P_{extr} + K_{exch} + H_{exch}	74.8
Shinyalu	Nt + $Bases_{exch}$	30.6
	Ca_{exch} + P_{extr} + SOC	32.5
	Ca_{exch} + P_{extr} + K_{exch} + SOC	33.3
Aludeka	P_{ext} + SOC	66.1
	P_{ext} + SOC + K_{exch}	64.8
	P_{ext} + SOC + K_{exch} + Ca_{exch}	63.0

Bases: sum of exchangeable Ca, Mg, K and Na; ECEC: effective cation exchange capacity; SOC: soil organic carbon; Nt: total soil N; Pt: total soil P

Between 40 to 60% of the variation was explained by models considering only management factors in all sites (Table 4.2.5). The best models included 4 terms in Emuhaia, 3 in Aludeka and 2 in Shinyalu. The distance from the homestead (DHI) and the planting date (PDI) were the most relevant factors in Emuhaia and Shinyalu, whereas the combination of plant density with other factors gave the best model in Aludeka. DHI and PDI were weakly correlated in all sites (see above and Appendix 4.2.2 – II a, b and c). However, a significant interaction site x field type had been found for PDI in Aludeka, showing a much delayed planting in the remote fields compared with the other sites (Table 4.1.2). This might explain why DHI and PDI did not appear together in the most explicative model (a 3-term model) for this site but one step later, in the best model with 4 terms.

Due to the negative correlation between plant density and both planting date and weed infestation in Emuhaia, and the positive correlation between distance from the homestead and weeds, their inclusion in the 4 and 5 –term models did not increase the amount of variance explained. As shown by the correlation analysis, the distance from the homestead (DHI) had a certain degree of association with the plant density, with the weed infestation level and with the topographic slope in Shinyalu (Appendix 4.2.2 – II b). Models with more than 2 terms did not increase the amount of variability explained for this site (Table 4.2.5). *Striga* infestation as an individual variable explained 35% of the maize yield variability in Emuhaia, (but only 5% in Aludeka and none in Shinyalu) and was associated with late planted, sparser and less frequently weeded crops (Appendix 4.2.2 – I and II a).

Explaining up to 60% of the variation in crop performance by only considering management factors appears, in principle, as an obstacle to study crop growth gradients as affected by soil fertility. However, such a 'management intensity gradient' would also have a certain pattern in response to differences in land quality, inherent and/or actual soil fertility, labour availability, risk and uncertainty. As it was shown in the previous section (Figs. 4.1.3 and 4.1.4, Table 4.1.8) soil properties varied between the land quality classes recognised by farmers and management factors such as planting date or weeding followed the same trend in terms of their intensity. On the other hand, the correlation analysis revealed important associations between soil fertility and management factors in all sites, supporting the idea that farmers deliberately manage their different fields according to their perceived quality.

Table 4.2.5: Subsets of management variables included in multiple term regression models to explain maize yield and the percentage of the variance explained by them.

Site	Best subsets of explanatory variable/s	% of variance explained
Emuhaia	PDI + DHI	55.0
	PDI + DHI + Striga	61.8
	PDI + DHI + Striga + Pl density	62.1
	PDI + DHI + Striga + Pl density + Weeds	59.9
Shinyalu	DHI + PDI	42.2
	DHI + PDI + Plant density	38.6
Aludeka	Pl. density + DHI	63.1
	Pl. density + DHI + Striga	64.2
	Pl. density + DHI + Striga + PDI	61.7

PDI: planting date index; DHI: distance from homestead index

Combining inherent and actual soil properties with management factors increased the amount of maize yield variability explained (Table 4.2.6), though not substantially for Emuhaia due to the high correlation between variables (Appendix 4.2.2 – II a). The best models included 9 variables for Emuhaia, 6 for Aludeka, and 4 for Shinyalu. Between 80 to 85% of the variability found in Emuhaia and Aludeka could be statistically explained, but only 64% for Shinyalu. Although no inherent properties (i.e. field slope and soil texture) were selected for the best multiple term explanatory model for any of the sites, the topography might have played an important role in Shinyalu (see below).

In Emuhaia most variables selected for the best explanatory model were soil properties and only *Striga* infestation as a 'management' factor in a 7-term model explaining 85% of the maize yield variability (Table 4.2.6). However, a model combining planting date, plant density and extractable P in the soil explained 70% of the variance. No substantial increase in the amount of variance explained was achieved by increasing the number of model terms from 6 to 7, since the C:P ratio (relating SOC and total P) and the extractable P concentration had a correlation coefficient of 0.29. Distance from the homestead and planting date, combined with extractable P and exchangeable K gave the best explanatory model for maize yield in Shinyalu. Adding total N or soil C to the model did not increase the amount of variance explained. For Aludeka, a number of management factors were combined with extractable P, soil C, exchangeable Ca and K to explain between 75 to 80% of maize yield variability.

Table 4.2.6: Subsets of (combined) soil fertility and management variables included in multiple term regression models to explain maize yield and the percentage of the variance explained by them

Site	Best subsets of explanatory variable/s	% of variance explained
Emuhaia	PDI + P_{extr}	67.0
	PDI + P_{extr} + Pl density	70.0
	PDI + H_{exch} + K_{exch} + Striga	73.0
	PDI + H_{exch} + K_{exch} + Striga + C:N ratio	81.5
	PDI + H_{exch} + K_{exch} + Striga + C:N ratio + C:P ratio	84.0
	Striga + P_{extr} + K_{exch} + Ca_{exch} + C:N ratio + H_{exch} + C:P ratio	85.0
Shinyalu	DHI + P_{extr}	46.8
	DHI + P_{extr} + K_{exch}	53.1
	DHI + P_{extr} + K_{exch} + PDI	64.2
	DHI + P_{extr} + K_{exch} + PDI + Nt	63.7
	DHI + P_{extr} + K_{exch} + PDI + SOC + Ca_{exch}	62.2
Aludeka	P_{extr} + SOC	66.1
	P_{extr} + SOC + DHI	69.7
	P_{extr} + SOC + Striga + PDI	74.7
	P_{extr} + Ca_{exch} + Pl density + DHI + Weeds	78.6
	P_{extr} + Ca_{exch} + Pl density + DHI + Weeds + K_{exch}	79.6

Bases: sum of exchangeable Ca, Mg, K and Na; ECEC: effective cation exchange capacity; SOC: soil organic carbon; Nt: total soil N; Pt: total soil P; Pextr: extractable P; PDI: planting date index; DHI: distance from the homestead index

Extractable P appeared as an explanatory variable in all models for all sites (Table 4.2.6), particularly in models with only 2 to 3 terms, which makes it an interesting variable to explain the gradients in crop performance as affected by soil fertility. Soil organic carbon played an important role in explaining yield variability for Aludeka, were soils have a sandier texture. Under the conditions of severe soil depletion of Emuhaia, variables such exchangeable acidity and Ca (indirectly including pH and exchangeable bases) appeared in the best models to explain yield variability (Appendix 4.2.2 – I). Exchangeable K was relatively important as an explanatory variable in Emuhaia and Shinyalu.

The distance from the homestead (DHI) played a role in Shinyalu, where it is associated to some degree with land quality and accessibility, and in the larger farms of Aludeka, where planting date and weeding tend to be delayed for the remote fields. Farmers tended to adapt plant densities to nutrient availability. In Aludeka, plant populations below 2 plants m^{-2} were measured in all types of fields (Tables 4.1.7 and 4.1.8). An increase of plant population may result from a higher conceived land quality or due to input use. Therefore, plant density was often associated to some extent with soil fertility variables (see below).

In Shinyalu – to a lesser extent in Emuhaia - fields that are close to the homestead, considered fertile by the farmer may have slopes steeper than 5% (sometimes only one portion of the field). Under the heavy and intense rainfall regime of Shinyalu those close fields are likely to be eroded. Thus, fields that are planted and weeded on time and where inputs are intensively used may show relatively large spots of crop failure, thereby increasing the variability in maize yields. In the remote fields crop performance tended to be poor as a result of infertile soils and low management intensity (see previous section). Late-planted, poorly growing stands tend to show a very sparse canopy with a low leaf area index. When these remote fields are on steep slopes the poor soil cover contributes to aggravate the erosive processes.

4.3 Intensity of resource use and a soil fertility index

Both the resource use index (RUI) and the soil fertility index (SFI) were meant as 'summary' indicators regarding nutrient flows (management) and status (soil fertility), respectively, though they were determined by completely different methods (see Chapter 2 and Appendix 2.3.4). The resource use index was derived by scoring (from 0 = no use to 3 = high use) the intensity of resource use in a certain field (fertilisers, manure, household wastes, etc.) during the interviews with the farmers. The soil fertility index was determined by scanning the soil samples under a near infrared spectroscope and calculating the ratio of likelihood (the log probability) of each sample with respect to a soil fertility class defined by ten soil parameters[9]. Due to the characteristics of the methods followed they present a different degree of variability and subjectivity, which must be considered for their interpretation and when they are incorporated into multiple regression models.

The highest intensity of resource use was recorded in the farms of higher resource endowment (types 1, 2 and 3) and for the home gardens and close fields (Table 4.3.1), whereas in the poorer farms and for the more distant fields the resource use index was low (score < 1). These results also show that farmers tended to allocate more resources in those fields they consider as 'fertile'. The patterns of resource allocation to different fields within the farm (Home gardens vs. Remote fields; 'Fertile' vs. 'Poor') are in the same line with the results of the resource flow maps (see Chapter 3). These patterns were consistently observed across sites and farm types (Table 4.3.1: note the non-significant interactions between farm types, field types and land quality).

The amount of maize yield variability explained by the resource use index varied from site to site (Appendix 4.3 - I). As stated before (Chapter 2 Resource use index), the index was not meant as a tool for between-sites but for between- and within-farm comparisons. In Shinyalu and Emuhaia, between 40 to 50% of the variance was explained by these indicator, and the highest yields were measured in those fields where the intensity of resource use was high (score = 3). However, relatively high yields (above 2 t ha^{-1}) were measured in Shinyalu when the intensity of resource use was scored as low and medium (1 and 2) and even when no nutrient resource was used. Under high use intensity practically no yield below 2 t ha^{-1} was measured. In Emuhaia, the yield ranges for the medium and high intensity use classes were wider, with measured yields as low as ca. 1 t ha^{-1}. Only c. 20% of the variability in maize yield was explained by this indicator in Aludeka. Most cases from this site fell into the 'no resource use' class, only one could be scored as high use intensity - steeping the linear relationship – and no differences were observed between the low and medium resource use classes.

The relationship between the resource use intensity and the yield of maize followed an expected trend in Shinyalu and Emuhaia: higher average yields in the fields where the degree of input use was higher, but a high yield variation within each class due to other

[9] A method developed by Shepherd and Walsh (2002) using a soil library of 801 samples from western Kenya (see Appendix 2.3.4)

simultaneously varying factors. Clearly, this is not a good indicator to explain yield variability in Aludeka where the average resource use intensity is very low. An important subjectivity was involved in determining such an index, but it resulted in a more accurate approach than trying to quantify, from interviews with the farmer, the exact amounts of nutrients applied to the crops. This is particularly true when inorganic fertilisers are combined with the varying application rates of organic resources of different composition, such as household wastes. Moreover, uneven application rates of both organic and inorganic resources within a certain field were often noticed.

Table 4.3.1: Resource use index (RUI). Mean values for farm type, field type and land quality class for the three working sites, standard errors of the differences and probability of the two-way interactions (n = 150). Comparison between sites are not relevant (see text)

Grouping factor	Site		
	Emuhaia	Shinyalu	Aludeka
Farm type			
Type 1	2.4	2.2	0.7
Type 2	1.2	2.3	1.0
Type 3	1.6	1.1	0.4
Type 4	1.0	1.1	0.1
Type 5	0.2	0.6	0.2
Significance (P value)	0.001	0.001	0.019
SED	*0.39*	*0.34*	*0.33*
Field type			
Home gardens	2.2	1.7	1.4
Close fields	1.6	2.7	0.6
Mid-distance fields	1.1	0.9	0.5
Remote fields	0.7	0.8	0.2
Significance (P value)	0.012	0.001	0.033
SED	*0.35*	*0.28*	*0.29*
Farm type * Field type (P value)	ns	ns	ns
Land quality classes			
Fertile	1.7	2.1	0.9
Average	1.2	1.1	0.4
Poor	0.5	0.7	0.3
Significance (P value)	0.001	0.001	0.036
SED	*0.31*	*0.26*	*0.26*
Farm type * Land quality (P value)	ns	ns	ns

SED: Standard error of the differences

The values of the soil fertility index (SFI) of the samples from the three sites were practically all negative, indicating a low log probability of those samples to fall in the 'fertile' class (see the critical limits for different soil indicators that define the 'fertile' class in Appendix 2.3.4). The values of the SFI were the least for Shinyalu, where relatively large maize yields were measured (Appendix 4.3 – II and cf. Table 4.1.3). The SFI did not show a clear pattern across field types, as indicated by their average values in Table 4.3.2, in which only the points where maize yield had been determined were considered. Only in Emuhaia the mean values of the SFI decreased from the home gardens to the remote fields, following the trend shown for maize yields. In Shinyalu, the width of the range of values increased from the home gardens to the remote fields. Positive values for the SFI were only measured in Aludeka, corresponding to the upper range of the distribution of values. In this site, the samples from the close fields had the highest values.

Table 4.3.2: Average value and distribution of the spectral soil fertility index (SFI) for the different field types in the three working sites. Only those sampling points where maize growth performance also was assessed were included in this table (n = 150)

Field type	No obs.	Mean	Minimum	25%	50%	75%	Maximum
Emuhaia							
Home garden	10	-2.3	-3.7	-2.9	-2.4	-1.9	-0.3
Close fields	11	-3.5	-5.1	-4.4	-3.6	-2.7	-0.9
Mid-distance fields	15	-3.8	-5.2	-4.7	-3.8	-3.2	-1.5
Remote fields	18	-4.0	-6.9	-5.3	-4.1	-3.3	0.0
Shinyalu							
Home garden	9	-5.5	-9.6	-7.0	-5.3	-3.4	-3.3
Close fields	10	-4.6	-10.1	-6.1	-4.4	-1.8	-0.2
Mid-distance fields	16	-5.9	-13.6	-8.1	-5.1	-3.2	0.2
Remote fields	13	-5.7	-19.8	-6.5	-4.0	-2.3	-0.3
Aludeka							
Home garden	5	-2.0	-3.4	-2.9	-2.5	-1.2	0.5
Close fields	14	-0.6	-3.6	-1.5	-0.4	0.7	2.5
Mid-distance fields	19	-1.7	-4.7	-3.2	-1.3	-0.2	1.1
Remote fields	10	-1.7	-3.6	-2.6	-2.1	-1.2	1.1

The relationship between maize yields and the soil fertility index (SFI) was plotted in Appendix 4.3 – III where it is shown that the largest amount of yield variability was explained by the SFI for Aludeka (c. 30%). The distribution of points for Emuhaia shows a narrow range in the SFI and a high variability in maize yields along this entire range. This point distribution resembles that of the plots relating maize yields with soil C and total N contents for Emuhaia (cf. Fig. 4.2.1). No clear relationship was observed between maize yield and SFI for Shinyalu, where the ranges of both variables were the widest, but for some extremely low values that corresponded with poor maize yields. Maize yields as high as 4 t ha^{-1} were measured in fields which soil samples had SFI values below –10. In Shinyalu, the main inherent source of variability in soil fertility is topography. It determines not only the distribution of soil types in the landscape but also their susceptibility to degradation (i.e. erosion). The slope of the fields (an indirect indicator of soil erosion) showed a certain degree of association with the soil fertility index, as will be shown later.

The SFI was also determined for subsoil (15 to 30 cm) samples, and a variable degree of association was found between the SFI values of the top and subsoil samples taken from the same point in the field (Table 4.3.3). The closest relationship was found for Shinyalu, where the organic soil horizons (i.e. A horizons) are deeper and the transitional (BA) horizons are relatively thick (Appendix 2.1.3 – II). A high degree of association between the fertility condition of the top and subsoil layers would indicate that no benefits might be brought about by including the latter in the regression models to explain maize yield variability. In Emuhaia and Aludeka, the fertility condition (SFI) of the subsoil explained 40% and 30% of that of the subsoil, respectively. The inherent variability in soil depth observed in Aludeka may explain such differences. In Emuhaia, the gradient in the soil fertility index from the top to the subsoil might be the result of (i) shallower A horizons with a less evident transitional subsoil (Appendix 2.1.3 – I), (ii) losses of a large part of the A horizons by soil erosion and/or (iii) nutrient accumulations due to the application of nutrient resources mixed with the topsoil.

Table 4.3.3: Linear regression equations for the relationship between the soil fertility index (SFI) of the top (0 – 15 cm) and subsoil (15 – 30) layers, with the latter as dependent variable (n = 38).

Site	Intercept	Slope	R^2
Shinyalu	0.03	1.02	0.96
Emuhaia	-2.63	0.56	0.41
Aludeka	-3.64	0.73	0.34

Multiple regression models

Incorporating the resource use intensity index (RUI) and the soil fertility index (SFI) into multiple regression analysis together with other management variables yielded models that explained between 50 and 70 % of the variation in maize yield (Table 4.3.2). The combination of weed infestation, resource use and plant density explained almost 70% of the variation in Emuhaia, and no improvement was achieved by incorporating the soil fertility index, field slope and plating date in the model. As in previous cases (see Table 2.4.6) the distance from the homestead, the planting date and the field slope were selected among the best variables to explain yield variability in Shinyalu. When they were combined with resource use intensity and soil fertility about 60% of the variation was explained. A similar set of variables were selected by the program to explain maize yields in Aludeka, but considering weed infestation instead of slope. In this case, when the resource use index (RUI) was removed from the model the amount of variance explained remained almost the same, around 50%.

Except for Aludeka, the resource use index (RUI) was selected among the best set of variables due to its relatively high explanatory power (Appendix 4.3 – a). However, since it is highly subjective, these results should be interpreted just as an indication of how deliberate, short-term management practices induce yield variability, and of what patterns of resource allocation are followed within a farm. Replacing the set of different soil variables by a single soil fertility index (with the advantage of increasing the available degrees of freedom for other type of variables, like slope) did not improve the explanatory power of the multiple regression models. For Emuhaia it was previously shown that the soil variables explained a larger proportion of the variability compared to the management factors (see Tables 4.6.1 and 4.6.2). However, the soil fertility index does not seem to reflect that from the results in Table 4.3.2 and, moreover, the explanatory power of the model remained the same when it was removed.

Table 4.3.2: Subsets of variables included in multiple regression models to explain maize yield variability, including the resource use and the soil fertility indexes (n = 150).

Site	Best subsets of explanatory variables	% of variance explained
Emuhaia	Weed + Striga + RUI + Pl density	68.6
	Weed + Striga + RUI + Pl density + SFI	68.2
	Weed + Striga + RUI + Pl density + SFI + Slope	67.6
	Weed + Striga + RUI + Pl density + SFI + Slope + PDI	67.0
Shinyalu	DHI + PDI + RUI + SFI + Slope	59.1
	DHI + PDI + RUI + SFI + Slope + Weed	58.8
	DHI + PDI + RUI + SFI + Slope + Weed + Pl density	58.1
Aludeka	PDI + Weed + SFI + DHI	49.9
	PDI + Weed + SFI + DHI + RUI	54.9
	PDI + Weed + SFI + DHI + RUI + Striga	54.2

PDI: planting date index; DHI: distance from the homestead index; RUI: resource use index; SFI: soil fertility index; Slope in %; Pl density in pl m^{-2}; Weed and Striga are scores (1 to 3) of infestation levels.

The variation in the resource use index (RUI) within a farm was related with the variation in the distance from the homestead in all sites, with determination coefficients around 0.3. The soil fertility index (SFI) presented a certain degree of association with the distance from the homestead in Emuhaia and Shinyalu (Table 4.3.3) but not in Aludeka, probably due to the high spatial variability of soil types in this site. For Shinyalu it was also associated to some extent with the slope of the fields. A different degree of association was observed from site to site between management factors such as planting date or pant density and both indexes (RUI and SFI). Weed infestation was more related to the resource use intensity than to the soil fertility status, except for Aludeka. This would suggest that more inputs are used in the fields that are managed better (timely planted and weeded) and not necessarily the (inherently) most fertile.

Table 4.3.3: Correlation matrix between the soil fertility index, the resource use index and other management factors

	Emuhaia		Shinyalu		Aludeka	
	RUI	SFI	RUI	SFI	RUI	SFI
SFI		1.000		1.000		1.000
RUI	1.000	-0.078	1.000	0.125	1.000	-0.007
DHI	0.309	0.217	0.321	0.184	0.269	0.001
PDI	0.467	-0.285	0.110	0.075	0.222	0.228
Pl density	-0.117	-0.233	-0.021	-0.163	0.149	0.084
Weed	0.186	0.011	0.339	-0.045	0.062	0.166
Striga	0.014	-0.003	-	-	-0.145	-0.019
Slope	-0.041	0.310	0.176	-0.235	-	-

5 Assessing the impact of management through dynamic simulation

Introduction

Adding a dynamic, temporal dimension to the calculation of nutrient balances had been proposed as an alternative approach to assessing the impact of management decisions on the establishment of soil fertility gradients (see Chapter 1). This chapter presents the results obtained by using a simulation model that operates at plot scale (see Chapter 2) to understand the mechanisms leading to differences in land quality and in general resource use efficiency as affected by management.

A set of simulation scenarios was selected considering the multiple sources of variability that affect soil fertility at plot scale. The scenario parameterisation was done with the field data collected during the interviews, the resource flow mappings and the soil sampling and laboratory analysis. The sensitivity of the model to the range of soil and management parameters that are common in the region was then tested. The simulation model was run for the different scenarios and the outputs were analysed and contrasted with reference values from own measurement (Chapters 3 and 4) and from literature. Finally, different options for soil fertility management were explored for different field types by means of the simulation model, as a way of illustrating the advantages of including the temporal dimensions and considering the spatial variability in the calculation of nutrient balances. These results also indicated to what extent the N balance at plot scale could be used as an indicator of resource use efficiency.

5.1 The development of simulation scenarios

As shown in previous chapters both crop performance, soil fertility and more generally nutrient balances are affected by land quality attributes and management decisions that vary from site to site, between farm types and for the different fields within a farm. This can be illustrated by three axes that define a space in which the multiple combinations of inherent properties, soil fertility variables and management practices occur (Fig. 5.1). The y-axis represents the effect of farm type (i.e. production orientation and wealth) and the x-axis accounts for differences between fields – field types – that are both cause and consequence of short and long-term management decisions. Though differences in the inherent properties can be identified between farm and field types, they are more widely affected by the site characteristics, represented by the z-axis.

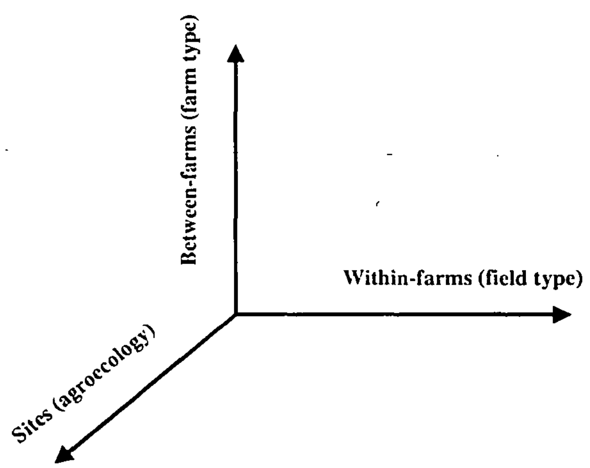

Figure 5.1: Illustration of the conceptual framework for the development of scenarios to run the model. Multiple combinations of inherent properties, soil fertility variables and management practices take place within the space defined by the three axes reflecting the effects of site, farm and field type.

This is the conceptual framework within which different scenarios were selected to investigate the potential of the simulation model as a tool to study the effect of management decisions on the establishment of soil fertility differences within a farm (i.e. soil fertility gradients). Using the available weather data in FST[1] format (see Chapter 2, Section 2.6.3), and as a way of reducing the number of possible combinations, the site effect was not directly[2] included in the development of simulation scenarios. Instead, six combinations of farm and field types were selected from the results of the resource flow maps (see Chapter 3) and simulated for only one of the three sites. They are presented in Table 5.1.1, where it is assumed that for a certain site both the level of resource endowment and the relative

[1] Fortran Simulator Translator

[2] Indeed, the inherent properties (e.g. slope, texture) are highly site-dependent in itself, and by choosing only one site they are limited to a certain degree

position of a field within a farm are the main sources of variability for the model (land quality and management) parameters. This simplification, however, still included a wide range of values for the most relevant variables studied in the previous chapters.

Table 5.1.1: Combinations of resource endowment and field position within the farm chosen for the development of simulation scenarios

	Relative position within farm		
	Close fields	Mid-distance fields	Remote fields
Resource endowment			
High	I	II	III
Low	IV	V	VI

Most land quality and management parameters varied widely along the rows and columns of Table 5.1.1, though some of them varied predominantly in one of the two directions. For instance, the use of organic resources such as cattle manure was certainly different between rich and poor farms, and it was mostly applied in the fields that are closer to the homestead or livestock facilities. The *quality* of that organic resource itself, however, was more likely to vary between farms rather than between field types, since cattle are better fed and therefore produce a higher quality manure in the wealthier farms. For inherent properties such as field slope or soil texture, wider differences between field types were observed. Since land is mostly acquired by inheritance, the hypothesis of richer families being able to purchase better quality land is secondary. Moreover, often the larger farms belonging to the upper classes show a higher internal variability in soil types and topography, from very fertile to very poor fields.

On the other hand the distance from the homestead to the remote fields is also different between rich and poor farms, and the mid-distance fields are mainly evident in the large farms of the former class. The home gardens contribute with an important proportion of food resources consumed by the households in the poorer classes, and less in the richer ones (see Chapter 3). Such considerations led to the selection of the scenarios I to VI that are presented in Table 5.1.2, where it becomes clear that they are case studies derived from the resource flow map information rather than simple combinations of factors. Farms of the contrasting types 2 and 5 were selected from Shinyalu to represent the high and low resource endowment scenarios, respectively. Farms type 2 are the largest, with numerous families and normally market-oriented (i.e. cash crops), whereas the type 5 are those land- and labour-limited, in which most of the family members work for other farmers (see Chapter 3).

Some of the parameters in Table 5.1.2 were not measured in the field or lab but estimated from secondary sources. The factors K and P were taken from literature on soil erosion under African conditions (see Chapter 2 Model description). The characteristic water constants were derived from information gathered in the area by Jaetzold and Schmidt (1982) and by the fertiliser use and recommendation program (FURP – Kenya National Agricultural Research Laboratory, 1985), considering soil texture, organic carbon and bulk density values. Management parameters were derived from the results of the resource flow maps and from the information gathered during the interviews (Chapter 3). For the parameters that were difficult to measure or estimate from existing literature conservative values were chosen, and they were kept constant across scenarios. Such is the case of the mineralisation:immobilisation and the C:N ratios of the microorganisms or the drainage coefficient and maximum drainage rate of the topsoil. Crop parameters were kept constant across scenarios, thus the effect of using improved varieties was not simulated.

Table 5.1.2: Characterisation of simulation scenarios, their range of model parameters and reference values for maize yield, N balance as estimated in previous chapters and total soil N from laboratory

Characterisation and model parameters	Unit	Scenario I	II	III	IV	V	VI
Resource endowment	-	High	High	High	Low	Low	Low
Farm type	-	2	2	2	5	5	5
Field type	-	CF	MF	RF	HG	CF	RF
Land quality							
Slope	m $100m^{-1}$	2.5	8.5	15	0.5	4.5	18
Slope length	m	23	40	35	11	24	21
Clay content	%	54	55	51	44	44	46
SOC	g kg^{-1}	15	12	6	16	11	4
SOM C:N	g C g^{-1}N	11	11	15	10	11	14
pH	-	5.9	5.6	5.4	6.1	5.5	5.2
Bulk density	kg m^{-3}	1250	1240	1310	1320	1260	1280
*Soil 'erodibility'	Factor K	0.09	0.09	0.12	0.08	0.14	0.18
Soil water constants							
*$WCST_T$	M3 m-3	0.50	0.50	0.50	0.62	0.62	0.62
*$WCFC_T$		0.38	0.38	0.38	0.42	0.42	0.42
*$WCWP_T$		0.26	0.26	0.26	0.23	0.23	0.23
Management							
Inorganic fertiliser use	-	yes	yes	no	no	yes	No
DAP (18: 46: 0)	kg ha^{-1}	60	45	0	0	20	0
Urea (46: 0: 0)	kg ha^{-1}	30	0	0	0	0	0
Organic fertiliser (OF)	kg ha^{-1}	1600	440	0	1210	320	0
N content OF	%	3	3	n/a	2.5	1	n/a
Residues left on field	%	50	50	100	0	20	80
Household wastes	kg ha^{-1} d^{-1}	0	0	0	1.0	0	0
Planting date	Julian day	61	79	91	83	92	104
Harvesting date**	Julian day	191	204	216	212	222	252
Plant density	plants m^{-2}	6.5	5.2	4	3.6	5.6	2.5
*Erosion control	Factor P	0.14	0.14	0.35	0.14	0.2	0.6
Reference values							
Maize yield estimation	t ha^{-1}	2.9	1.8	0.8	1.7	1.8	0.6
Partial N balance	kg ha^{-1}	-45	-66	-78	-31	-44	-36

CF, MF and RF: close, mid-distance and remote fields; HG: home garden; SOC: soil organic carbon; SOM C:N: carbon-nitrogen ratio of soil organic matter; Factors K and P of universal soil loss equation (USLE); WCST, WCFC and WCWP: topsoil (T) characteristic water contents at saturation, field capacity and permanent wilting point; DAP: di-ammonium phosphate; n/a: not applicable

*Values estimated from secondary sources.

**Harvest was assumed to take place as soon as the crop is mature, which is a simplification of what happens in reality.

5.2 Sensitivity of the model to the local conditions

The analysis of the partial sensitivity of the main model outputs to different soil and management parameters is presented in this section. Since most of the parameters that were studied are naturally interrelated, they vary simultaneously in reality and the artificial modification of one of them keeping the rest unchanged may yield results that are not sensible and difficult to interpret. Such is the case of changing the clay content of the soil, which at the same time implies changes in the soil water constants or in the factor K (soil erodibility) of the universal soil loss equation. Changes in the fertiliser application rates will have different effects on clayey than on sandy soils for the calculation of leaching. The effect of a steeper slope on soil erosion will also vary between sandy and heavy soils, and will be affected by management practices such as plant density.

Therefore, the situation of a 'typical' and relatively flat close field (see Chapters 2 and 3) was adopted as a compromise to set the basis for the analysis, and 'average' management practices were applied. The basic characteristics of such a field are given in the form of parameters in Table 2.6.3, in the central column (under 'Normal'). Changes in the clay content were introduced as changes in the texture class, using examples from different fields, and the changes in related parameters (e.g. water characteristics) that were introduced as well are presented in Appendix 5.2 a. The N application as both organic and inorganic fertilisers were introduced by simply increasing the application rates, but not their N content (nor the C:N ratio of the organic fertilisers). For each parameter the model was run for several situations (6 to 9) including changes in the parameter under study that ranged between the values considered 'High' and 'Low' in Table 2.6.3; the partial sensitivity was calculated for each instance and averaged. The mean partial sensitivity values are presented in Tables 5.2.1 and 5.2.2.

5.2.1 Soil and landscape parameters

The N balance at plot scale was highly sensitive to changes in the field slope between 0.5 and 15%, basically due to the sensitivity of the simulated N outflow as soil erosion (Table 5.2.1). Since the slope was artificially changed from that of the original field and no other properties of the system where changed (e.g. depth of the organic topsoil - as it would happen in reality) most outputs variables were little sensitive to slope. The slight changes in N mineralisation (and consequently in the amount of soil mineral N) resulted from changes in the infiltration rate of water in the soil (i.e. different runoff rates for different slopes) that affected the moisture correction factor for mineralisation [F]. Soil clay content had an important impact on most output variables, particularly on N losses by leaching and erosion, which must be carefully interpreted. Changes in clay content (i.e from 28 to 54%) were operated by selecting data sets from different fields, including changes in the other texture fractions, in the soil water parameters, in bulk density and in soil erosion parameters (see above and Appendix 5.2). Though this is not the common procedure for sensitivity analyses it was far more representative of what happens in reality, particularly in the site under study. In the model itself, texture affects several processes that are involved in crop performance and in the soil N balance (e.g. water retention and its effect on growth rate by hampering crop transpiration, N mineralisation, etc.).

Soil organic carbon (SOC) content and the C:N ratio of the soil organic matter had a strong effect on the nutrient balance at plot scale (Table 5.2.1). In the model, they were introduced as initialisation parameters, which in turn affected the initial amount of N in the soil. The soil organic matter content, determined by the parameter SOC, affects other physical soil properties such as susceptibility to erosion (factor K, according to the nomograph of Whitmore and Burnham (1969). Both the amount and the C:N ratio of the soil organic matter affect the N mineralisation-immobilisation processes, and having an important effect on the soil mineral N balance. That was also reflected by the sensitivity of the flows of N as leaching and as uptake by the crop, thereby affecting crop performance (i.e. N effect on growth). Maize grain yield was more sensitive than total biomass to changes in the amount of mineral N, because the shortage of N was mainly observed during the grain filling stages in the multiple simulation runs. In reality, crops adapt their vegetative growth to the amount of N available, and the rate of re-mobilisation of N from the vegetative biomass and reallocation to grains are probably much larger than the ones simulated here. On the other hand, other growth limiting factors (such as P availability) were not introduced in the model and they may interact to down regulate crop growth, continuously redefining the N demand by the crop. Total biomass and grain yields were equally sensitive to changes in clay content due the effect on water retention that operated during the entire growth period.

Table 5.2.1: Relative sensitivity of different response variables to selected soil parameters. A value > 1 would indicate that the variation in the output is more than proportional than the variation in the input.

	Parameters (inputs)			
Response variables (outputs)	Slope (%)	Clay (%)	SOC (g kg^{-1})	SOM C:N
Crop performance				
Grain yield	-	-0.22	0.26	0.59
Total biomass yield	-	-0.29	0.17	-0.39
N effect on growth*	-	-0.09	0.19	-0.44
N balance and flows				
N balance at plot scale	1.53	-1.08	-2.58	3.25
Soil mineral N	-0.01	1.16	0.88	-3.29
N lost by erosion	1.33	1.30	0.99	-0.80
N lost by leaching	-	2.01	1.44	-1.74
N uptake	-	-0.16	0.72	-1.74
N mineralised	-0.02	0.22	-6.75	3.74

Values lower than 0.01 are not presented (dash)
*average for the entire growing period

5.2.2 Management parameters

Sowing date was the management factor that had the strongest effect on crop performance and, particularly, on N flows and balance (Table 5.2.2). Sowing date determined the synchrony between crop growth and the environmental factors (i.e. radiation, temperature and rainfall), affecting the processes leading to resource use efficiency. Additionally, changes in the sowing date led to changes in the strength of the crop N demand by limiting crop growth through water availability (the water effect on growth, WEFGR in the model listing, had a partial sensitivity to sowing date of –0.14). The partial sensitivities of the N balances at plot scale and in the soil were largely driven by the leaching and uptake flows, both related to the time course of the N demand by the crop. The high sensitivity of the N outflow by soil erosion was determined by changes in the rainfall pattern during the crop growth period for each sowing date and by the evolution of the factor C (i.e. the effect of soil cover by the crop) in the universal soil loss equation. The rainfall pattern during the growth period showed several peaks that may become critical according to the development stage of the crop, when: (i) heavy showers take place before the leaf area reaches its maximum development (affecting erosion) or (ii) the N uptake is still very small during early development stages (affecting leaching). However, the daily time step simulation is not sensitive enough to processes that take place in hours. Such is the case of leaching, due to the time step of the rainfall data. On the other hand, the amount of mineral N in the soil was sensitive to the sowing date due to the effects of different temperature and moisture (i.e. correction factors) regimes on the mineralisation process. The effect of the sowing date clearly reflects the advantages of incorporating a dynamic dimension in the calculation of nutrient balances at plot scale.

Table 5.2.2: Relative sensitivity of different response variables to selected management parameters. A value > 1 would indicate that the variation in the output is more than proportional than the variation in the input.

Response variables (outputs)	Parameters (inputs)			
	Sowing date	Plant density	N applied (inorganic)	N applied (organic)
	Julian day	Plants m^{-2}	kg ha^{-1}	kg ha^{-1}
Crop performance				
Grain yield	0.78	0.41	0.09	-0.03
Total biomass	0.75	0.39	0.06	-0.02
N effect on growth	0.08	-0.10	0.06	-0.01
N balance and flows				
N balance at plot scale	4.89	0.01	-0.10	0.19
Soil mineral N	1.72	0.08	0.09	-0.02
N lost by erosion	0.41	-0.15	-	-0.05
N lost by leaching	3.38	-1.61	0.62	-0.06
N uptake	1.24	0.16	0.23	-0.04
N mineralised	0.43	-0.69	0.82	0.68

Values lower than 0.01 are not presented (dash)
*average for the entire growing period

Crop performance was sensitive to plant density (Table 5.2.2) due to its relationship with the leaf area index which, in spite of affecting light interception, defines N uptake in the model through its rate of expansion (Goudriaan, 1994; see Chapter 2). For the same reason, N leaching was highly sensitive to plant density, and the rate of N loss by soil erosion was affected again by soil cover. Since N mineralisation in the model is regulated by the availability of soil mineral nitrogen (to cover the immobilisation demand), the extent of N uptake as well as the rate of N application as inorganic fertilisers affected the amount of N mineralised from the soil and applied organic matter pools. Crop growth was only partly sensitive to the amount of N applied as inorganic fertilisers (probably due to the initial N availability in the soil or to the relatively low application rates), though the N uptake by the crop and the N leaching losses were affected by it. Under the simulated conditions (base scenario: a flat, *close* field with a crop planted 'on time') the N loss by soil erosion was not sensitive to the N application rates. The amount of N mineralised during the growing period was the only N flow that was highly affected by the incorporation of organic fertilisers.

However, the N balance at plot scale was more sensitive to organic than to inorganic N fertilisations, due to 'accumulation' of N in the plot, namely the N held in the remaining organic material after each season. The losses of N by leaching and the N removal from the plot with the crop produce (N taken up by the crop) where highly sensitive to the application of inorganic fertilisers.

5.2.3 Limitations

According to this analysis crop growth does not seem to be sensitive enough to the applications of N as inorganic fertilisers. This would limit the performance of the model to assess the efficiency of inorganic fertilisation as a soil fertility management strategy. However, the absolute figures of crop biomass indicated an increase in (simulated) grain yield of 1.2 t ha^{-1} when the (simulated) fertilisation rate with urea (46: 0: 0) was increased from 0 to 150 kg ha^{-1}. From experiments carried out in western Kenya (FURP, 1994) between the years 1988 and 1992, a fertilisation rate of 75 kg N ha^{-1} (roughly 150 kg ha^{-1} of urea) was recommended as a threshold for a substantial crop response. The yield response functions to N fertilisation derived from those experiments (for Kakamega and Vihiga districts) had slopes of 6.8 and 11.6 [with the units kg grain ha^{-1} kg^{-1} applied N ha]. A nitrogen application rate of 75 kg ha^{-1} will produce, according to these functions, grain yield increases of 0.51 and 0.87 t ha^{-1}, respectively, which are below (but comparable) with the yield increase simulated by the model. The intercepts of those equations were much higher (4.2 and 3.9 t ha^{-1}, respectively) than the yield simulated by the model under no fertiliser application (2.1 t ha^{-1}, a realistic figure for a *close field*, see Chapter 3). Larger yield increases could be expected in the field when the threshold yield (without fertiliser) would be smaller than in those trials, provided that the effect of other growth-limiting and growth-reducing factors were removed or reduced.

As revealed by the extensive soil sampling and laboratory analysis (Chapter 4) and by the maize growth performance assessment in the field (nutrient deficiencies), P availability is one of the most important factors affecting crop production in western Kenya. This was confirmed by the relative importance of extractable P as one of the variables explaining maize yield variability, which consistently appeared in the multiple regression models developed for all the sites (cf. Table 4.2.6). However, P availability and its effect on crop production were not included in the simulation model. To reduce the effects of such omission, the simulation scenarios (i.e. examples of fields) chosen from the case study farms were only those in which the extractable P concentration in the soil (according to soil analysis data) was above a threshold value of 10 mg kg^{-1}. Another factor of the highest importance for crop (maize) production is the effect of weeds, and specially of *Striga* infestations (i.e. growth-reducing factors), as demonstrated for all sites in Chapter 4. Since Shinyalu was chosen as the site for which the simulations were run, the omission of *Striga* is mostly not a problem (a 'zero' level of *Striga* infestation was recorded at Shinyalu, see Chapters 3 and 4). However, the effect of weeds would have an important impact on crop performance and through this also in the N balance at plot scale. Additionally weeds might also reduce N leaching by taking up N and soil erosion by covering the soil surface, and should be considered in the dynamic simulation of nitrogen balances.

5.3 Simulation results

5.3.1 Maize yield, N balance and resource use efficiency

Maize grain yields from the simulation results for the proposed scenarios (see above, Table 5.1.2) were close and followed a similar trend as the yields estimated with the allometric models (Chapter 2) using field measurements from these case study farms (Table 5.3.1, compare with Table 5.1.2). The width of the range in crop yields found in Shinyalu was satisfactorily represented by the simulated yields for the selected scenarios. However, the model underestimated the reference grain yields by 5 up to 33% except for the close fields of the farm type 5 (scenario V). The average yields in the home gardens, the close and remote fields estimated for Shinyalu are also larger (Chapter 4) but not for the mid-distance fields (i.e. the most difficult to estimate due to their high variability). These differences could be partly ascribed to the differences in rainfall regime, since the weather data used here was recorded at 52 km from Shinyalu and at a lower altitude (less rainfall). For the same reason, cooler temperatures in reality would allow longer growing periods than those in Table 5.3.1. An additional source of variability comes from the fact that the values used to parameterise the model for each scenario were derived from soil samples corresponding to a single point within a field. The within-field variability was not considered in the simulation, whereas it was 'estimated' for the reference yields by calculating weighted averages from different measuring points within a field (Chapter 2). The simulated length of the growth period (determined by the temperature sum) fluctuated between 125 to 148 days. The amount of global radiation and rainfall received on the fields during these periods varied according to their length and to the sowing date (i.e. environmental potential).

Table 5.3.1: Results from the simulation of the selected scenarios and calculations of the gross use efficiencies of the environmental resources (i.e. resource availability / crop biomass)

	Unit	Scenario					
		I	II	III	IV	V	VI
Simulation results							
Grain yield	t ha^{-1}	2.8	1.5	0.6	1.4	2.1	0.4
Growth period	days	130	125	125	129	130	148
Global radiation	MJ m^{-2}	2.7 10^3	2.6 10^3	2.5 10^3	2.6 10^3	2.6 10^3	3.0 10^3
Rainfall	mm	620	600	550	550	560	490
N balance (model)	kg ha^{-1}	32.3	2.8	-13.9	21.4	-25.6	-17.3
N balance (full)	kg ha^{-1}	21.9	-6.6	-21.3	13.0	-38.0	-24.7
N lost by leaching	kg ha^{-1}	16.3	10.6	3.8	18.3	9.8	2.3
N lost by erosion	kg ha^{-1}	0.6	3.2	9.9	0.8	1.7	14.9
*Resource use efficiency**							
Global radiation	g dm MJ^{-1}	0.17	0.12	0.07	0.09	0.18	0.04
Rainfall	g dm mm^{-1}	0.73	0.50	0.30	0.42	0.83	0.23

*Considering total aboveground biomass at harvest

The N balance at plot scale was positive in the close and mid-distance fields of the case-study farm type 2 and in the home garden of the farm type 5 (Table 5.3.1: N balance model). The most negative balance corresponded to the close field of the latter case-study farm.

These trends were also observed when the partial nutrient balances were calculated from the resource flow maps (Chapter 3), though calculations were then done in a less detailed way (i.e. gross and partial nutrient balances included not only maize but all types of crop produces, with rough yield estimations given by the farmer). The results from most *annual* nutrient balances found in literature are highly variable and depend on the system definition and on the calculation procedure. Estimations of full N balances (i.e. considering all flows listed in Table 1.3, Chapter 1) showed negative figures for fields continuously cropped with maize in different African countries, and for the central highlands of Kenya (Embu and Nyeri) values of –44 to –75 kg N ha^{-1} $year^{-1}$ were indicated (de Jager *et al.*, 2001). The seasonal values calculated here seem to be of the same order as those.

The partial balance calculated in Table 2.6.1 (Chapter 2), considering only N deposition, non-symbiotic N fixation and N volatilisation estimated with transfer functions (Smaling, 1993) for the long rains season gave a negative value close to –10 kg N ha^{-1}(for a soil with 1.5% SOC, 25% Clay and with an application rate of N of 46 kg ha^{-1}). This amount was included in the calculation of the balance but considering the parameters of the scenarios under simulation, as presented in Table 5.1.3 (N balance full). These values were then closer to those found in literature (de Jager *et al.*, 2001), considering the fact that they were calculated only for the long rains season. N losses by leaching assumed by different authors for African farming conditions are also 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). According to the simulation results (Table 5.1.3) the seasonal amount of N lost by leaching was substantially larger than 10 kg ha^{-1} only in the close fields of the case-study farm type 2 and in the home garden of the case-study farm type 5.

N losses by soil erosion measured in western Kenya for different cropping systems ranged between 41 and 159 kg N ha^{-1} $year^{-1}$ (Rao *et al.*, 1999), higher than the seasonal values presented in Table 5.1.3. Those measurements covered 7 cropping seasons with annual crops and included different rates of P fertilisation and rotations with and without agroforestry options (e.g. a *Sesbania sesban* fallow). The experiments were carried out on a Kandiudalfic Eutrudox, in a field with 5% of slope (Ochinga, Vihiga district). The value of the factor K (soil erodibility in USLE, see Chapter 2) for that soil according to its texture and C content should be around 0.23 (Whitmore and Burnham, 1969), much larger than the values adopted for the simulation scenarios. Another value that was difficult to parameterise in the model was the factor P (the effect of the soil erosion control methods). An additional, interesting outcome of that study was that the average maize yields during the long rains season fluctuated between 1.1 to 2.9 t ha^{-1} (comparable to the estimations presented here) for the different treatments, and showed important variations within the experimental plot (increasing form the upper to the lower part of the field).

The gross efficiencies of resource use, calculated for the total amount of global radiation and rainfall reaching the surface of the field, decreased from the close to the remote fields (Table 5.1.3). Obviously, the sparsely and late planted remote fields had the lowest radiation and rainfall capture efficiencies. However, the efficiencies calculated for the home gardens are also rather low (less dense maize stands). As revealed by the sensitivity analysis, both sowing date and plant density are management factors that have an important impact on crop growth and through this also in the resource use efficiency. The time course of the N balances (model) for the different simulation scenarios are illustrated in Appendix 5.3 a. These dynamic profiles indicate that the N balance in the remote fields would be negative even without harvesting any outputs, and that N applications to home gardens occur daily, through household wastes and chicken manure.

Both (inherent and actual) soil fertility and management factors combine and interact in the different fields of a farm, having synergistic effects on the establishment and maintenance of soil fertility gradients. These type of interactions (e.g. when the sloping remote fields are planted late in the season and the peak of rainfall occurs with the soil uncovered with crops) and their effect on nutrient balances can be satisfactorily studied with the use of the simulation model. Multiple management practices and strategies can be explored for the different fields of a farm, as it would be illustrated in the following section.

5.3.2 Exploring alternatives for soil fertility management

An additional application of the simulation model for nutrient balances is the exploration of soil fertility management practices in terms of their efficiency and feasibility. To illustrate this, N fertilisations with different application rates of urea (46: 0: 0) at planting (a common practice in the region, see Chapter 3) were simulated for a close and a remote fields of one of the case study farms from Shinyalu (Table 5.3.2). The characteristics of both fields and the initialisation parameters are given in Appendix 5.2 b. The remote field was selected in order to avoid large differences in soil losses by erosion with the close field, and keeping approximately the same texture class. Thus, a remote field[3] of a type 2 farm, with a 9% of field slope but terraced at intervals of 20 m was chosen. The sowing date was the same for both fields (March 14th), though remote fields are normally planted later than close fields (see Chapter 4). The simulated N fertilisation rates presented in Table 5.3.2 ranged from 0 to 92 kg N ha^{-1}, which corresponded to a range of 0 to 200 kg urea ha^{-1}. The simulated range is rather low compared with the one often used in N fertilisation trials. However, the simulation results showed no further increase in grain yield beyond this range, due mainly to the limitation imposed by the plant densities used (taken from the case study: 5.1 and 3.5 plants m^{-2}, respectively). In reality, no N application rate larger than 50 kg N ha^{-1} was recorded in any of the 60 farms visited. Nevertheless, given the set of factors constraining crop growth under these field conditions no yield increases could be expected from higher N fertilisation rates.

The simulated grain yields did not increase with urea application rates larger than 150 and 100 kg ha^{-1} for the close and remote fields, respectively (Table 5.3.2). The simulated yields were within the range of those measured in the field under different levels of resource use intensity (see Chapter 3 and 4). For this particular farm yields of 1.9 and 0.5 t ha^{-1} were measured in the close and remote fields, respectively. During the visit to the farm the resource use intensity (RUI, see Chapters 2 and 4) was scored 1 for the close field (corresponding approximately with applying 50 kg urea ha^{-1} and no organic fertiliser), and 0 for the remote field. This yield responses presented N harvest efficiencies (*NHE = amount of N in the grain pool / amount of N applied as fertiliser*) between 0.3 and 0.6, which were higher for the close field and decreased in both fields as the N fertilisation rate increased. Thus, the simulated overall N use efficiency (*grain yield / amount of N applied as fertiliser*) or 'gross use efficiency[4]' of the N fertilisation followed a similar trend.

The amounts of N removed with the harvested biomass (grain and residue) and that lost by leaching were the main N outflows affecting the N balance at plot scale (Table 5.3.2). According to the patterns of resource flows observed in that farm, 80% of the crop residues

[3] The 'severe' examples of remote fields were avoided

[4] To distinguish it from the NUE (N use efficiency) which considers N in the crop (uptake) instead of N application rate.

are removed from the close field to prepare compost, while only 30% are removed from the remote field (due to the distance to the homestead and compost pit). Losses by leaching were slightly larger for the close field due to the larger amount of mineral N in the soil throughout the growing season. The effects of synchrony between crop N demand and soil N supply referred to in the previous sections were artificially removed here, to make the results more comparable (i.e. both fields were planted, fertilised and harvested at the same dates).

Table 5.3.2: N efficiency indicators calculated with the simulation results from exploring increasing application rates of inorganic N fertilisers (urea 46:0:0) in different fields of a case study farm. Leaching was a key flow in determining N balances. N losses by soil erosion ranged around 1.6 and 5.8 kg N ha^{-1} for the close and remote fields, respectively.

Indicator	N fertilisation rate (kg urea ha^{-1})					
	0	50	75	100	150	200
Grain yield (t ha^{-1})						
Close field	1.6	2.6	2.7	2.8	2.9	2.9
Remote field	0.6	1.7	1.9	2.0	2.0	2.0
N harvest efficiency (kg N in grains kg^{-1} N applied)						
Close field	-	0.6	0.5	0.5	0.5	0.4
Remote field	-	0.4	0.4	0.4	0.4	0.3
Overall N use efficiency (kg grain kg^{-1} N applied)						
Close field	-	111	79	62	41	31
Remote field	-	73	55	43	28	21
N removed by harvest (kg N ha^{-1})						
Close field	15.4	29.4	38.1	46.9	62.2	77.2
Remote field	4.5	16.3	24.9	33.3	48.4	48.4
N lost by leaching flow (kg N ha^{-1})						
Close field	3.4	14.1	21.3	28.5	42.9	57.4
Remote field	0.6	10.6	17.1	23.5	36.5	49.4
N balance at plot scale (kg N ha^{-1})						
Close field	18.5	16.9	12.5	7.9	1.1	-5.3
Remote field	-6.2	-9.3	-13.1	-16.5	-21.7	-11.9

The N balance at plot scale decreased as the fertilisation rate increased, and was in all cases higher for the close than for the remote field (Table 5.3.2). With the simulated doses used here crop growth was stimulated and therefore the removal of N from the plot through harvest was larger, reducing the amount of N remaining in the system (i.e. soil/crop system, see Chapter 2). This is in agreement with the observation that the balance was more negative in the fields where the yields were higher (Chapter 3). For the remote field, however, an increase in the N balance occurred when the (simulated) application rate of urea increased from 150 to 200 kg ha^{-1}. Due to the presence of other limiting factors, further increases in the N application rate cannot be capitalised by the crop and N begins to 'accumulate' in the system (though it would be subjected to losses by leaching, erosion, volatilisation, etc.). Indeed, when an application rate of 300 kg urea ha^{-1} was simulated for this field (data not shown) an increase in the N balance up to + 7.7 kg N ha^{-1} was obtained. As indicated by the N use productivity and the by the balances, N could be more easily 'captured' in the system when it was applied to the close field (i.e. when the effect of other growth-limiting factors was less).

The N balance at plot scale would only increase after a growing season when N is applied to the system in a form that is not readily available to the crop (which would be desirable when e.g. pursuing a long term accumulation or re-capitalisation of N strategy). To simulate such a strategy the different N fertilisation rates were combined with the application of organic resources of different quality (i.e. with N contents of 3 and 0.7%, assuming that the lignin and polyphenol contents are not hampering decomposition). To avoid the 'synchrony' effect both fields were fertilised at similar dates. Organic fertilisers application rates of 1 t ha^{-1} were adopted, a rather low rate but affordable by farmers. The simulation results (Appendix 5.3 b) showed an increase in the N balance in all cases, which was obviously higher when a 'good' quality organic resource was used. The N balance remained low and even negative in the remote field when the use of a poor quality resource was simulated. An organic fertiliser application rate of 1 t ha^{-1} in a remote field is a quite unrealistic figure according to the results of the resource flow maps (Chapter 3) and the only organic resource that those fields may receive are poor-quality crop residues. Similarly, the amounts of good quality organic resources available to the farmer even in the wealthier farms are often small, and their application in the close fields (exactly what farmers do) seems more profitable.

The simulation results from these explorations illustrated the advantages of both adding a temporal dimension to the calculation of nutrient balances and accounting for the spatial differences within a farm. These advantages reside in the fact that management decisions such as on when, where and how to use fertilisers can be explored and the viable options selected for further experimentation. Additionally, these results indicated that the differences in land quality within a farm (i.e. the broad sense soil fertility gradients) are large enough to be considered when soil fertility management strategies are designed at tested in the field. As revealed in the previous chapters, farmers recognise such differences and empirically adapt their management strategies, constrained by their resource availability.

6 General discussion and concluding remarks

Widely different approaches have been followed so far to assess the origin, the magnitude and the importance of soil fertility gradients. This chapter summarises and discusses them, inter-linking their results. Some final considerations are made about the methods used, their practicality and performance. The main conclusions from the Chapters 3, 4 and 5 are extracted and contrasted with previous research findings, and a conceptual framework is proposed to summarise them. Finally, the most relevant concluding remarks are presented.

6.1 Methodological considerations

The three sites selected for the study showed important differences in terms of socio-economic and biophysical aspects that allowed for an interesting set of combinations of the factors affecting within-farm soil fertility gradients (Tables 2.1.1 and 2.2.2, Appendix 2.1.3 - I, II and III), according to the SWIM[1] analysis (Vanlauwe, 2001; cf. Section 1.3). Aludeka (Teso district) appeared as an interesting site from the perspective of its low population density, high soil variability and relative isolation from factor markets. However, its inclusion generated a certain degree of distortion in the characterisation of the farming systems due to the low livestock population (Table 2.1.2), strongly affected by a long lasting *Tse-Tse* fly problem in the area. The farms within each site were initially selected by following lists of farmers that were identified as 'good' and 'poor' soil fertility managers by the key informants, a similar approach as the one used by Rotich *et al.* (1999) for a participatory learning and action research project in Kakamega (western Kenya). This way of identifying farmers produced lists in which not only the rich were the good soil fertility managers, breaking through that generally accepted association by including cases of good farming performance under low-input situations.

The interviews conducted at the selected farms (20 per site) for longitudinal monitoring of farm household activities and management practices, in combination with farm transects allowed to gather the necessary information to categorise farms by means of the proposed typology (see below). The number of farms visited per site was rather small, and certain features related to management practices could not be statistically analysed. However, much information is available to characterise the farming systems in western Kenya from previous studies (e.g. Braun *et al.*, 1997), which was complementarily used with the data generated from the interviews. Surveys including a larger numbers of farms in combination with multivariate techniques would improve the clustering of farms showing homogenous characteristics in terms of socio-economic indicators and farm management practices (i.e. farm types). Nevertheless, a case-study approach was adopted to select the farms in which the resource flow mapping was conducted, choosing one farm per farm type per site (15 in total), and it yielded widely different resource allocation patterns from farm to farm. The differences between the case-study farms were important enough to allow studying the effect of management practices and decisions on the establishment of soil fertility gradients.

[1] Acronym for Site, Wealth, Inherent properties and Management factors

Maize yield estimations and their variability

The allometric models provided reasonably accurate estimates of maize yields that could be validated against the yield data from both research trials (Appendix 2.4.1 Figs. 1) and farmers yield estimations during the resource flow map exercise (Appendix 4.1.2). Additionally, genotype- and site-specific parameters could be derived, which were used to parameterise the crop module of the simulation model (Chapter 2, Section 2.6; Appendix 2.4.1 Table 2). For the maize genotypes included in this study, the use of simple linear regression models considering plant height predicted grain and total biomass yield almost as accurately as the multiple regression models that considered also cob length and diameter (Appendix 2.4.1 Fig. 2). The main uncertainty in estimating yields at field and farm scale originated from the need to estimate the proportion of field area for which a certain measuring point was representative. Time saved by measuring only plant height in the field may be better used to increase the size of the measuring plots (a larger number of plants per measuring point) or, more desirably, the number of sampling points per farm.
The sampling points on each farm were selected by looking at the general status of the crop and deliberately choosing contrasting situations that were representative of the gradient in crop growth performance (Chapter 2, Section 2.4). This sampling design was far from being randomised, and therefore samples were representative of the crop productivity of each particular field but *not* of the overall productivity of the farm. Mean yields at farm scale were calculated as weighted averages, assigning a proportionality coefficient to each particular sampling point on the basis of the fraction of the farm area under maize that it represented. Thus, yields at farm and at field scale were two different variables and the interesting triple interactions Site x Farm type x Field type for maize yield and soil properties could not be satisfactorily tested.
The correlation between factors in the multiple regression models explaining maize yield variability was studied first, and closely correlated variables (e.g. exchangeable Ca and pH) were not included in the same model. Additionally, interesting results were found by studying the correlation between all variables, such as the association between the distance from the homestead and several soil properties (Fig. 4.2.3, Appendix 4.2.2). An important omission among the variables considered in explaining maize yield variability is related to the temporal dimension of the climatic conditions, particularly rainfall, and the effect of previous crops and/or management practices (i.e. rotation). Grain yield, instead of total biomass, was used as response variable to build the multiple regression models (Chapter 4). Grain yield estimations from plant measurements were as accurate as those of total biomass (Appendix 2.4.1), with the advantage that comparisons with yields estimated from the resource flow maps could be easily accomplished. However, grain yield is more susceptible to factors such as rainfall and temperature during the critical reproductive periods of maize development, and may introduce a strong variability in drier years. Such an effect was to some extent shown by the relative importance of planting date among the management factors affecting maize yield (Fig. 4.2.1 B, Tables 4.2.5 and 4.2.6), specially under the drier conditions of Aludeka and of more variable rains of Shinyalu (Fig. 4.2.2 B and Table 4.2.2). On the other hand, differences in the amount and *distribution* of rainfall from year to year may affect the relative importance of other explanatory variables. For example, variables that are associated with the water holding capacity of the soils (i.e. texture, soil organic matter, soil depth) would have a larger impact and possibly a greater relative importance in explaining maize yield variability during drier years. Crops growing on 'Fertile' fields, well managed and with a good initial development (i.e. a large leaf area) would suffer the most

from temporary water shortages. In other words, water and nutrient limitations may alternate as main factors affecting crop performance in the different fields between years. This concept is close to that elaborated by Brouwer and Bouma (1997), who demonstrated that soil (micro)variability might be exploited by farmers to achieve yield stability in the long term (i.e. including 'normal' and dry years). Nevertheless, the inclusion of the temporal variability by repeating this exercise in different years may yield much valuable information on the efficiency of resource use along a soil fertility gradient and its effect on crop performance.

6.2 Socio-economic and biophysical farm heterogeneity

The analysis at site scale revealed a socio-economic characterisation of the households that was in agreement with those found in previous works (e.g. Crowley and Carter, 2000) and in the district surveys (Kenya ministry of Agriculture and Rural Development, 2001). Gender and educational level of the household heads, family structure, wealth indicators such as livestock ownership, self-sufficiency of food and fuel, labour availability, and input use intensity varied widely between sites (and, of course, within sites). This made it difficult to adopt a wealth ranking that could be consistent across sites. As indicated by others (e.g. Place *et al.*, 2001), access to off-farm income appeared as one of the main variables affecting household livelihood and farm management across and within sites and, due to its importance, it was used as one of the criteria to categorise farms (Farm typology, see below).
The alternative sources of income available to farmers vary widely in terms of labour/returns ratios, and depend on personal qualification as well as on access to labour markets (i.e. proximity to urban areas). Off-farm income may have clearly different effects on soil fertility status. Cash flows generated by these sources of income allow a higher rate of input use but represent a shortage of labour in the farm that, according to the magnitude of these cash flows, may or may not be compensated by hiring casual labour. At all sites, farmers tended to remove the factor constraints partly by hiring land and labour. However, this was mostly restricted to the wealthier farms (i.e. types 1 and 2, and to some extent type 3 farms) and highly affected by the characteristics of the factor market: hiring labour was common in the more populated areas (Emuhaia) while hiring land was often seen in the less populated ones (Aludeka). Concomitantly, a trend towards production intensification was observed in Emuhaia, contrasting with the extensive production system relying on crop rotation and fallow practices and with virtually no use of fertilisers observed in Aludeka.

Farm system models: wealth, objectives, constraints

The inclusion of household objectives and factor constraints improved the categorisation of farms for identifying consistently different resource flow patterns with respect to the initial wealth stratification (Tables 3.2.2, 3.2.3 and 3.2.4, Fig. 3.2.3, Appendix 3.2.2). The relative importance given to both the classical wealth indicators (i.e. land size, cattle ownership, etc.) and the alternative sources of income gave insight in how that wealth is generated and re-invested, affecting resource flows within and between farms. Considering the age of the household head and the family structure was meant as a way of introducing the concept of the 'farm developmental cycle' (Crowley, 1997) in the farm categorisation. The attitude towards risk (investments) and innovation are highly variable according to the phase of the farm developmental cycle in which the household is (the land, capital and/or labour constraints are also related to this). The type and magnitude of the off farm income flow was also considered as a criterion due to its impact on resource flows (see above). Though this typology yielded quite site-specific results, the criteria behind it could be applied to all sites yielding resource flow map models that were comparable across sites. The five farm models proposed represent the outcome of the system characterisation phase as in a 'participatory modelling' approach (Herrero, 1999). They might set the basis for the development of farm system models that are required for multi-disciplinary approaches to soil fertility studies (e.g. the NUANCES framework). However, the number of categories included in this typology responded to the objective of identifying different resource allocation patterns, relevant to this study. Following a similar methodology but with different objectives may yield a different number of categories.

Categorising within-farm variability: a systematic approach vs. 'asking the farmer'

Fields within a farm were initially classified according to their relative position with respect to the homestead. This criterion, however, was not objective enough to distinguish management practices and was therefore complemented with a more general conceptualisation. In principle, the distance from the homestead affected the allocation of production activities and resources when labour was scarce and/or when a biophysical gradient existed within the farm, affecting the distribution of production units (i.e. when the house was built in the upper part of a topographic gradient and the farthest fields were in a valley bottom). When labour was available and/or when no association existed between farm layout and land quality, the distance from the homestead did not provide a clear differentiation between fields in terms of management.
A broader concept to classify fields is that in which the difficulty to access to or to implement crop husbandry practices in the fields is considered. Extremely steep fields are difficult to plough or to weed, while the valley bottoms below them are difficult to access carrying certain inputs like cattle manure. In areas of steep topography, such as Shinyalu, sloping fields may also be near the homestead. Closer fields and home gardens were of poor quality when they were on a slope or when the place chosen to build the house was (as often seen in Aludeka) rocky, sandy or with shallow soils. Alternatively, a land quality classification by farmers gave a more accurate differentiation of the soil fertility status, the type and frequency of management practices and the resource allocation criteria than the initially proposed field typology. In spite of being a subjective method (farmers classified their own fields without comparing them with other farmers'), the importance of involving the farmer improved the understanding of the resource allocation patterns, since what drives their decisions is what *they* perceive as good or poor quality land.

6.3 Production activities, resource flows and management practices

The resource flow maps helped in describing resource allocation patterns and choices of production activities that can be used to identify spatio-temporal niches for targeting soil fertility management strategies. However, the resource flow maps have a short time (seasonal) horizon, and they should be repeated to be used as a monitoring tool due to the dynamics of the system. Such dynamism is determined by shifts in technology, production alternatives, land degradation, markets and population growth. Farmers change and adapt their strategies in response to the dynamics of the system by identifying soil fertility (land quality) and market niches (i.e. multidimensional niches), and exploit them until a new shift is imposed by the above-mentioned factors. Probably one of the most conspicuous examples of niche identification, which summarises the adaptive and *dynamic* character of the farming strategies in response to a process of land degradation and increasing land availability constraints (and illustrates the influence of markets), is the current expansion of the area under Napier grass.

Napier grass is nowadays widely grown in the densely populated areas of western Kenya, and is often seen growing in public lands alongside the roads in places such as e.g. Emuhaia. It has become one of the main sources of forage for the livestock system (Kenya Ministry of Agriculture and Rural Development, 2001) and constitutes an emerging cash crop (Table 3.3.2, Appendix 3.1.3 and 3.2.3), specially for farmers without cattle. The reasons for the expansion of this crop in the area are, among others: (i) it is easy and cheap to implant (vegetative reproduction) and maintain, (ii) requires no inputs and stands relatively poor soil fertility, (iii) the constantly shrinking land size and the lack of communal range-lands generate a constant demand for forages, and (iv) it is easily handled and transported (in bundles mounted on a bicycle or as a head-load), which facilitates trading at farm gate or in local markets. Due to its relatively low quality as a forage (low N content) it has to be mixed with protein containing resources before being offered to cattle (ICRAF, 2001), thence opening up an opportunity (i.e. niche) for the introduction/utilisation of N-fixing forage legumes with the parallel purpose of restoring soil fertility. However, Napier grass is recognised as a high nutrient-demanding crop which depletes the soil after some years of continuous crop (Chamberlain, 2001), affecting the sustainability of such a (sub)system.

Nutrient balances and nutrient status within the farm

Most farmers in Emuhaia and Shinyalu used inorganic fertilisers, as revealed by the interviews and in agreement with surveys and other studies carried out in the region (Braun *et al.*, 1997). However, the application rates were extremely low and the nutrient (nitrogen) balances were negative in most fields. The partial nutrient balances at field scale also revealed the existence of C and N *accumulation* areas within the farm, chiefly in the home gardens and grazing sites. Household wastes and crop residues from other fields are brought to them under the form of compost or animal feeds, respectively. This resource flow pattern, however, was not always clearly reflected by the results of the soil analysis (Tables 4.1.5 and 4.1.6). The N balances simulated for the home gardens by means of the dynamic model showed the impact of processes such as leaching and/or the effect of management practices (e.g. planting date, plant density) on the sign of the balance, which were not accounted for by the *partial* balances. The accumulation effect in the home gardens of Emuhaia and Shinyalu was clearly observed for P, due to its low mobility, and to some extent for K and Ca, probably due to the application of ashes to those fields (Table 4.1.6). Nutrients accumulated in the home gardens would not be efficiently used by grain and pulse crops often sparsely planted and shaded by banana plants and trees, but they certainly sustain the production of nutrient-demanding vegetables in those fields for household consumption or for the market.

The main differences in soil fertility indicators between sites were related to inherent properties, such as soil texture, which determined to a large extent the C content (i.e. C saturation potential – Feller and Beare, 1997) and the related total N and P contents as well as the effective cation exchange capacity of the soils (Figs 4.1.1 and 4.1.2). However, most samples had values for the different indicators that were below the critical limits for sufficiency given in literature (e.g. Cochrane *et al.*, 1985; Landon, 1991). This was confirmed by the negative values of the soil fertility index obtained by spectral reflectance (SFI: the log probability of a sample to fall into the 'fertile' class – Shepherd, personal communication) for practically all the samples. Differences in soil fertility indicators (i.e. nutrient status) were also observed between field types in all sites (Tables 4.1.5 and 4.1.6). In Emuhaia and Shinyalu, the main differences in nutrient status between fields were observed for extractable P and exchangeable K, largely in favour of the home gardens (see above). In Aludeka, the close fields had the highest P and K concentrations, though the differences with respect to other field types were smaller (Table 4.1.6). The differences in soil C and pH between field types were not important when the average values for all the farms were considered (Table 4.1.5), though these indicators were highly variable in the samples from each particular farm and even within a single field. The soil fertility indicators varied accordingly with the land quality classification given by farmers (Table 4.1.7).

Soil fertility gradients and management intensity gradients

In spite of the site-specific factors, important differences in management practices related with crop husbandry were observed between field types and, specially, between land quality classes as perceived by farmers (Tables 4.1.8 and 4.1.9). These associations helped to demonstrate that management factors are inextricably related with soil fertility (compare for instance weed infestation levels between the 'fertile' and 'poor' fields in all sites – Table 4.1.9). Crop variability was mainly explained either by soil fertility or by management factors depending on the site-specific characteristics (Tables 4.2.4, 4.2.5 and 4.2.6). Among the soil fertility indicators, extractable P was the most important in explaining maize yield variability in all sites (Table 4.2.6). The relative importance of different management practices varied also for different sites (e.g. planting date was more important in areas of more variable rainfalls). In the smaller farms of Emuhaia soil variables explained a larger amount of the yield variability, compared with the management factors (Tables 4.2.4 and 4.2.5). However, more than 50% of the variation in maize yields for this site could be explained by means of a resource use intensity index (RUI, a score from 0 to 3), which indicates that management decisions may still overwhelm the underlying soil fertility in explaining crop growth performance. Unfortunately, the spectral soil fertility index (SFI) explained only a small amount of the variability in maize yields. This could be partly the result of the experimental design, since not all the range in soil fertility status but only samples from 'poor' soils were included, and not only soil fertility but also management and input use (co-) varied from field to field. However, single soil variables such as extractable P explained a larger amount of the yield variability than the SFI, in spite of these experimental constraints. On the other hand, these are the type of conditions (i.e. poor soils and large unaccounted variability) under which a quick method for soil fertility assessment is largely needed.

The dynamically calculated N balance at plot scale integrated all sources of variability (inherent and actual soil properties plus wealth and management) and their effect on N status in the system (cf. Table 5.3.1). Interactions and synergistic effects between soil fertility and management practices, as they occur in reality, could be studied with the simulation model. However, important growth-limiting and growth-reducing factors such as P availability and weed infestation were not included in the model. In spite of the absolute values calculated for the N balance at plot scale, which showed a different degree of agreement with previous calculations (e.g. de Jager *et al.*, 2001; Anthofer and Kroschel, 2002), it followed a similar trend as the different resource use efficiency indicators calculated (cf. Tables 5.3.1 and 5.3.2). The advantage of the N balance as an efficiency indicator is that it can be temporally aggregated to reveal trends in N depletion and accumulation, and then the effect of adopting a certain strategy can be studied for longer terms (i.e. several seasons or years) to monitor sustainability. Variations in the N balance and in other resource use efficiency indicators revealed widely different results when 'blanket' N fertilisations were simulated (Table 5.3.2 and Appendix 5.3 b), indicating that the magnitude and complexity of the soil fertility gradients should be considered when designing soil fertility management strategies. Such considerations are to some extent similar to those made by the farmer when making resource allocation decisions.

6.4 Summary and conclusions: The resource allocation cycle

The interaction between the factors from different origin and scales affecting soil fertility can be conceptualised by means of a cyclic diagram, the 'resource allocation cycle' (Figure 6.1). In a certain site the inherent biophysical conditions (i.e. agroecology) determine the 'initial' land quality (i.e. broad-sense soil fertility) of the different fields within a farm, which is at the same time affected by the level of resource endowment of the household. These factors interact with the specific socio-cultural and economic ones at that particular site (e.g. access to markets, tradition) to determine the choice of production activities[2] to be carried out in the various fields or production units. According to the technical requirements of such production activities, to expectations about their performance (i.e. risk), and to the level of resource endowment, management decisions are made and a pattern of resource allocation to the different fields within the farm emerges, largely constrained by socio-cultural values (i.e. costumes, tradition, acceptance).

In this context, both land quality properties and management factors will affect the basic soil, crop and animal processes that will in turn determine to a large extent[3] the (biophysical) performance of the several production activities, their efficiency and secondary effects (i.e. degradation). Choices of production activities and management decisions for the next cycle will be affected in some degree by the results of the present cycle, though the above mentioned biophysical and socio- economic factors specific for that site will remain chiefly determining those choices (Figure 6.1). The overall performance of the production activities carried out in the farm will have an impact on the wealth of the household. On the other hand, they will affect different aspect of the properties that define land quality in general, and soil fertility in particular (resulting land quality or actual soil fertility), which will represent the 'initial' conditions for the following cycle.

This simplified cycle constitutes a conceptual exercise that can be of help in the development of farming system models. It applies initially to seasonal periods and at field scale, but it can be adapted to different time steps and spatial scales. It is easier though to imagine such a cycle working seasonally for every single field and then try to aggregate it to a farm scale. In such a case, the boxes representing land quality and production

[2] According to the definition adopted while using linear programming optimisation models (de Haan *et al.*, 2000) a production activity includes the crop plus the management and/or resource allocation (i.e. inputs). Here, a distinction is made between both for illustrative purposes.

[3] It will not be the case if, for instance, the crops are attacked by a plague

choice/management should be multiplied as many times as different land qualities and/or production units are there in the farm, and the *interaction* between the resulting multiple 'boxes' identified. Whether the number of boxes necessary to represent a farm is determined by the number of land quality classes or of production activities depends on the interactions between the supra-scale factors (i.e. site-specific biophysical and socio-economic) and between those and the household wealth and objectives. In this respect, the origin and the magnitude of the soil fertility gradients will also play a key role when characterising farm systems, as it is exemplified below.

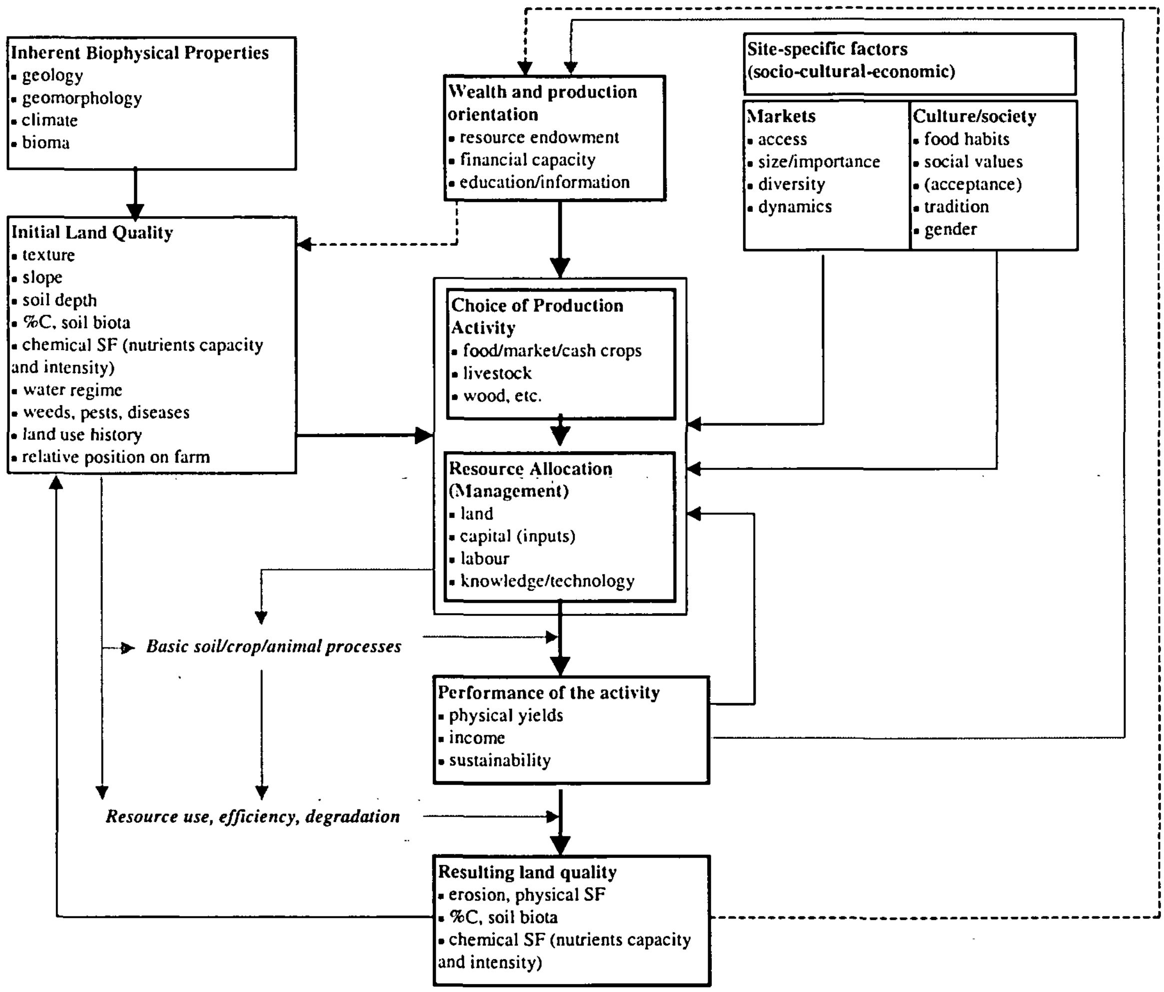

Figure 6.1: Illustration of the conceptual 'resource allocation cycle' in smallholder farming systems of western Kenya. The choice of production activities and decisions on resource allocation are determined by inherent biophysical as well as socio-cultural and economic factors and affected by household wealth. The consequent basic, underlying soil, crop and animal processes will affect the performance of the production activities and their efficiency, having consequences for the resulting land quality and impacting on wealth. The resulting land quality is what farmers face for the next step of the cycle.
Black lines indicate main effects or influences; grey lines indicate underlying processes; dashed lines indicate indirect and/or secondary effects.

In the semi-urban, densely populated localities such as Emuhaia, farms have an average size of less than a hectare, with a largely recognised soil exhaustion by continuous farming with few or no nutrient inputs. The magnitude of the within-farm soil fertility gradients in those farms (excluding the larger type 2 farms) tended to be relatively smaller than for the other sites (see e.g. the ranges in soil C, N and P in Fig.4.2.1, or the variability in maize yields at different distances from the homestead in Fig. 4.2.1 and Table 4.2.2 for Emuhaia); the differences in resource allocation to the various field types were less pronounced and crop rotation was prohibitive due to lack of land. In such cases, farming systems can be fairly characterised by their production activities as main components (e.g. maize/beans intercrop unit/s, banana/maize/local vegetables in the home gardens, Napier grass unit, and dairy livestock unit; see Appendices 3.1.3 and 3.2.3). They will determine the number of 'boxes' in a resource allocation cycle such as that of Fig. 6.1, but adapted to represent a scale of aggregation of the different fields within a farm (i.e. each box should represent a production activity).

Under these conditions, farmers make resource allocation decisions strongly driven by the production activities, which are partly dictated by the market (e.g. the expansion of Napier grass production) and by the household wealth and objectives. The land has been subdivided to such an extent that it tends to be homogenous in terms of its inherent biophysical properties (only large, wealthy farms have substantially different niches within their farms). For the same reason, farming has become a secondary activity for many farmers in a place like Emuhaia. Additionally, the importance of the box representing markets in Fig 6.1, particularly labour markets, should be highlighted due to (i) the impact of off-farm income on resource *in*flows to the farm, and (ii) the existence of a 'fresh' market (i.e. market for milk and vegetables in densely populated and peri-urban areas) affecting the type and amount of the flows from and into the farm.

By contrast, to characterise farming systems in distant and sparsely populated areas such as Aludeka, with a high variability in soil types, or where the main source of variability in land quality is originated by topography, as in Shinyalu, the differences in land quality should be considered from the starting point. As discussed in Chapters 3 and 4 farmers identified and managed (inherent and actual) soil fertility 'niches', allocating activities and resources according to their production potential (Table 3.3.2), and constrained by socio-economic factors. Different *soilscape* units could be identified within a single farm (Box 3.1.2) and one or more production units were counted within them, determining the number of 'boxes' necessary to represent the farm (i.e. each box should represent a land quality class). Certain management decisions such as crop rotation or fallow, depended on their feasibility (i.e land availability, particularly good quality land), whereas others, such as using nutrient inputs or weeding with hired labour, were mainly driven by the perceived land quality of those units (typically investing in the less risky, more fertile ones, see Figures 3.3.3 and 3.3.5, Tables 4.1.8 and 4.1.9). Such a resource allocation pattern leads to increasing the magnitude of the soil fertility gradients, as indicated by (i) the results from the resource flow maps in combination with the soil data, (ii) the association between soil fertility and management factors explaining maize yield variability, and (iii) the synergistic effects of management decisions and inherent properties on land degradation illustrated by the modelling exercise.

Concluding remarks

The set of hypothesis initially put forward postulated the facts that are summarised as follows. The soil fertility gradients originate from the inherent productivity of the soils plus the effect of the differential management practices that farmers consequently apply to them. The magnitude of such gradients, strongly affected by (site-specific) biophysical and socio-economic conditions, is sufficiently large to affect the basic soil and plant processes that dictate the efficiency of resource use and capture within the system. Their importance should be recognised (exactly as farmers do) and they should be targeted when designing soil fertility management strategies. The methodological approach combined different techniques to study the various aspects that appear in the central row of the resource allocation cycle in Fig. 6.1 (wealth, production activities, resource allocation, crop performance and resulting land quality), and led to the results that were discussed in the previous paragraphs. Additionally, some aspects of the methodology, and the adaptations made to them during the development of this thesis, helped in increasing the understanding of the managerial aspects of the household that affect the origin and magnitude of the soil fertility gradients. These considerations, plus the points discussed in the previous sections can be grouped (in the order in which they were discussed) in the following concluding remarks:

1 - Adding household objectives and socio-economic constraints to the resource endowment criterion, improves the performance of the farm categorisation procedure when management decisions, resource allocation patterns and nutrient flows are to be assessed.

2 – Considering farmers' perceptions in the characterisation of within-farm variability helps in identifying resource allocation patterns in relation to soil fertility gradients as well as niches to target soil fertility management strategies.

3 - Crop performance cannot be explained only by soil fertility variables. Alongside the variability in soil fertility, or as a consequence of it, a management intensity gradient is established, which interacts with the former to explain crop variability. It is not possible to unravel the effects of soil fertility and management, and their relative importance vary from site to site, strongly influenced by population density and access to markets.

4 – A dynamic simulation approach for the calculation of nutrient balances, build upon the system characterisation carried out in the field and in combination with the resource flow maps, allows for the assessment of the impact of management practices on the establishment of soil fertility gradients. It can be used to generate resource use efficiency indicators and to explore strategies that are alternative to 'blanket' fertilisations by adding the spatial and temporal dimensions to the nutrient balances.

5 - In an area of high population pressure (such as Emuhaia), the intensity of input use, the proximity to factor markets and the access to off-farm income override the inherent biophysical properties in determining the pattern of resource allocation and the magnitude of the soil fertility gradients within a farm.

6 - In areas of sparse population density and/or high variability in the inherent biophysical background, perceived land quality determines the resource allocation pattern emerging from farmers' management decisions. Since scarce resources and investments are preferably allocated to less risky land units, such a pattern operates in the direction of increasing the within farm soil fertility gradients.

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Appendix to Chapter 2

Contents No.

Appendix 2.1.3 – I Profile description of a representative/dominant soil in Emuhaia

Fertiliser use and recommendations programme – Maragoli Site (Gachene and Smaling, 1985)

Genetic horizon	Depth (cm)	Boundary	Morphological description
Ah1	0 - 23		Colour (moist) 5 YR 3/3 dark reddish brown. No mottling, no concretions. Clay texture. No cutans. Weak medium subangular blocky structure. Many very fine and fine, and common medium biopores. Friable; slightly sticky-plastic. Field pH not determined. Compacted due to tractor ploughing.
Ah2	23 - 40	Gradual smooth	Colour (moist) 2.5 YR 3/2 dusky red. No mottling, no concretions. Clay texture. No cutans. Weak medium subangular blocky structure. Many very fine and fine, and common medium biopores. Friable; sticky-plastic. Field pH 4.7.
Bu1	40 -70	Abrupt smooth	Colour (moist) 10 R ¾ dusky red. No mottling, no concretions. Clay texture. Patchy thin clay cutans. Weak medium subangular blocky structure. Many very fine and fine, and common medium biopores. Friable; sticky-plastic. Field pH 4.6.
Bu2	70 - 118	Diffuse	Colour (moist) 10 YR ¾ dusky red. No mottling, no concretions. Clay texture. Patchy thin clay cutans. Moderate fine medium subangular blocky structure. Many very fine and fine, and common medium biopores. Friable; sticky-plastic. Field pH 4.8.

Appendix 2.1.3 – II Profile description of a representative/dominant soil in Shinyalu

Fertiliser use and recommendations programme – Kakamega Site (Gachene, 1985)

Genetic horizon	Depth (cm)	Boundary	Morphological description
Ah1	0 – 23		Colour (moist) 5 YR 3/3 dark reddish brown. No mottling, no concretions. Clay texture. No cutans. Weak medium subangular blocky structure. Many very fine and fine, and common medium biopores. Friable; slightly sticky-plastic. Field pH 5.5.
Ah2	23 – 37	Gradual smooth	Colour (moist) 5 YR 3/3 dark reddish brown. No mottling, no concretions. Clay texture. No cutans. Weak medium subangular blocky structure. Many very fine and fine, and common medium biopores. Friable; sticky-plastic. Field pH 5.0.
BA	37 - 50	Clear smooth	Colour (moist) 5 YR ¾ dark reddish brown. No mottling, no concretions. Clay texture. Patchy thin clay cutans. Moderate medium angular blocky structure. Many very fine and fine, and common medium and few coarse biopores. Friable; sticky-plastic. Field pH 4.6.
Bt1	50 -80	Clear smooth	Colour 2.5 YR ¾ dark reddish brown. No mottling, no concretions. Clay texture. Broken moderately thick clay cutans. Moderate fine medium angular blocky structure. Many very fine and fine, and common medium and few coarse biopores. Friable; sticky-plastic. Field pH not determined.
Bt2	80 - 110	Gradual smooth	Colour 2.5 YR 3/6 dark reddish brown. No mottling, no concretions. Clay texture. Continuous thick clay cutans. Moderate fine angular blocky structure. Many very fine and fine, and common medium and few coarse biopores. Firm; sticky-plastic. Field pH 4.9
Bt3	110 –160 (augering)	Gradual smooth	Colour (moist) 2.5 YR 4/6 dark reddish brown. No mottling, no concretions. Clay texture.

Appendix 2.1.3 – III Profile description of a representative/dominant soil in Aludeka

Fertiliser use and recommendations programme – Alupe Site (Gachene, 1986)

Genetic horizon	Depth (cm)	Boundary	Morphological description
Ah	0 – 20		Colour (moist) 7.5 YR 3/2 dark brown. No mottling, no concretions. Clay texture. No cutans. Weak medium subangular blocky structure. Many very fine and fine, many medium and few coarse biopores. Firm; slightly sticky-plastic consistence. Field pH 4.9. Compacted due to tractor ploughing.
Bt1	20 – 34	Clear irregular	Colour (moist) 7.5 YR 3/2 dark brown. No mottling, no concretions. Clay texture. Patchy thin clay cutans. Moderate medium subangular blocky structure. Many very fine and fine, many medium and few coarse biopores. Friable; sticky-plastic. Field pH 4.4.
Bt2	34 –50	Clear irregular	Colour (moist) 7.5 YR 3/2 dark brown. No mottling; Fe concretions < 10% rounded (<4 mm). Clay texture. Patchy thin clay cutans. Moderate medium subangular blocky structure. Many very fine and fine, many medium and few coarse biopores. Friable; sticky-plastic. Field pH 4.4.
Btcs	50 – 80	Clear irregular	Colour (moist) 7.5 YR 3/2 dark brown. No mottling; Fe + Mn concretions, >25% rounded (<5 mm). Gravelly clay texture. Patchy thin clay cutans. Moderate fine medium subangular blocky structure. Many very fine and fine, many medium and few coarse biopores. Friable; sticky-plastic consistence. Field pH not determined.
Cms (murram)	+ 80	Diffuse	Colour (moist) 7.5 YR 3/2 dark brown.

Appendix 2.1.3 – IV Local names given to the main soilscape[1] units and their properties

Local names*	Identifiers	Key local criteria	Classification (FAO)	Characteristics
Luhya sites				
Ingusi	Dark soil, reddish or brown	Fine texture, deep, medium porosity to clayey, fertile to medium	Humic and ferralohumic Acrisols, Nito humic Ferralsols, dystro mollic Nitisols	Well drained, deep to very deep, yellowish red to dark reddish brown, friable to firm sandy clay, with an acid or a thick, acid humic top soil, on high lying areas and moderate slopes
Oluyekhe/ igulu	Sandy soils/low fertility soils	Variable, including eroded soils	Variable, some classified as orthic Acrisols or or dystric Cambisols	Complex of excessively drained soils or thick layers of sandy sediments over *Ingusi* soils, often associated with rocky outcrops and with low lying areas. Generally scattered on the landscape
Esilongo/ Shitambasi	Dark soils of valley bottoms	Lack, smooth, high fertility, valley bottom	A complex of Gleysols with Vertisols and Histosols	Complex of poorly to imperfectly and well drained, deep, very dark grey to brown and black, mottled, firm consistency and fine textures
Eviyalu/ m'machina	Murram soils	Gravel on surface, stony	Regosols with ferralic and humic cambisols, lithic, rocky and stony Lithosols	Excessively drained, stony soils that may appear on surface or at different depths underlying *Ingusi* soils
Teso site				
Apokor	Dark red soils	Loamy clay dark reddish brown	Orthic and ferralo-orthic Acrisols with orthic Ferralsols, partly petroferric phases	Well drained, moderately deep to deep, dark reddish brown to strong brown, sandy clay loam to clay, over petroplinthite, in places shallow. Fertile
Asing'e	Sandy soils	Porous, low fertility	(ferralo-) orthic Acrisols, petroferric phase, with ferralic Arenosols	Well to excessively drained, sallow to moderately deep, dark yellowish brown to brown, friable sandy clay loam; over petroplinthite
Ongaroi	Murrams	Gravely, brown or red, infertile	Dystric Regosols and Rankers	Complex of excessively drained , shallow, stony and rocky soils of varying colour, consistency and texture
Akapian	Swamps	Clayey, fertile, black or dark, watery	Dystric Planosols, dystric and vertic Gleysols and pellic Vertisols and saline-sodic phases	Complex of imperfectly to poorly drained, deep to very deep, very dark grey to brown, mottled, sandy clay to clay, in many places abruptly underlying a sandy loam topsoil

*The Luhya names apply to Emuhaia and Shinyalu and the Teso names to Aludeka. Linguistic differences were found between the former two sites. Sources: Folk ecology project – TSBF, 2001; Participatory characterisation and on-farm testing in Mutsulio villlage, Kakamega – KARI, 1999.

[1] The same local names are often given to the soil as well as to the position in the landscape. For example, the swampy areas in Aludeka are called Akapian, as well as the soil type found there.

Appendix 2.2.2 First approach questionnaire

Form for first approach (quick) farm description

Date
Nr.order

Site (district, division)
Village
Farm/er identification
Potential wealth class (estimation)

Family members / labour use

Name of head of household	Sex	Marital status	Education

(number)		(estimated amount)
Male and female household members		Use own labour
Living and working on the farm		Hire casual labour
Living in farm working full-time elsewhere		Both
Living in farm working part-time elsewhere		Permanent labour
%of income coming from farming		If hiring, for what activities?

Land use and soil management

General		Specific
Farm size (owned and hired)		Fallow some land
Number of units (low and high quality)		Crop rotation
Cropped land (%)		Compost
Woodlot		Legumes
Cash crops (type, proportion)		Cattle manure
Food crops (type, proportion)		Inorganic fertilisers
Livestock (types and units)		Food (maize) production
Market for outputs		Self-sufficiency / surplus
Market for inputs/food		Use of hybrids

Farm sketch and other comments

GPS measurements

Homestead		Participation in previous projects
Corners		
Cattle/poultry facilities		Extension services
Others		

Appendix 2.3.1 – I On farm procedure for Resource flow mapping[2]

Objectives

- To visualise farmers' soil fertility management practices and analyse their management strategies
- To identify factors driving decision making processes in terms of resource allocation;
- To gain insight in farmers' perception of soil fertility variability within their farms;
- To collect basic data on inflows, outflows and internal flows for the calculation of nutrient balances and for the parameterisation and validation of simulation models;
- To identify management patterns that can be used to generate a field typology and to set scenarios for simulation model-aided studies.

Farm(er)s selection

In each working site (i.e. Emuhaia, Shinyalu and Aludeka) one farm was selected out of each of the five farm types previously identified, totalling 5 farms per site. To make sure that the selected farms were representative enough and suitable for the resource flow map exercise, the following main criteria were considered:

1. The farm type to which the farm belongs, with emphasis on the wealth component of the typological criteria;
2. The topographic situation of the farm, as well as the soilscape unit/s to be found within it. Farms placed in the upper- or lowermost extremes of a soilscape sequence were avoided;
3. The production activities and income sources should be 'common' for the site and farm type to which the selected farm belongs;
4. Farmers should show willingness to participate in the resource flow map exercise and be collaborative and quite eloquent. They should show a high degree of involvement in farming activities so as to provide information as accurately as possible.

Developing symbols and codes[3]

Symbols and codes are needed to represent farm components, crop produce and residue flows, production and household inputs, etc. Arabic numbers were used to identify the different fields (primary production units) within the farm. Arrows were used to indicate shifts in production activities (e.g. crop rotation) and all types of flows: red arrows represent input flows, blue arrows are outputs (produce) and black arrows are crop residues. Several variants of cycle arrows represent crop residue management patterns (grazing of standing residues, burning, etc.).
Symbols used to represent crops, livestock and farm components were agreed upon with each farmer before or during the resource flow map exercise. However, in some cases farmers adopted symbols that had been previously developed by other farmers (depicted on a flip chart). This had the advantage of enabling farmers to understand maps drawn at other farms.

Simplified stepwise field procedure

1. Farms were visited and the objectives, procedures and expected results were explained to the farmers. An initial tour through the farm was used to observe the farm layout, the production activities and to identify boundaries, production units and other relevant farm features;
2. The household heads were requested to choose a suitable place for drawing the map, and all necessary materials were provided (paper, colour pens and the list of symbols);
3. Farmers were guided to draw the farm boundaries, the different fields, the homestead, livestock facilities, waste heaps or composting units, wood lots, etc. Production units were numbered starting from the compound fields (# 1). Annexed and/or hired fields during the season under study were represented by a square figure outside the farm boundaries;
4. Farmers were guided to identify and picture – by means of symbols – the production activities that were taking place in each field, and those that had taken place the previous season. An arrow was drawn connecting both activities (the previous one on the left hand side, the current one on the right hand side), representing the shift;
5. Farmers were requested to represent the use of inputs (i.e. fertilisers) in the different fields during the season under study as well as their origin by means of red arrows. Quantities indicated by the farmers were recorded on the map and on questionnaire forms;
6. The main outputs (crop and animal produce) from the different production units and their destination (i.e. household consumption, market) were identified. Farmers were requested to quantify those and /or to estimate yields

[2] The procedure followed is largely based on the experiences gained in the region by Mr. Rotich at KARI - Kakamega and by colleagues Izaak Ekise (TSBF) and Walter Munyuere (Kenya Agricultural Extension Service).
[3] Ir. Simone de Hek is specially acknowledged for her collaboration at this point

from fields that had not been harvested at the time of the interview. Quantities that were expressed in local units were converted into formal units in agreement with the farmer;

7. The pattern of residue management at each field was identified by asking the farmers to estimate the percentage of crop residues that were left on the field, burnt, composted or fed to animals, using stones or fingers[4];

8. Farmers were interrogated about the timing and labour requirements of different activities regarding farm management during the season, recording the answers by drawing a timeline representing the different phases of a typical maize/bean intercrop;

9. The final outputs (Maps) were discussed with the farmer and cross-checked with other family members and/or neighbours present. The perceived value of such an exercise was discussed with the farmer and concluding remarks were drawn from the outputs.

Most quantitative information required for the calculation of nutrient balances was recorded in the forms presented in the following appendices.

[4] This implies asking the farmer questions of the type "out of this ten fingers representing the totality of crop residues, how many of them would represent the amount of residues used as fuel in the kitchen?"

Appendix 2.3.1 - II Farmers' perception of soil fertility gradients - resource flow maps*

Soil fertility management and resource flows

Date
Nr.order

Site (district, division)
Village
Farm/er identification
Potential wealth class

Sub-division of farm according to farmer's criteria (indicate in reource flow map)

Farm parts (niches)

Criteria for classification

Soil type	Slope
Soil texture	Weed type
Water holding capacity	Distance from homestead
Fertility	Others

Farmer's perception and management

1 How long have you lived on this land?	2 Rank most important crops based on their use.
3 Last season harvest (amount) of five major crops	4 Has the amount harvested changed during last 10 years? (How? / Why?)

5 Reasons for differences in yield between fields (relate to plots and resource flow map) Pest or diseases Use of different varieties Management inputs Water-logging/erosion Declining soil fertility Others

6 When do you usually prepare your land? (before, just, after rains begin)	7 Does it vary with plots (niches)? In which order and why?

Other comments, observations

Soil fertility management practices

Plot nr./crop (owned/hired)	Expected Yields	Inorganic fertilisers Type	 Amount	Organic fertilisers Source/type	 Amount	Previous and next crops (rotation)	Crop residues management

* the last section of this questionnaire shows basically the same kind of form accompanying the resource flow map, though in a condensed version. The first two sections were used to gather information in 45 farms in total, whereas the last chart was completed only for 15 farms.

Appendix 2.3.1 – III Resource flow maps

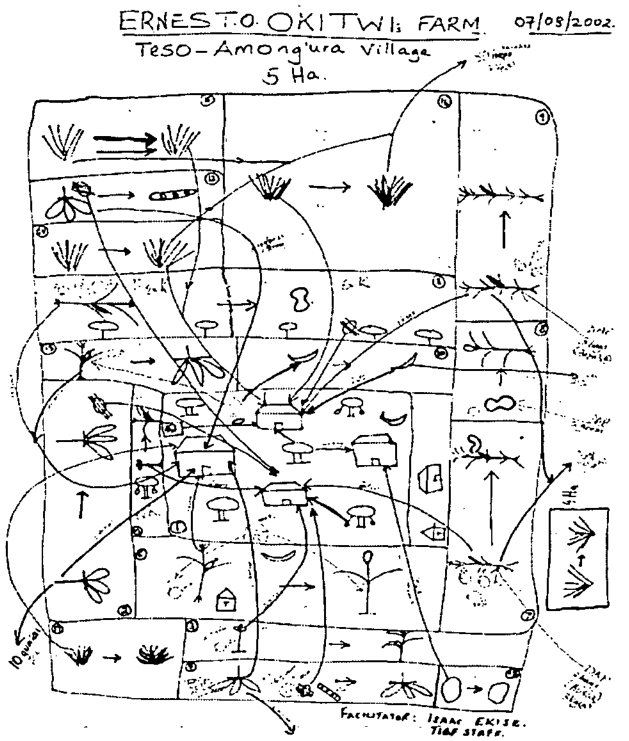


Figure a: A resource flow map drawn at Ernest Okitwi's farm in Aludeka site (Amon'gura village, Teso district, western Kenya). Red arrows indicate inputs, blue arrows outputs and black arrows residues or fuel materials flows. In each plot (field) crop rotation is indicated by drawing a symbol of the crops grown in the first and second rainy seasons, connected by an arrow. The plot drawn outside the farm represents an annexed (owned) piece of land.

Picture b: Mr. Isaac Ekise (TSBF staff - front) facilitating the resource flow map exercise at Mr. Ernest Okitwi's (back) farm in Aludeka site.

Appendix 2.3.1 - IV Sampling points, geo-references, land use and infrastructure

Detailed farm description

Date
Nr.order

Site	
Village	
Farm/er	
Class	

Plot no.	Location within farm	Use (crop type)	Size (m x m)	Soil observations			GPS Lat/Long	Slope %	Boundary type	Soil erosion control measures
				Sample	Profile	Texture				

Profile descriptions

Obs	Location within farm	Topogr. Position	Slope %

Horizons

nr.	morphology (structure)	depth (cm)	colour	Text.	Roots (1- 3)	compactness (impedance)	Other comments
1							
2							
3							
4							
5							
6							
7							

Obs	Location within farm	Topogr position	Slope %

Horizons

nr.	morphology (structure)	depth (cm)	colour	Text.	Roots (1 -3)	compactness (impedance)	Other comments
1							
2							
3							
4							
5							
6							
7							

Appendix 2.3.4 Soil condition classification using soil spectral libraries[5]

For applications such as soil fertility evaluation it is often sufficient to classify a soil with respect to a critical test value, rather than needing the precise estimate of a soil property. That is the case when an indication of soil condition is obtained from screening tests used to screen soils into soil fertility classes at watershed scale. The soil condition (F) of a watershed, at a hypothetical point in time, can be mathematically represented as:

$$F(\Phi) = \sum_s p_s \, MVN(\mu_s, \Sigma_s)$$

where p is the proportion of soil sampling units in condition (s), which may be ranked on an ordinal scale from, for instance, good to poor in s classes, and $MVN(m_s, S_s)$ are the respective multivariate normal probability densities of measurement endpoints (or soil condition indices with mean vectors m_s and covariance matrices S_s).
Ten commonly used agronomic soil fertility indicators were used to estimate parameters in the above equation for three soil classes: 'good', 'average' and 'poor' for a subset of $n = 801$ soil library samples originating from 267 plots in the Kenya Lake Victoria Basin (tropical soils). The soil fertility indicators used were pH, clay, silt, ECEC, Ca, Mg, K, P, organic C, and mineralisable N potential. The model was fitted using the Expectation-Maximisation (EM) algorithm as implemented in the graphical modelling software MIM® v. 3.5 (Edwards, 2001). Where necessary, Box-Cox transformations (Box and Cox, 1964) were applied prior to analysis to obtain approximately multivariate normally distributed values. The posterior probability for a new observation (x = vector of soil properties) belonging to a given class (s), is calculated as:

$$Pr(s \mid x) = p_s \, MVN(x, \Sigma_i) \, / \sum_s p_s \, MVN(x, \Sigma_i)$$

with s equal to G, A or P (good, average or poor), and for which p_s represents the respective proportion of the three condition classes. Using a one-third holdout sample for validation, reasonable predictive performance was achieved for all the soil screening tests (see results in web-site cited below) with positive likelihood ratios ranging from 2.7 to 11.4.
This measurement of the likelihood (log probability) of a certain soil sample to belong to a certain class is what is used here as a soil fertility index (SFI). Thus, the SFI index is the log odd ratio of being in the good (fertile) soil class. It ranges from negative (low odd ratios) to positive values (high odds ratios). An odds ratio is another way of expressing a probability. Thus the higher the number the higher the probability of being in the good soil class, and negative values for SFI correspond to soil samples that are far from falling within the 'fertile' or good class. Table a gives the definition of the screening tests with the critical limits adopted for the soil fertility classes (other soil parameters were not included due to their high correlation with those in Table a).

Table a: Definition of soil fertility screening tests (adapted from Shepherd and Walsh, 2002)

Soil test*	Critical limit**	
	Low	High
pH, units	<5.5	>7.3
ECEC, $cmol_c\ kg^{-1}$	<4.0	>8.0
Exchangeable K, $cmol_c\ kg^{-1}$	<0.2	>0.4
Extractable P, $mg\ kg^{-1}$	<7	>15
N min. potential, $mg\ kg^{-1}\ d^{-1}$***		>4.1

*pH in 1:2.5 soil/water suspensions; ECEC = sum of exchangeable acidity and exchangeable cations.
**If the logical condition is met then the case is classified as abnormal, else normal.
***Based on the 67^{th} percentile of N mineralisation potential values in the soil library.

[5] An extended and more detailed version of this procedure appears in the web page: www.worldagroforestrycentre.org. Dr. Keith Shepherd is thankfully acknowledged for his support and advice during the design of the sampling, the lab work, the processing of the data as well as for his authorisation to reproduce these notes.

Appendix 2.4.1 Allometric models: Calibration of the relationship between plant morphology and yield of maize

Objective

To identify mathematical relationships between easy, non-destructive measurements of plant morphological attributes and yield of maize stands in order to be able to (i) estimate yields of maize stands on-farm through simple measurements, (ii) have useful measurements of variables such as dry matter content and harvest index for the locally grown varieties and (iii) relate farmer's yield indicators (cob length and thickness, color, etc.) with actual measurements of biomass and grain yields.

Procedure

Plant measurements and biomass harvests taken from TSBF's experimental plots in Nyabeda -where different trials on soil fertility options for maize crops are conducted and from on-farm plots demarcated in farmers' maize fields at Msinde (Vihiga district), Shinyalu (Kakamega district) and Aludeka (Teso district). Plant materials included were the commonly used hybrids HB 513, HB 614 and HB 622 and the local varieties *Nyamulu*, *Isokha* and *Otati.*

Individual plants (20 to 30 for each cultivar) that were in a mid-grain filling stage or later were selected covering the range of morphological features found in the field and demarcated with tabs. For each of them height to top of the tassel, cob length from its insertion in the main stem and cob diameter in its thickest part were measured at development stages ranging around physiological maturity. A score from 1 to 3 (0=absent, 1=low, 2=medium, 3= high) was adopted to classify general growth performance, colour and deficiency symptoms (purpling, yellowing and browning). Presence of weeds and particularly *Striga* sp. infestations were scored using the same scale. Presence of pests and diseases, soil and landscape characteristics and any relevant information on management were properly recorded. The individual plants previously measured were harvested at maturity for determination of total and grains fresh and dry yields per plant (TFM, GFM, TDM and GDM, respectively, in g $plant^{-1}$).

At the same sites and for all cultivars plots of 3.5 x 1.5 m (validation plots) were demarcated in different spots on the field, trying to capture the variability in terms of plant growth performance, plant density, weeds infestation, deficiency symptoms, etc. In each plot the plants and cobs were counted, the distances between rows and between plants in a row were measured at 6 different positions and all the measurements described above (plant height, cob diameter, etc.) were repeated. The validation plots were bulk harvested at the same time and total and grain fresh and dry yield (TFW_{obs}, GFW_{obs}, TDW_{obs} and GDW_{obs}, respectively, in t ha^{-1}) calculated.

Simple and multiple linear regression models (allometric models) were fitted between plant morphological attributes and total and grain yields per plant (Table 1). These relationships, together with the plant population per plot calculated from the measurements on plant spacing were used to estimate total and grain yields (TFW_{exp}, GFW_{exp},TDW_{exp} and GDW_{exp}, respectively, in t ha^{-1}). Yields estimated in this way were contrasted with the yield measurements from the validation plots.

Results

Table 1 presents the different allometric models to estimate maize total and grain dry matter yields per plant (GDM and TDM) from non-destructive measurements of plant height, cob length and diameter for the most often grown varieties in the different working sites. Examples of the relationship between plant height and grain yield per plant are illustrated in Fig. 1 for the three local varieties included. All regressions were highly significant ($P < 0.001$). For hybrid 614 no measurements of cobs were performed and therefore only simple regression models were fitted. Simple linear regression models using cob variables were far less accurate (data not shown). The best model to estimate grain yield (g $plant^{-1}$) varied with each cultivar. Estimations of total biomass yield (g $plant^{-1}$) by including all three variables (height, cob length and diameter) showed the highest accuracy (R^2 around 0.9). However, the accuracy of the estimations of both total and grain yield per plant are not substantially improved by the inclusion of cob measurements in most cases. A major limitation of all these models for the local varieties is their intercept, implying that they cannot be used for maize stands with average plant heights lower than ca. 100 cm for GDM or ca. 260 cm for TDM. In most cases, however, GDM estimations can be carried out without problems considering the average plant heights observed in the field.

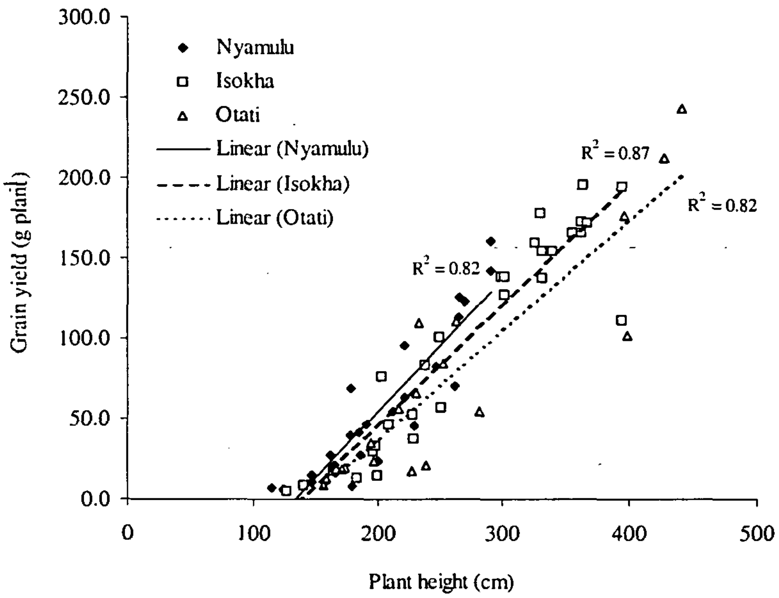


Figure 1: The relationship between plant height to top of the tassel and grain yield per plant for three local varieties of maize grown in western Kenya. The equations of the linear regression lines are given in Table 1.

Table 2 presents average values for dry matter content (DMC, %) of the total biomass at harvest and average harvest indexes (HI) for the genotypes included in this experiment. The importance of these measurements resides in their use as parameters for the calculation of nutrient balances (Resource flow maps) and to parameterise simulation models.

Table 1: Allometric models for on-farm maize yield estimation, from plant measurements taken at the development phase of late grain filling (c.a milky stage)

Cultivar	Explanatory Variable/s	*n*	Grain dry matter (GDM) estimations (g plant^{-1}) Model	R^2 / significance	Total dry matter (TDM) estimations (g plant^{-1}) Model	r2 / significance
			Simple linear regressions			
Local variety 'Nyamulu'	Ht	25	*GDM = 0.827*Ht – 111.2*	0.82 ***	*TDM = 1.908*Ht - 253.4*	0.85 ***
Local variety 'Isokha'		29	*GDM = 0.759*Ht – 106.6*	0.87 ***	*TDM = 1.983*Ht - 296.9*	0.89 ***
Local variety 'Otati'		19	*GDM = 0.688*Ht – 101.5*	0.82 ***	*TDM = 1.751*Ht - 248.3*	0.84 ***
Hybrid 513		26	*GDM = 0.451*Ht - 24.3*	0.76 ***	*TDM = 1.148*Ht - 52.8*	0.88 ***
Hybrid 614		20	*GDM = 0.283*Ht - 32.5*	0.77 ***	*TDM = 0.758*Ht - 60.7*	0.80 ***
Hybrid 622		28	*GDM = 0.262*Ht - 16.3*	0.78 ***	*TDM = 1.819*Ht - 230.6*	0.83 ***
			Multiple linear regressions			
Local variety 'Nyamulu'	Ht, Tk	25	*GDM = 0.5226*Ht + 21.93*Tk – 148.5*	0.89 ***	*TDM = 1.35*Ht + 40..2*Tk - 321.7*	0.89 ***
Local variety 'Isokha'		29	*GDM = 0.717*Ht + 3.02*Tk - 114.3*	0.87 ***	*TDM = 1.8*Ht + 13.3*Tk - 330.7*	0.88 ***
Local variety 'Otati'		19	*GDM = 0.524*Ht + 9.99*Tk - 118.6*	0.83 ***	*TDM = 1.296*Ht + 27.9*Tk - 296.2*	0.86 ***
Hybrid 513		26	*GDM = 0.3302*Ht + 14.06*Tk - 73.7*	0.79 ***	*TDM = 0.907*Ht + 28.0*Tk - 151.3*	0.90 ***
Hybrid 622		28	*GDM = 0.152*Ht + 8.97*Tk - 36.9*	0.81 ***	*TDM = 1.105*Ht + 58.1*Tk - 364.3*	0.87 ***
Local variety 'Nyamulu'	Ht, Tk, Lg	25	*GDM = 0.417*Ht + 16.82*Tk + 1.16*Lg - 128.4*	0.89 ***	*TDM = 0.921*Ht + 19.5*Tk + 4.71*Lg - 240.4*	0.91 ***
Local variety 'Isokha'		29	*GDM = 0.369*Ht + 5.91*Tk + 1.829*Lg - 99.9*	0.89 ***	*TDM = 1.103*Ht + 19.1*Tk + 3.66*Lg - 302*	0.90 ***
Local variety 'Otati'		19	*GDM = 0.380*Ht + 6.23*Tk + 1.60*Lg - 109.5*	0.84 ***	*TDM = 0.709*Ht + 12.6*Tk + 6.5*Lg - 259.4*	0.91 ***
Hybrid 513		26	*GDM = 0.347*Ht + 18*Tk - 0.62*Lg - 82.8*	0.78 ***	*TDM = .881*Ht + 22.0*Tk + .95*Lg - 137.3*	0.90 ***
Hybrid 622		28	*GDM = 0.166*Ht + 10.1*Tk - 0.317*Lg - 37.6*	0.81 ***	*TDM = 1.051*Ht + 53.9*Tk - 1.22*Lg - 361.9*	0.87 ***

Explanatory variables: Ht = plant height to top of the tassel [cm]; Tk = cob diameter in the thickest section [cm]; Lg = cob length [cm].
Significance: *,** and *** indicate probability levels for the regression ANOVA of 0.05, 0.01 and 0.001, respectively.

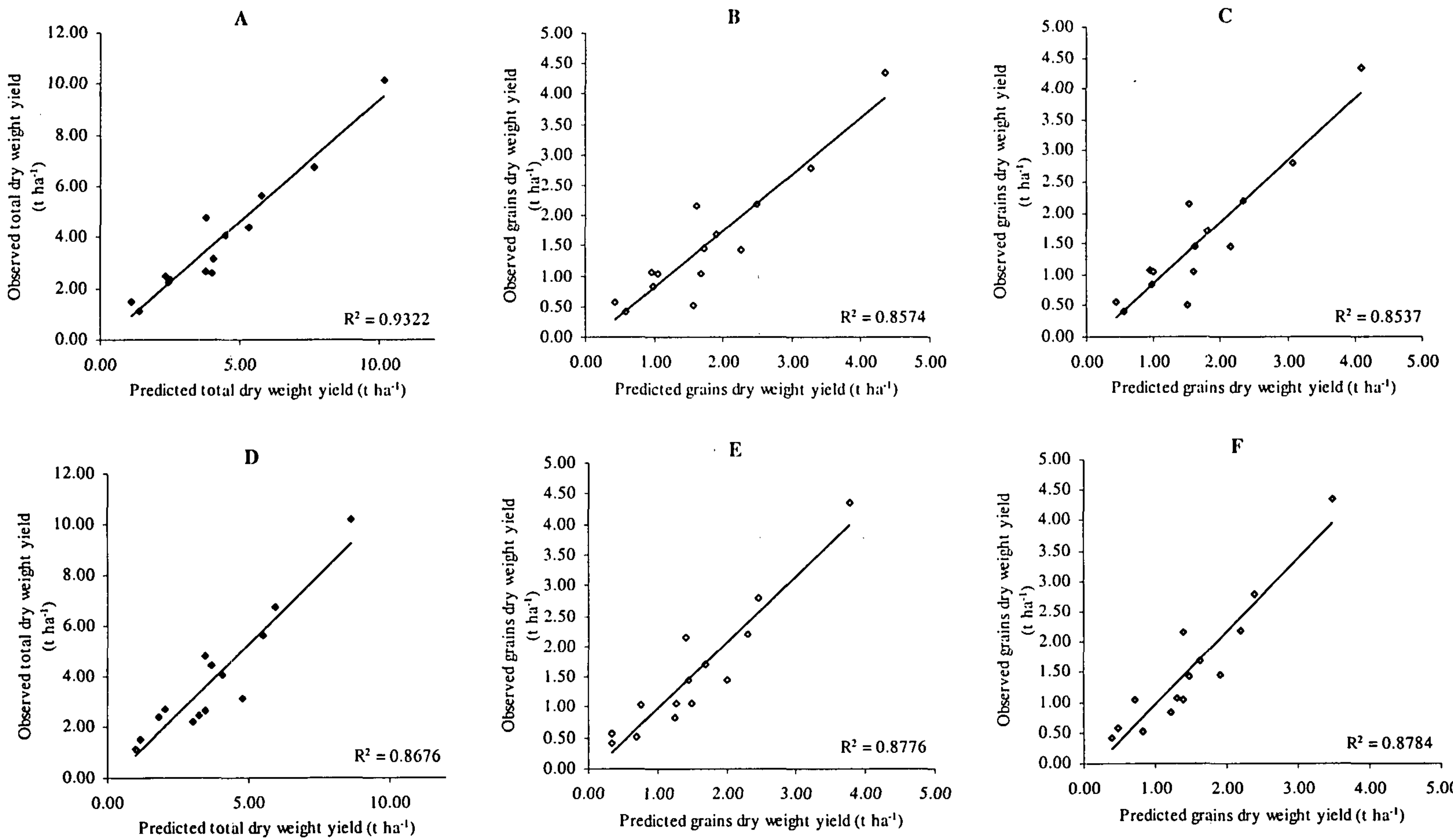


Figure 2: Yield estimations using the allometric models developed for the local maize variety *Nyamulu* (Predicted) vs. measured yields form the experimental plots (Observed). Total and grain dry matter yield estimations by means of simple linear regression models with plant height (A and B) and of multiple linear regression with plant height, cob length and diameter (D and E). Grain dry matter yield estimations by multiplying the average harvest index of the validation plots times the total dry matter yield estimated by simple (C) or multiple (F) linear regression.

Figure 2a-f illustrates the results of the validation for the local variety *Nyamulu*, by comparing independentky measured yields with the yield estimates obtained (i) by using the simple linear regression with plant height (Fig. 2a-c) and (ii) by using the multiple linear regression with plant height, cob length and diameter (Fig. 2d-e). The total and grain yields (TDW_{exp} and GDW_{exp}, in t ha^{-1}) estimated using the allometric models and the plant population for the validation plots were acceptably accurate (R^2 0.85 to 0.93) when compared with the corresponding yields (TDW_{obs} and GDW_{obs}) measured on them (Fig. 2a, b, d and e). Since TDW estimations tended to be more accurate, an alternative way of estimating GDW considered the average harvest index for the cultivar through the following calculation: *GDW = TDW * HI.* The accuracy of the estimations, however, was not improved (Fig. 2c and e).

Table 2: Average dry matter content of total and grain biomass and harvest index for the maize cultivars mostly grown in the region (Standard deviations are indicated in *Italics*)

Cultivar	Site of major adoption	Dry matter content of total biomass at harvest (%)	Harvest index
Nyamulu	Emuhaia*	57.4 +/- *0.09*	0.40 +/- *0.06*
Isokha	Shinyalu	64.8 +/- *0.11*	0.41 +/- *0.07*
Otati	Aludeka	63.4 +/- *0.10*	0.36 +/- *0.09*
HB 513	Emuhaia and partly Aludeka	47.7 +/- *0.10*	0.37 +/- *0.02*
HB 614	Shinyalu and Emuhaia	52.0 +/- *0.05*	0.42 +/- *0.06*
HB 622	Aludeka	51.9 +/- *0.11*	0.34 +/- *0.04*

*This is not the name given to the local variety in Emuhaia but *Munyore*. Both plant materials are extremely similar and are used under the same agroecological conditions

Appendix 2.4.2 Form for maize growth performance

On-farm assessment of maize growth

Scoring

1 low
2 medium
3 high

Date

Nr. order

Site	
Village	
Farm/er	
Class	

Plot no.	Location within farm	Variety	Sow. date	Stage	Plant dens.	Growth performance					General growth score	Deficiencies			Weed	Striga	Comments
						Colour	Height	Stem diam.	Ear length	Ear thick.		Purpling	Yellowing	Browning			
					pl/m^2	(1 - 3)	(m)	(cm)	(cm)	(cm)	(1 - 3)	(1 - 3)	(1 - 3)	(1 - 3)	(1 - 3)	(1 - 3)	

The number and size of the cells in this chart have been condensed to fit in the page. Each measurement point (plot) included at least 20 plants, and between 2 and 6 measurement points were taken per farm.

Appendix 2.5.1 Variables in the multiple regression analysis

Table 2.5.1: Variables included in the multiple regression models to explain maize yield variability

Variable	Units	Determination/calculation
Inherent properties (IP)		
Field slope	%	Direct measurement (clinometer)
Soil depth	m	Observation pits (transect walks – soilscape)
Texture (Clay, silt, sand)	%	TSBF Laboratory*
Sol fertility (SF)		
Soil organic carbon (SOC)	$g\ kg^{-1}$	TSBF Laboratory*
Total soil nitrogen (Nt)	$g\ kg^{-1}$	TSBF Laboratory*
C:N ratio	-	SOC / Nt
Total P (Pt)	$g\ kg^{-1}$	TSBF Laboratory*
C:P ratio	-	SOC / Pt
Extractable P (P_{extr})	$mg\ kg^{-1}$	Modified Olsen
Exchangeable Ca, Mg, Na, K and H	$meq\ 100\ g^{-1}$	TSBF Laboratory*
Exchangeable bases ($Bases_{exch}$)	$meq\ 100\ g^{-1}$	Sum of Ca_{exch}, Mg_{exch}, Na_{exch} and K_{exch}
Effective cation exchange capacity (ECEC)	$meq\ 100\ g^{-1}$	$Bases_{exch} + H_{exch}$
Base saturation	%	($Bases_{exch}$ / ECEC) * 100
Ca saturation	%	(Ca_{exch} / ECEC) * 100
pH water (1: 2.5)	-	TSBF Laboratory*
Soil fertility index (SFI)	-	Spectral reflectance (likelihood ratio)*
Management factors (MF)		
Planting date index (PDI)	-	(actual pl. date – optimum pl. date) / optimum pl. date
Plant density	plants m^{-2}	Direct measurement on farm
Resource use index (RUI)	-	On farm scoring (0 = no use to 3 = intense use)
Weed infestation	-	On farm scoring (0 = low to 3 = high)
Striga spp. infestation	-	On farm scoring (0 = low to 3 = high)
Distance from homestead index (DHI)	-	distance to homestead / maximum possible distance

*see method description in the main text

Appendix 2.6.1 Time step of the simulation model

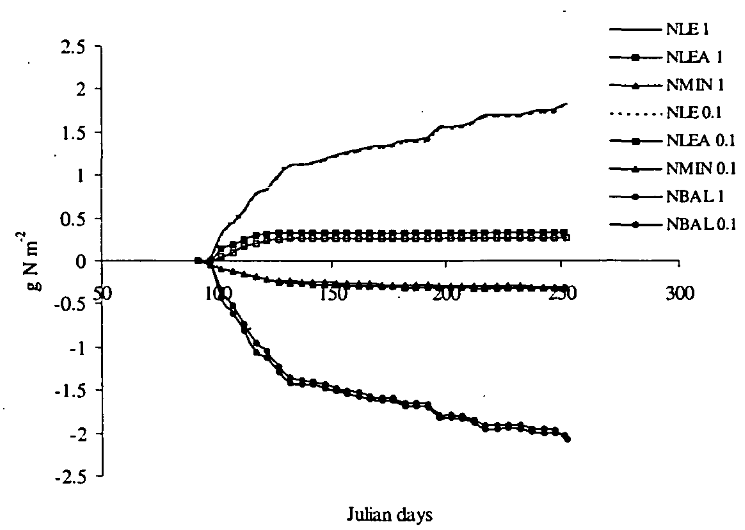


Figure 2.6.1: Variations in the calculation of the nutrient balance (NBAL), and the N flows by erosion (NLE), leaching (NLEA) and mineralisation (NMIN) by changing the time step of the simulation from 1 day to 0.1 day.

Appendix 2.6.2 Model listing: Dynamic nitrogen balance at plot scale

The model is subdivided in different modules (sub-models) according to the processes they simulate. Each module was numbered after the section in the main text where it is described. For the description of the several state and rate variables and their units see main text.

```
DEFINE_CALL PENMAN(INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,    OUTPUT,OUTPUT)

TITLE DYNAMIC NITROGEN BALANCE
INITIAL

**********************************************************************
*INITIAL CONDITIONS
**********************************************************************
*WLTI        amount of water in topsoil layer (mm)
*AOF,ASL,AY relative ages of organic fertiliser, old
*            and young soil organic matter, respectively
*IDW         initial dry weight (g/m2)
*ILAI        initial leaf area index (m2/m2)
INCON ZERO= 0.; WLTI = 100.;  AOF = 1.41 ; ASL= 24.; AY = 4.;...
      ILAI= 0.0074

**********************************************************************
*RUN CONTROL
**********************************************************************
TIMER STTIME=72.; FINTIM=351.; DELT=1.; PRDEL=5.

PRINT NBAL,NLE,NLEA,NMIN,NREM,SOILMN

TRANSLATION_GENERAL DRIVER= 'EUDRIV'

**********************************************************************
*PARAMETERISATION
**********************************************************************
*--------------------------SITE AND FIELD----------------------------
*BULKD  topsoil bulk density (kg/m3)
*SOC    topsoil organic carbon content(%)
*SOMCNI Initial C:N ratio of soil organic matter
*YOMCNI Initial C:N of young organic matter
*OLD    fraction of total soil OM that is in the old pool
*AREA   plot area (m2), 1 m2 considered
*CLAY   clay content of topsoil (g/g)
*PH     topsoil pH
*WCWPT, WCFCT, WCSTT topsoil water constants (mm H20/ mm soil)
*MDRATE maximum drainage (percolation) rate (mm/d)
*DRAICO drainage coefficient of topsoil
*TKLT   thickness of topsoil layer (mm)
*LENGTH length of the field slope (m)
*SLOPE  steepness of the field (m/m)
*FACK   factor K (erodibility) for USLE, Whitmore & Burnham (1969)
*ADM    assimilation:dissimilation ratio of soil microorganisms
*CNM    C:N ratio of soil microorganisms

*General
PARAM BULKD = 1280.; TKLT =300.; AREA = 1.; CLAY = 0.46; PH = 5.2

*Soil water
PARAM DRAICO =2.; MDRATE =200.; WCWPT = 0.23; WCFCT=0.42; ...
      WCSTT=0.62; WCADT = 0.08

*Organic matter dynamics
PARAM SOC=0.8; SOMCNI=14.; YOMCNI=17.; ADM=2.; CNM=10.; OLD=0.6

*Soil erosion
PARAM LENGTH = 21.; SLOPE = 0.05; FACK = 0.18
*--------------------------------------------------------------------

*---------------------CROP GROWTH ----------------------------------
*Crop parameters (Tropical Maize)See acronyms in Appendix 2.6.3
PARAM INTC=0.25;LAPL = 0.53;TBASE = 10.;TMAT = 1479.;...
      TFLO = 693.; K=0.43; RUE = 2.6; NCG= 0.015; IDW = 0.5;...
      SPAN = 31.; NUPPER = 3.3
*--------------------------------------------------------------------
```

Appendix 2.6.2 Model listing: Dynamic nitrogen balance at plot scale (cont.)

```
**********************************************************************
*PARAMETERISATION (cont.)
**********************************************************************
*----------------------------MANAGEMENT-------------------------------
*SDATE   sowing date (Julian day)
*HDATE   harvest date (")
*IFAR    inorganic fertiliser application rate (kg/ha)
*NCIF    N content inorganic fertiliser (kg/kg)
*IFDATE  inorganic fertilisation date (Julian day)
*OFAR    organic fertiliser application rate (kg/ha)
*NCOF    N content organic fertiliser (kg/kg)
*OFDATE  organic fertilisation date (Julian day)
*OFCNI   Initial C:N ratio of organic fertiliser
*HWAR    household waste application rate g/m2/d
*NCHW    N content in household wastes (kg/kg)
*FACP    factor P (0 - 1) for soil conservation practices
*RESID   amount of crop resides from the previous crop (kg/ha)
*PLDENS  plant density (plants / m2)
*STVHRV  proportion of stover removed from the plot
*GHVEFF  grain harvesting efficiency

*Nutrient management
PARAM IFAR = 50.; NCIF = 0.46; OFAR =1000.; NCOF = 0.025;...
      HWAR = 0.1; NCHW = 0.03
*General management practices
PARAM RESID= 500.; FACP = 0.25;  A=0.05; PLDENS =2.5;...
      STVHRV = 0.2; GHVEFF = 0.8
*Dates
PARAM SDATE = 104.; OFDATE =105.; IFDATE =105.; HDATE = 250.
*---------------------------------------------------------------------

*------------------------INITIALISATION-------------------------------
*Calculations for initialisation and auxiliary variables

*Initial amount of mulch on soil surface (g/m2)
IMULCH = (OFAR*0.5 + RESURF) * 0.1
*It is assumed that 50% of the OF or residue remains on surface
RESINC = RESID * (1. - STVHRV)
RESURF = RESINC * 0.5

*Maximum leaf area index (m2/m2), leaf area per plant times pl density
LAIM = LAPL * PLDENS
*Maximum fraction of radiation absorbed
FMAX = 1. - EXP(-K * LAIM)
*Initial leaves and stem DM
ILDW = IDW * 0.7
ISDW = IDW * 0.3
*Initial N content in vegetative biomass (g N/m2)
INVEGE = IDW * NMAXVE
PARAM NMAXVE = 0.0125

*Initial soil organic matter and organic N
*in g/m2 for HALF the depth of the top soil layer (TKLT)
ISOM = (SOC * 1.725 * 10.) * BULKD * (TKLT/2000.) * AREA * OLD
IYOM = ISOM * (1. - OLD)
ISON = (ISOM * 0.58) / SOMCNI
IYON = (IYOM * 0.58) / YOMCNI

*Initial C:N ratio of organic fertiliser
OFCNI = (OFAR * 0.45) / (NCOF * OFAR)

*IOFON initial organic N in applied organic matter (g/m2)
IOFOM = (OFAR + RESINC) * 0.1
IOFON = (OFAR * NCOF + RESINC * 0.01) * 0.1

*Initial soil mineral N, annually 5% of soil organic N (g/m2)
ISMN = ISON * (0.05/12.) * 4.5
*---------------------------------------------------------------------
```

Appendix 2.6.2 Model listing: Dynamic nitrogen balance at plot scale (cont.)

```
DYNAMIC

*********************************************************************
*  N BALANCE AT PLOT (FIELD) SCALE - SOIL/CROP SYSTEM UNIT (2.6.1)
*********************************************************************
*Ins and Outs of N to and from the soil/crop unit
*NBAL   N balance at field scale (g N/ m2 soil), to a 0.3 m depth
*DNBAL  Daily rate of change in the balance                [g m-2 d-1]
*DNIF   N applied as inorganic fertiliser, on daily basis  [g m-2 d-1]
*DNOF   N applied as organic fertiliser, on daily basis    [g m-2 d-1]
*DNHW   N applied as org.household wastes, on daily basis  [g m-2 d-1]
*DNLE   Daily rate of N loss by erosion                    [g m-2 d-1]
*DNLEA  Daily rate of N loss by leaching                   [g m-2 d-1]
*DNREM  N removal from plot as harvested grains and stover[g m-2 d-1]

*Total N balance (g N/m2 soil)
NBAL = INTGRL (ZERO, DNBAL)

*Daily N balance (g N/m2 soil/d)
DNBAL = (DNIF + DNOF + DNHW) - (DNLE + DNLEA + DNREM)


*********************************************************************
*  SOIL N BALANCE (2.6.1.1)
*********************************************************************
*Ins and Outs of soil mineral N
*DNIFAR  rate of N input form inorganic fertiliser [g m-2 d-1]
*NRELEA  rate of N release from the organic pool   [g m-2 d-1]
*DNLEA   rate of N loss by leaching                [g m-2 d-1]
*DNUPT   rate of N uptake by the crop              [g m-2 d-1]
*DMNLE   rate of mineral N loss by erosion         [g m-2 d-1]
*NRSMN   net rate of change in soil mineral N      [g m-2 d-1]

*Soil mineral N (g/m2)
SOILMN = INTGRL (ISMN,NRSMN)

*Net rate of change of mineral N (g/m2/d)
NRSMN = DNIF + NRELEA - DNLEA - DNUPT - DMNLE

*N from inorganic fertiliser application, daily rate (g/m2/d)
DIFAR = IFAR * PUSHIF * 0.1
DNIF = DIFAR * NCIF
PUSHIF = INSW(TIME - IFDATE, 1.,0.)
*--------------------------------------------------------------------
*Summary variables for soil N

*Total soil N (g/m2) and total soil N content (gN / kg soil)
TOTSN = SON + YON + SOILMN
SLTNC = TOTSN / (BULKD * (TKLT/1000.))
*Soil mineral N content (g/kg)
SLMNC = (SOILMN / (BULKD * (TKLT/1000.))) * PUSHNU


*********************************************************************
**CROP GROWTH  (2.6.1.2)
*********************************************************************
*--------------------DEVELOPMENT-------------------------------------
*Crop development (thermal time, C d and development stage)
TSUM = INTGRL (ZERO, DTT)
DVS = TSUM/ TMAT

*Daily increase in TSUM
DTT = INSW (DVS - 1., TT * SOW, 0.)

*Daily thermal accumulation above Temp. base
TT = MAX (TMEAN - TBASE, 0.)

*Development rate (1/d)
DVR = DTT / TMAT

*Auxiliary variable to control crop growth starting
SOW   = INSW (SDATE - TIME, 1., 0.)
*--------------------------------------------------------------------
```

Appendix 2.6.2 Model listing: Dynamic nitrogen balance at plot scale (cont.)

```
*********************************************************************
**CROP GROWTH  (2.6.1.2)- Cont.
*********************************************************************
*-------------------LEAF AREA AND LIGHT INTERCEPTION-----------------
*Leaf area index (m2/m2)
LAI  = INTGRL (ILAI, NLAI)
*Cumulative PAR intercepted (MJ/m2)
CPAR = INTGRL (ZERO, IR)

*Leaf area development (m2/m2/d)
NLAI = GLAI - DLAI
*Leaf area expansion rate (m2/m2/d)
GLAI = INSW(LAI - LAIM, CGR * SLA * PTL, 0.)
*Death rate of leaf area (m2/m2/d)
DLAI = INSW(TSUM - TFLO, 0., LAI * (1./SPAN))

*Daily PAR intercepted (MJ/m2/d)
IR   = INSW (DVS - 1.,FRABS * RAD * 0.5 * SOW, 0.)
*Fraction of incoming radiation absorbed by canopy
FRABS = MIN ((1.-EXP(-K*LAI)), FMAX)

*Specific leaf area (m2/g)
SLA = AFGEN (SLATB, DVS)
FUNCTION SLATB= -1.,0.,0.,0.035,0.39,0.016,100.,0.016
*--------------------------------------------------------------------

*-------------------BIOMASS------------------------------------------
*TOTAL crop aboveground live biomass (g/m2)
TDW = SDW + GLDW + GDW

*Crop parts biomass: grains, green and dead leaves, stem (g/m2)
GDW  = INTGRL (ZERO, GFILL)
GLDW = INTGRL (ILDW, NLGR)
DLDW = INTGRL (ZERO, LDR)
SDW  = INTGRL (ISDW, NSGR)

*Crop growth rate g/m2/d)affected by N and water availability
CGR = IR * RUE * WEFGR * NEFGR * SOW

*Leaves net growth rate (g/m2/d)
NLGR = LGR - LDR
*Leaves gross growth rate (g/m2/d)
LGR = PTL * CGR
*Partitioning towards leaves
PTL = AFGEN (PTLTB, DVS)
FUNCTION PTLTB= -1.,0.7,0.,0.7,0.165,0.7,0.44,0.15,0.475,0.,100.,0.
*leaves death rate (g/m2/d)
LDR = INSW(TSUM - TFLO, 0., GLDW * (1./SPAN))

*Stems NET growth rate (g/m2/d)
NSGR = SGR - SDR
*Stems gross growth rate (g/m2/d)
SGR = PTS * CGR
*Partitioning towards stems
PTS = AFGEN (PTSTB, DVS)
FUNCTION PTSTB= -1.,0.3, 0.,0.3, 0.165,0.3, 0.44,0.85, 0.475,1.,...
                0.5025,1.,0.6,0., 100.,0.
*Stems death rate (g/m2/d)
SDR =  SDW * RDRS
*Relative death rate of stems
RDRS = AFGEN (RDRSTB, DVS)
FUNCTION RDRSTB = 0.,0., 0.75,0., 0.75001,0.02, 1.,0.02, 5.,0.02

*grain filling rate (g/m2/d)
GFILL = CGR * PTG
*Partitioning towards grains
PTG = INSW (TFLO - TSUM, AFGEN(PTGTB, DVS), 0.)
FUNCTION PTGTB= -1.,0., 0.475,0., 0.5025,0., 0.6,1., 100.,0.

*Harvest index (excluding roots)
HI = GDW / TDW
*Dry matter distribution
DMDIST = GDW / (SDW + GLDW)
```

Appendix 2.6.2 Model listing: Dynamic nitrogen balance at plot scale (cont.)

```
************************************************************************
*NITROGEN UPTAKE AND REMOVAL (2.6.1.3)
************************************************************************
*Total N in the crop (g N/m2 soil), discounting abscised leaves
*N in the vegetative str. is limited by a minimum N content
NCROP = NGRAIN + NVEGE

*N taken up allocated to vegetative (gN/m2 soil)
NSTAT = INTGRL (INVEGE, DNURV)
NMINV = LAI*SLNDL
NVEGE = MAX(NSTAT, NMINV)

*N taken up allocated to grains (g/m2)
NGRAIN = INTGRL (ZERO, DNURG)

*Daily N demand, uptake rate (g/m2 soil/d)
DNUPT =MAX(0., DNURV + DNURG)

*Daily N demand from vegetative biomass [g N/ m2 soil/d]
DNURV =MIN(DNSUP,(GLAI*NCANO)-(DLAI*SLNDL))-REMOB
*Affecting N content in leaves by light distribution in canopy
NCANO = NUPPER * FRABS

*Daily N demand from grain biomass [g/ m2 soil/d]
DNURG  = MIN (GFILL * NCG, DNSUP + REMOB)
*Rate of remobilization of N from vegetative to grains
REMOB =INSW(DVS-0.8, 0., DLAI*(SLN-SLNDL))

*Daily N supply [g N/ m2]
DNSUP = (SOILMN / DELT) * PUSHNU

*Limitation for no N availability
PUSHNU = INSW (ZERO - SOILMN,1., 0.)

*Specific leaf nitrogen [g N/ m2 LA], minimum and for dead leaves
PARAM SLNDL = 0.41

*--------------GROWTH LIMITATION BY N ------------------------------

*N effect on growth rate
NEFGR = MIN(1.,NOTNUL(NCROP)/NOTNUL(NTARG))

*Target N: minimum amount of N in the crop (low-input situation)
NTARG = NGRMN + NVEGMN

*Minimum N amount in vegetative structures
NVEGMN = (TDW - GDW) * NCVGMN
NCVGMN = AFGEN (NVMNTB, DVS)
*Minimum N content in vegetative biomass (g/m2)
FUNCTION NVMNTB = 0.,0.01 ,0.5,0.002, 1.,0.002, 5.,0.002

*Minimum amount of N in grains
NGRMN = GDW * NCGMN
*Minimum content of N in grains (gN/gdm)
PARAM NCGMN = 0.0095

*----------------N REMOVAL BY HARVEST ------------------------------

*N removed from the plot (gN/m2) by harvest
NREM = INTGRL (ZERO, DNREM)

*N removal, daily rates of grain harvest and stover extract. (g/m2/d)
DNREM = DNHARV + DNSTOV

*N harvest with grains (g/m2/d)
DNHARV = (NGRAIN/DELT) * GHVEFF * PUSHF

*N harvest with stover (g/m2/d)
DNSTOV = ((NCROP-NGRAIN)/DELT) * STVHRV * PUSHF

*Auxiliar variable to simulate harvest (all at once, in this case)
PUSHF = INSW(TIME - HDATE, 0.,1.)
```

Appendix 2.6.2 Model listing: Dynamic nitrogen balance at plot scale (cont.)

```
*******************************************************************
*ORGANIC MATTER DYNAMICS (2.6.1.4)
*******************************************************************
*Organic matter dynamics and N release using NDICEA approach
PARAM POT1 = -1.6

*Old, young and applied organic matter (g/m2 for the topsoil depth)
SOM = INTGRL (ISOM, RSOM)
YOM = INTGRL (IYOM, RYOM)
OFOM = INTGRL (IOFOM, ROFOM)
*Substrate ageing (Janssen 1984), for soil and applied organic matter
AGESL = INTGRL (ASL, DASLDT)
AGEY  = INTGRL (AY, DAYDT)
AGEOF = INTGRL (AOF, DAOFDT)
*Ageing rates
DASLDT = F / 365.
DAYDT  = F / 365.
DAOFDT = F / 365.
*Soil organic matter decomposition rate (g/m2/d)
RSOM = ((-2.82 * SOM * F * (AGESL)**POT1)/365.)*0.1
RYOM = ((-2.82 * YOM * F * (AGEY)**POT1)/365.)*0.1
*Decomposition rate of applied organic matter (g/m2/d)
ROFOM =((-2.82 * OFOM * F *(AGEOF)**POT1)/365.)*0.1 * NLIMIT
*N limitation to decomposition of applied OM
NLIMIT = INSW (SOILMN - SMNMIN, 0., 1.)
*Minimum soil mineral nitrogen for decomposition
PARAM SMNMIN = 0.1

*------------------------N release (mineralisation)------------------
*Soil and applied organic N (g/m2)
SON = INTGRL (ISON, RSON)
YON = INTGRL (IYON, RYON)
OFON = INTGRL (IOFON,ROFON)
*Cumulative N mineralisation (g/m2)
NMIN = INTGRL(ZERO, NRELEA)

*Mineralisation rate of soil OM (g/m2/d)
RSON = ((1.+ADM)/(SOM/SON) - (0.58*ADM)/CNM) * RSOM
RYON = ((1.+ADM)/(YOM/YON) - (0.58*ADM)/CNM) * RYOM
*N mineralisation rates from applied OM (g/m2/d)
ROFON =((1.+ADM)/(OFOM/OFON)-(0.58*ADM)/CNM)*ROFOM
*N release rate (g/m2/d)
NRELEA = -1. * (RSON + RYON + ROFON)

*Actual C:N ratios of the organic pools
SOMCN  = (0.58 * SOM) / NOTNUL (SON)
YOMCN  = (0.58 * YOM) / NOTNUL (YON)
OFOMCN = (0.58 * OFOM) / NOTNUL (OFON)

*-----------------------Correction factor F--------------------------
F = FTEMP + FMOIST + FTXT + FPH

*Temperature correction factor (Janssen - Yang, 2001)
FTEMP = INSW (TMEAN - 27., 2.**((TMEAN - 9.)/9.), 4.)
*Moisture correction factor adapted from Rijtema (1980)
FMOIST = INSW(CLAY - 0.2, FMSAND, FMCLAY)
FMCLAY = INSW(WCLT - WCFCT,  AFGEN(FMTB1, WCLT), 1.)
FUNCTION FMTB1 = 0., 0., 0.2, 0., 0.35, 1., 1., 1.
FMSAND = INSW(WCLT - WCFCT,  AFGEN(FMTB2, WCLT), 1.)
FUNCTION FMTB2 = 0.,0., 0.05,0.,0.15, 1., 1.,1.
*Texture correction factor
FTXT = AFGEN(TXTTB, CLAY)
FUNCTION TXTTB= 0.,1., 0.1,1.,0.4,0.65, 0.5,0.6, 0.8,0.5
*pH correction factor
FPH = 1./(1.+ EXP(-1.5 * (PH - 4.)))

*-------------------------Organic resource applications---------------
*N applied as organic fertiliser, daily rate (gN/m2/d)
DOFAR = OFAR * PUSHOF * 0.1
DNOF = DOFAR * NCOF
PUSHOF = INSW(TIME - OFDATE, 1.,0.)
*N applied as household wastes, daily rate (gN/m2/d)
DNHW = NCHW * HWAR
```

Appendix 2.6.2 Model listing: Dynamic nitrogen balance at plot scale (cont.)

```
**********************************************************************
*WATER BALANCE (2.6.1.5)
**********************************************************************
*Tipping bucket for one soil layer (topsoil T)

*Water balance: amount of water (mm) in the topsoil layer (0.3 m)
WLT = INTGRL(WLTI, RWLT)

*Water content in the topsoil layer(mm/mm)
WCLT = WLT/TKLT

*Net flow rate of water in topsoil layer (mm/d)
RWLT= WLFLT - WLFLS - TRANSP - EVAPO + CPRISE
*Inflow of water to the toplayer (mm/d)
WLFLT= RAIN - AINTC - RNOFF
*Inflow in the subsoil or outflow from the topsoil (mm/d)
WLFLS= MAX(0.,MIN((WLT - WCFCT*TKLT)/(DRAICO*DELT),MDRATE))
*Interception of rain water by canopy (mm/d)
AINTC = MIN (RAIN, INTC*LAI)
*Runoff water losses (mm/d)
RNOFF = MAX(0.,0.15*(RAIN-AINTC-10.),RAIN-AINTC-(WCSTT*TKLT-WLT)/...
        (DRAICO*DELT))
*Capillary rise (mm/d), only when topsoil dries up
CPRISE = INSW (WCWPT - WCLT, 0., ACTETP)

---------------Crop transpiration and growth limitation---------------

*Subroutine for potential evaporation and transpiration
CALL PENMAN( TMEAN,VP,RAD,LAI,WN,AINTC,PEVAP,PTRAN)

*Potential evapotranspiration (mm d-1)
POTETP = PEVAP + PTRAN
*'Actual' evapotranspiration (mm d-1)
ACTETP = EVAPO + TRANSP

*Reduction factor for potential to actual transpiration, considering
*a critical water content of 80% of field capacity
RED =INSW(WCLT - WCCRIT, LIMIT (0.,1., (WCLT - WCWPT) /...
          (WCFCT - WCWPT)), 1.)
*Critical water content below which transpiration is affected
WCCRIT = WCWPT + (WCFCT - WCWPT) * 0.8

*Actual transpiration rate [mm d-1]
TRANSP = PTRAN * RED * AVAILF
*Actual evaporation affected by soil water content, air-dry limit
EVAPO  = (PEVAP * LIMIT( 0., 1., (WCLT-WCADT)/(WCFCT-WCADT) ))*AVAILF
*Limiting evapotranspiration by water availability
AVAILF = MIN( 1., ((WLT-WLADT)/DELT)/NOTNUL(POTETP) )

*Water effect on crop growth rate (actual/potential transpiration)
WEFGR = TRANSP / NOTNUL (PTRAN)

*Amount of water at air-dry point, wilting point, critical point,
*field capacity and saturation (mm) in the topsoil
WLADT  = WCADT * TKLT
WLWPT  = WCWPT * TKLT
WLCRIT = WCCRIT * TKLT
WLFCT  = WCFCT * TKLT
WLSTT  = WCSTT * TKLT

*-------------------------LEACHING N LOSSES-------------------------

*N leaching (g N / m2 soil)
NLEA = INTGRL (ZERO, DNLEA)

*Daily N leaching (gN/m2soil/d)
DNLEA = LEACH * (SOILMN / WLT)

*Percolation of water from the topsoil layer (mm/d)
LEACH = WLFLS
```

Appendix 2.6.2 Model listing: Dynamic nitrogen balance at plot scale (cont.)

```
**********************************************************************
*SOIL EROSION (2.6.1.6)
**********************************************************************
*USLE equation with adaptation for tropics and on a daily basis

*Soil loss by erosion in kg/m2
SLOSS = INTGRL(ZERO, DLOSS)
*Soil loss in t/ha (original unit on a yearly basis)
ERLOSS = SLOSS * 10.

*Daily erosion, in kg/m2/d
DLOSS = (FACR * FACLS * FACK * FACC * MF * FACP) * 0.1

*Daily value of factor R according to Roose (1975) rainfall index
R = INTGRL (ZERO, FACR)
FACR = 0.5 * RAIN * 1.73
*Factor LS, length (m) and steepness (%)
FACLS = ((LENGTH/22.)**0.5) * (0.065 + 0.045 * SLOPE*100. +...
        0.0065*((100.*SLOPE)**2.))
*Factor C according to soil cover and mulch effect
FACC =INSW(TIME - HDATE, AFGEN(FACCTB, LAI)*MF, 1.)
*Mulch effect Colvin (1981), a function of cover by residues left (%)
MF = EXP(- A * RC)
*Relating soil cover with mulch (g/m2), varying over the year
RC = AFGEN(RCTB, MULCH)
MULCH = INTGRL (IMULCH, DECAY)
DECAY = - MULCH * 0.01
*Example for maize, millet and sorghum (Roose, 1975) in West Africa
FUNCTION FACCTB = 0.,1.,0.5,0.9, 1.,0.7, 3., 0.4, 5.,0.4, 8.,0.02
FUNCTION RCTB = 0.,0., 500.,0.7, 1000.,0.9, 2000.,1.

*------------------------EROSION N LOSSES --------------------------

*Total N loss by erosion g/m2 and daily Total N loss by erosion g/m2/d
NLE  = SLOSS * SLTNC
DNLE = DLOSS * SLTNC
*Mineral N loss by erosion g/m2, daily miner. N loss by erosion g/m2/d
MNLE  = SLOSS * SLMNC
DMNLE = DLOSS * SLMNC


**********************************************************************
*WEATHER DATA AND CHARACTERISATION
**********************************************************************
*Weather file Kenya (Kisumu), 1986
WEATHER WTRDIR='C:\SYS\WEATHER\';CNTR='KENYA';ISTN=1;IYEAR=1986
*Meteorological variables
*  Reading weather data: KENYA, 1986:
*  RDD     Daily global radiation in    J/m2/d
*  TMMN    Daily minimum temperature in degree C
*  TMMX    Daily maximum temperature in degree C
*  VP      Vapour pressure in           kPa
*  WN      Wind speed in                m/s
*  RAIN    Precipitation in             mm
*  LAT     Latitude of the site         degree

*Weather characterisation:
*Cummulative rainfall (mm)
RNFALL = INTGRL (ZERO, RAIN)
*Cummulative global radiation (Mj/m2)
RGLOB = INTGRL (ZERO, RAD)
*Mean temperature (C)
TMEAN = (TMMN + TMMX)*0.5
*Effective temperture for accumulation, an alternative to TMEAN
DTEFF=0.25*TMMN+0.75*TMMX
*Daily global radiation (MJ/m2/d)
RAD = RDD / 1000000.
*Vapour saturation curve
ES  = 0.1* 6.107 * EXP((17.4 *TMEAN)/(TMEAN + 239.))
*Relative humidity (%)
RH  = (VP / ES)*100.
*Vapour pressure deficit
VPD = ES - VP
*Water deficit (mm/d)
WDEF = RAIN - POTETP
```

Appendix 2.6.2 Model listing: Dynamic nitrogen balance at plot scale (cont.)

```
***********************************************************************
* RE -RUNS: SCENARIO PARAMETERISATION
***********************************************************************
END
*General
PARAM BULKD = 1120.; CLAY = 0.54; PH = 5.8

*Soil water
PARAM WCWPT = 0.21; WCFCT=0.46; WCSTT=0.60

*Organic matter dynamics
PARAM SOC=1.; SOMCNI=10.

*Soil erosion
PARAM LENGTH = 21.; SLOPE = 0.05; FACK = 0.09

*Nutrient management
PARAM IFAR = 200.; NCIF = 0.46; OFAR =0.

*----------------------------------------------------------------------
END
STOP
* --------------------------------------------------------------------*
*  SUBROUTINE PENMAN                                                  *
*  Purpose: Computation of the PENMAN EQUATION                        *
* --------------------------------------------------------------------*

      SUBROUTINE PENMAN(TMEAN,VP,RAD,LAI,WN,AINTC,
     $                  PEVAP,PTRAN)
      IMPLICIT REAL (A-Z)

      DTRJM2 = RAD * 1.E6
      BOLTZM = 5.668E-8
      LHVAP  = 2.4E6
      PSYCH  = 0.067

      BBRAD  = BOLTZM * (TMEAN+273.)**4 * 86400.
      SVP    = 0.611 * EXP(17.4 * TMEAN / (TMEAN + 239.))
      SLOP  = 4158.6 * SVP / (TMEAN + 239.)**2
      RLWN   = BBRAD * MAX(0.,0.55*(1.-VP/SVP))
      NRADS  = DTRJM2 * (1.-0.15) - RLWN
      NRADC  = DTRJM2 * (1.-0.25) - RLWN
      PENMRS = NRADS * SLOP/(SLOP+PSYCH)
      PENMRC = NRADC * SLOP/(SLOP+PSYCH)

      WDF    = 2.63 * (1.0 + 0.54 * WN)
      PENMD  = LHVAP * WDF * (SVP-VP) * PSYCH/(SLOP+PSYCH)

      PEVAP  =     EXP(-0.5*LAI)  * (PENMRS + PENMD) / LHVAP
      PTRAN  = (1.-EXP(-0.5*LAI)) * (PENMRC + PENMD) / LHVAP
      PTRAN  = MAX( 0., PTRAN-0.5*AINTC )

      RETURN
      END
```

Appendix 2.6.3 Fixed model parameters

Table 2.6.4: Fixed model parameters used in the different simulations

Parameter	Acronym	Value	Unit
Crop growth and development			
Base temperature for crop development	TBASE	10	°C
Temperature sum emergence-maturity	TMAT	1479	°C day
Temperature sum emergence-(silk) flowering	TFLO	693	°C day
Radiation extinction coefficient	K	0.43	-
Leaf area per plant (max)	LAPL	0.53	m^2 LAI $plant^{-1}$
Radiation use efficiency	RUE	2.6	g dm MJ^{-1}PAR
Life span of a leaf	SPAN	31	days
Organic matter, N release and N uptake			
Fraction of old organic matter in soil	OLD	0.6	-
Assimilation:dissimilation of microorganisms	ADM	2.0	-
C:N ratio of microorganisms	CNM	10	-
Apparent initial age of old soil organic matter	ASL	24	years
Apparent initial age of young soil organic mat.	AFR	4	years
Apparent initial age of organic fertilisers*	AOF	1.41	years
N content in upper leaves of the canopy	NUPPER	3.3	g N m^{-2} LAI
N content in grains	NCG	0.015	g N g^{-1} grain dm
Empirical coefficient for mulch effect	A	0.05	-
Water balance			
Canopy rain-interception coefficient	INTC	0.25	-
Drainage coefficient of the topsoil	DRAICO	2.0	-
Maximum drainage rate of topsoil	MDRATE	200	mm d^{-1}
System parameters and initial conditions			
Thickness of topsoil layer	TKLT	300	mm
Area of the soil/crop unit	AREA	1	m^2
Initial dry weight of plant dry matter	IDW	0.5	g dm m^{-2}
Initial leaf area index	ILAI	0.0074	m^2 leaf m^{-2} soil
Initial amount of water in topsoil layer	WLTI	100	mm

*When reliable data is available, this variable can be easily changed to simulate quality of different organic resources

Appendix 2.6.4 - I Weather data used in the simulation program

Ahero (0° 9'S : 34° 36'E, 1200 m) meteorological station, western Kenya

```
*----------------------------------------------------------------------
-*
* Station name: Ahero (Kisumu), Kenya
* Year: 1986
* Author: Peter Uithol
* Source: IRRI/WMO Special project
* Longitude: 34 36 E, latitude: 0 9 S, altitude: 1200. m
*
* Column  Daily value
* 1       station number
* 2       year
* 3       day
* 4       irradiation                    (kJ m-2 d-1)
* 5       minimum temperature            (degrees Celsius)
* 6       maximum temperature            (degrees Celsius)
* 7       early morning vapour pressure  (kPa)
* 8       mean wind speed (height: 2 m)  (m s-1)
* 9       precipitation                  (mm d-1)
*----------------------------------------------------------------------
-*
  34.60   -0.15   1200.  0.00 0.00
```

1	1986	1	21179.	16.8	28.1	1.103	1.5	2.3
1	1986	2	21769.	14.0	28.3	0.915	1.6	12.9
1	1986	3	23353.	14.4	29.5	0.906	1.6	0.0
1	1986	4	22874.	15.0	30.0	0.828	1.7	2.5
1	1986	5	22136.	15.5	30.3	0.902	1.4	0.0
1	1986	6	20740.	14.5	29.0	0.920	2.1	0.0
1	1986	7	18086.	16.0	28.0	1.104	1.3	10.0
1	1986	8	20408.	15.0	30.0	0.947	1.3	0.0
1	1986	9	19782.	14.5	29.4	0.924	1.4	0.0
1	1986	10	19818.	14.2	30.0	0.870	1.2	0.0
1	1986	11	21586.	15.0	30.4	0.874	2.2	0.0
1	1986	12	13482.	16.0	30.4	1.110	1.3	0.8
1	1986	13	18454.	13.0	29.0	0.821	1.5	2.5
1	1986	14	19890.	14.5	30.0	0.853	1.7	0.0
1	1986	15	21035.	13.5	30.5	0.762	1.8	0.0
1	1986	16	20848.	15.0	31.3	0.819	2.1	0.0
1	1986	17	22360.	14.0	32.0	0.630	1.9	0.3
1	1986	18	20149.	14.5	30.2	0.836	1.6	0.0
1	1986	19	21218.	14.5	31.1	0.785	1.8	2.0
1	1986	20	16909.	16.0	29.0	1.046	1.4	2.4
1	1986	21	19706.	14.5	30.0	0.968	1.3	0.8
1	1986	22	22763.	16.0	31.5	0.919	1.6	0.0
1	1986	23	22874.	15.0	31.5	0.944	1.8	2.7
1	1986	24	23832.	14.5	33.0	0.575	1.3	0.0
1	1986	25	26226.	12.0	32.0	0.497	1.5	0.0
1	1986	26	22655.	12.5	33.2	0.635	1.5	0.0
1	1986	27	23573.	12.1	33.0	0.486	1.7	0.0
1	1986	28	20848.	13.9	32.5	0.723	1.7	0.0
1	1986	29	20995.	15.5	33.0	0.693	1.6	0.0
1	1986	30	21992.	14.8	32.2	0.775	1.5	2.3
1	1986	31	23465.	16.0	33.0	0.741	2.2	0.0
1	1986	32	22064.	17.5	31.0	1.069	1.7	9.1
1	1986	33	24275.	15.2	33.0	0.683	1.6	0.0
1	1986	34	23760.	16.5	32.8	0.757	1.5	0.0
1	1986	35	22100.	17.4	33.8	0.907	1.5	0.3
1	1986	36	18454.	17.0	28.0	1.177	2.3	0.0
1	1986	37	22248.	17.0	28.2	1.334	1.5	30.2
1	1986	38	24127.	14.6	29.3	0.950	1.7	0.5
1	1986	39	24016.	16.6	30.0	1.004	1.8	0.0
1	1986	40	25049.	14.5	31.0	0.864	1.6	6.0
1	1986	41	25121.	13.0	31.6	0.752	1.6	0.0
1	1986	42	23573.	13.6	31.0	0.628	1.9	0.0
1	1986	43	22028.	15.6	30.2	0.862	1.4	0.0
1	1986	44	20261.	16.0	30.0	0.968	2.5	0.0
1	1986	45	24422.	17.0	31.0	0.958	2.3	0.4
1	1986	46	24790.	14.5	33.6	0.767	1.5	5.5
1	1986	47	25564.	14.2	31.5	0.663	2.1	0.0
1	1986	48	24862.	15.5	28.1	1.151	1.7	6.9
1	1986	49	25636.	14.8	30.0	0.889	2.1	0.0
1	1986	50	25232.	15.5	30.2	0.723	1.7	0.0
1	1986	51	26042.	13.0	32.0	0.701	1.6	0.0
1	1986	52	23170.	13.8	33.5	0.603	1.9	0.0
1	1986	53	25711.	15.0	33.0	0.843	1.9	0.0
1	1986	54	24347.	14.0	33.0	0.576	1.5	0.0
1	1986	55	25488.	13.0	33.0	0.580	1.5	0.0
1	1986	56	21550.	15.8	33.0	0.751	1.4	0.0
1	1986	57	23022.	14.6	33.0	0.657	1.9	0.0
1	1986	58	24754.	15.5	29.0	1.070	2.0	22.2
1	1986	59	22028.	17.0	28.6	1.138	1.3	0.0
1	1986	60	25819.	14.4	32.2	0.770	1.5	0.0
1	1986	61	24973.	15.7	33.0	0.785	1.3	0.2
1	1986	62	18346.	17.5	32.0	0.981	1.2	0.0
1	1986	63	17165.	16.0	27.0	1.236	1.5	3.2
1	1986	64	21550.	15.5	30.0	1.086	1.2	8.8
1	1986	65	22100.	15.7	30.0	0.946	2.1	0.0
1	1986	66	15692.	16.6	26.0	1.505	1.7	12.5
1	1986	67	25967.	14.5	29.0	0.943	1.4	19.7
1	1986	68	24530.	16.0	29.5	1.030	2.1	0.0
1	1986	69	23684.	15.5	29.5	0.983	1.5	12.0
1	1986	70	26190.	15.7	30.0	1.023	1.6	4.9
1	1986	71	25636.	15.0	30.5	0.782	2.0	0.0
1	1986	72	25340.	15.0	32.5	0.753	1.9	0.0
1	1986	73	25895.	15.0	31.8	0.734	2.1	0.0
1	1986	74	28544.	15.0	30.5	0.792	2.3	0.0
1	1986	75	18346.	16.5	28.0	1.212	1.5	0.0
1	1986	76	15437.	16.0	25.5	1.319	1.3	11.3
1	1986	77	23094.	14.5	29.5	1.001	1.5	0.6
1	1986	78	26410.	15.8	30.5	0.956	1.8	0.6
1	1986	79	24052.	17.0	29.5	1.084	1.8	0.0
1	1986	80	26298.	17.0	27.5	1.235	1.5	48.2
1	1986	81	23206.	15.0	28.5	1.130	1.4	14.4
1	1986	82	21658.	14.9	31.0	0.832	0.9	0.0
1	1986	83	25636.	14.0	31.0	0.795	1.5	0.0
1	1986	84	25452.	14.8	29.5	0.878	1.7	0.0
1	1986	85	24901.	15.0	33.0	0.898	1.5	0.0
1	1986	86	20959.	15.4	31.0	0.923	1.3	0.0
1	1986	87	24052.	14.1	33.0	0.781	1.5	0.0
1	1986	88	25636.	16.0	31.0	0.928	1.9	0.0
1	1986	89	21917.	17.0	29.2	1.226	1.7	0.0
1	1986	90	25416.	17.4	29.5	1.291	1.9	14.1
1	1986	91	23684.	15.5	29.5	0.978	1.6	0.6
1	1986	92	25528.	15.7	29.5	1.000	1.5	9.5
1	1986	93	20516.	17.9	29.0	1.254	1.1	2.2
1	1986	94	24091.	17.2	30.0	1.039	1.6	0.0
1	1986	95	20516.	17.5	30.2	1.033	1.1	0.0
1	1986	96	13410.	17.5	29.0	1.217	0.9	0.0
1	1986	97	18601.	18.0	28.0	1.376	1.2	9.5
1	1986	98	21107.	17.0	28.5	1.348	1.6	1.1
1	1986	99	16394.	16.5	25.5	1.416	1.1	24.0
1	1986	100	18860.	16.2	26.0	1.362	1.6	47.5
1	1986	101	24127.	16.0	30.0	1.072	1.2	0.0

Appendix 2.6.4 - II Weather data used in the simulation program (cont.)

1	1986	102	25711.	17.0	29.5	1.237	1.0	15.0
1	1986	103	24127.	18.0	29.0	1.248	1.1	0.0
1	1986	104	22691.	17.0	29.5	1.200	1.3	0.0
1	1986	105	23904.	18.0	29.0	1.262	1.1	9.8
1	1986	106	24937.	17.0	31.0	1.160	0.9	18.8
1	1986	107	24937.	16.0	30.0	1.012	1.4	0.5
1	1986	108	24163.	16.5	29.0	1.078	1.3	41.4
1	1986	109	21438.	18.0	29.6	1.304	0.9	0.0
1	1986	110	22324.	15.5	29.5	1.202	0.9	0.4
1	1986	111	16538.	18.5	29.0	1.264	0.9	0.0
1	1986	112	19782.	18.5	27.0	1.462	1.0	4.3
1	1986	113	18932.	18.0	28.0	1.461	1.1	2.2
1	1986	114	18234.	18.0	27.5	1.479	0.8	0.4
1	1986	115	17536.	17.8	28.0	1.587	0.9	41.3
1	1986	116	13262.	17.5	24.5	1.597	1.4	12.2
1	1986	117	23720.	16.0	27.5	1.245	1.1	15.7
1	1986	118	17352.	17.5	28.0	1.459	1.3	0.0
1	1986	119	19966.	17.5	27.0	1.423	1.4	0.0
1	1986	120	19411.	17.0	27.0	1.292	0.7	0.0
1	1986	121	23389.	16.5	28.2	1.272	1.8	0.0
1	1986	122	21697.	16.2	27.7	1.290	0.9	15.5
1	1986	123	20959.	16.4	28.5	1.185	1.1	0.0
1	1986	124	20002.	17.5	28.1	1.401	1.0	0.0
1	1986	125	20516.	17.5	27.8	1.359	1.1	8.7
1	1986	126	18932.	17.0	26.0	1.418	1.4	30.7
1	1986	127	24422.	16.0	28.4	1.084	1.2	0.0
1	1986	128	19746.	19.9	28.4	1.473	1.1	2.4
1	1986	129	23317.	19.9	29.0	1.333	1.1	10.2
1	1986	130	23170.	15.5	28.5	1.108	1.0	24.4
1	1986	131	20628.	15.5	29.0	1.112	0.9	0.0
1	1986	132	23904.	14.5	29.0	0.960	1.1	0.0
1	1986	133	23429.	15.8	29.5	1.002	1.0	0.0
1	1986	134	21805.	16.5	29.4	1.065	1.3	0.0
1	1986	135	22248.	16.4	27.5	1.256	1.0	6.3
1	1986	136	21107.	17.0	29.0	1.206	1.1	0.0
1	1986	137	22360.	16.6	29.2	1.170	1.2	0.5
1	1986	138	18493.	15.8	28.0	1.094	1.0	1.2
1	1986	139	20740.	16.2	28.4	1.133	0.9	0.1
1	1986	140	20628.	16.5	28.0	1.259	1.2	1.0
1	1986	141	22100.	14.3	28.5	1.091	1.0	3.1
1	1986	142	22324.	14.5	29.0	1.005	1.0	0.0
1	1986	143	20002.	16.0	28.0	1.177	0.8	0.8
1	1986	144	22579.	17.5	29.5	1.205	0.9	10.5
1	1986	145	19192.	16.5	28.6	1.324	0.9	0.0
1	1986	146	18529.	17.1	28.6	1.132	0.7	3.3
1	1986	147	21438.	14.6	29.0	0.908	0.9	0.7
1	1986	148	23022.	14.5	30.0	0.934	0.7	0.1
1	1986	149	18086.	16.0	28.5	1.145	0.8	0.0
1	1986	150	18310.	16.5	29.6	1.095	1.0	1.5
1	1986	151	18749.	15.8	29.5	1.132	0.8	18.3
1	1986	152	16135.	16.1	28.5	1.029	0.9	0.0
1	1986	153	19746.	14.5	28.5	1.140	0.8	11.2
1	1986	154	23206.	14.5	28.8	1.069	1.0	0.7
1	1986	155	15692.	15.2	27.3	1.265	1.0	1.1
1	1986	156	22136.	15.5	27.9	1.061	1.0	0.5
1	1986	157	20113.	15.4	27.9	1.220	1.1	0.0
1	1986	158	20848.	12.9	29.0	0.910	0.7	11.8
1	1986	159	18270.	13.0	28.8	0.821	1.6	0.0
1	1986	160	15728.	14.7	26.0	1.292	0.2	2.0
1	1986	161	20333.	17.1	27.2	1.271	1.0	0.0
1	1986	162	19930.	14.5	28.0	1.000	0.9	0.0
1	1986	163	11016.	16.1	26.0	1.438	1.2	6.3
1	1986	164	14994.	16.1	25.0	1.536	0.9	10.4
1	1986	165	20261.	16.0	28.2	1.297	0.9	0.0
1	1986	166	19854.	16.2	28.5	1.180	0.9	0.0
1	1986	167	18788.	16.5	27.5	1.264	1.1	0.0
1	1986	168	7517.	17.5	23.0	1.629	0.4	4.3
1	1986	169	14846.	16.0	25.0	1.392	0.9	2.2
1	1986	170	20333.	15.0	27.5	1.092	1.0	0.0
1	1986	171	21143.	15.0	29.0	1.038	0.8	0.0
1	1986	172	20923.	15.5	28.8	1.119	0.8	0.0
1	1986	173	14882.	17.4	26.1	1.217	1.1	0.0
1	1986	174	15692.	16.9	28.0	1.170	0.7	0.0
1	1986	175	18162.	17.0	28.4	1.074	1.0	0.0
1	1986	176	15473.	16.9	27.9	1.204	0.9	2.6
1	1986	177	18641.	15.5	27.5	1.223	1.2	0.0
1	1986	178	20516.	15.8	28.0	1.272	0.8	21.2
1	1986	179	21733.	15.4	28.0	1.023	0.9	0.0
1	1986	180	20664.	15.0	27.5	0.935	0.9	0.0
1	1986	181	19267.	14.2	29.1	0.985	0.9	0.0
1	1986	182	22507.	15.0	29.8	0.920	0.9	0.0

1	1986	183	21953.	14.9	29.0	0.868	1.0	0.0
1	1986	184	21143.	14.5	28.7	0.727	1.1	0.0
1	1986	185	20480.	18.9	27.7	1.390	1.1	0.0
1	1986	186	22507.	14.2	27.7	0.719	1.1	0.0
1	1986	187	21438.	14.2	29.2	0.716	1.0	0.0
1	1986	188	20297.	14.6	28.8	0.941	1.1	0.0
1	1986	189	18788.	13.0	27.7	0.871	1.2	0.0
1	1986	190	19080.	14.5	28.6	1.001	1.0	1.3
1	1986	191	21622.	14.2	29.5	0.940	1.1	5.0
1	1986	192	22176.	13.0	30.5	0.845	1.1	0.0
1	1986	193	21254.	14.5	29.6	0.993	1.5	0.0
1	1986	194	20333.	16.2	29.0	0.966	1.5	0.0
1	1986	195	13813.	15.5	26.3	1.258	0.9	42.8
1	1986	196	15106.	15.5	27.5	1.253	0.8	0.0
1	1986	197	15250.	14.5	27.6	1.092	1.0	0.0
1	1986	198	18234.	15.6	27.7	1.149	1.1	0.0
1	1986	199	19303.	12.8	28.5	0.867	0.9	1.5
1	1986	200	20848.	14.6	28.7	0.998	1.0	0.0
1	1986	201	21290.	14.5	29.5	0.920	1.1	0.0
1	1986	202	19854.	15.6	28.8	0.825	1.1	0.0
1	1986	203	18418.	16.0	28.5	0.973	0.9	0.0
1	1986	204	18050.	15.8	29.8	0.986	1.1	3.5
1	1986	205	16578.	16.7	28.9	1.254	1.3	0.0
1	1986	206	16762.	14.1	28.7	0.900	0.8	0.0
1	1986	207	19451.	13.5	30.5	0.910	1.0	0.0
1	1986	208	14256.	15.2	29.7	1.098	1.0	0.0
1	1986	209	17093.	14.4	28.0	1.082	0.9	9.8
1	1986	210	18788.	13.0	28.0	0.977	0.8	4.9
1	1986	211	17312.	15.5	28.5	0.902	0.9	0.0
1	1986	212	20848.	13.5	29.0	0.845	1.1	0.0
1	1986	213	21953.	13.2	28.5	0.911	1.3	15.1
1	1986	214	19818.	19.0	28.0	1.269	1.1	0.1
1	1986	215	19339.	13.0	30.6	0.814	1.0	0.3
1	1986	216	23389.	12.1	29.0	0.780	1.2	9.0
1	1986	217	23134.	12.0	30.0	0.678	1.2	0.0
1	1986	218	21366.	13.0	30.0	0.776	0.8	0.0
1	1986	219	21035.	13.0	29.5	0.761	1.4	0.0
1	1986	220	21550.	13.5	30.0	0.779	1.1	0.0
1	1986	221	20113.	13.5	30.0	0.822	0.9	0.0
1	1986	222	19192.	14.8	29.0	0.982	1.3	0.0
1	1986	223	19598.	15.0	29.0	0.887	1.2	0.0
1	1986	224	12564.	17.0	27.0	1.131	0.9	0.0
1	1986	225	19746.	14.5	29.0	0.780	1.3	0.0
1	1986	226	21845.	15.0	29.0	0.814	1.1	0.0
1	1986	227	21697.	15.5	30.0	0.906	1.2	0.0
1	1986	228	22763.	13.0	30.5	0.713	1.0	0.0
1	1986	229	22324.	13.5	31.5	0.666	0.8	0.0
1	1986	230	20480.	14.5	31.0	0.801	1.3	0.0
1	1986	231	19890.	13.5	30.5	0.875	1.1	1.3
1	1986	232	23501.	14.2	30.5	0.836	0.9	4.0
1	1986	233	19559.	15.0	30.5	0.916	1.3	0.0
1	1986	234	20516.	14.5	30.5	0.943	0.9	1.6
1	1986	235	20959.	13.5	31.3	0.802	0.9	2.9
1	1986	236	25049.	12.4	31.5	0.663	1.1	3.4
1	1986	237	25157.	12.2	30.5	0.684	1.2	3.4
1	1986	238	24754.	12.0	32.0	0.633	1.1	0.0
1	1986	239	23944.	12.0	31.0	0.619	1.0	0.0
1	1986	240	22471.	15.0	30.5	0.788	1.1	0.0
1	1986	241	18162.	15.1	30.0	0.914	1.2	0.5
1	1986	242	24718.	14.0	30.5	0.744	1.0	0.0
1	1986	243	20959.	15.5	31.0	0.909	1.2	0.0
1	1986	244	15106.	13.5	30.5	0.915	0.9	0.0
1	1986	245	14332.	17.0	27.5	1.295	0.9	2.0
1	1986	246	17424.	16.0	30.5	0.984	1.2	0.0
1	1986	247	23648.	12.5	30.5	0.766	1.0	20.3
1	1986	248	26298.	12.8	30.0	0.716	1.2	0.0
1	1986	249	19706.	13.0	29.5	0.703	1.0	0.6
1	1986	250	23242.	13.5	31.0	0.853	1.4	0.0
1	1986	251	18641.	13.1	31.0	0.748	1.2	0.0
1	1986	252	21769.	15.5	30.8	0.842	1.2	5.8
1	1986	253	23170.	15.8	31.2	0.855	1.2	0.0
1	1986	254	18234.	18.5	29.0	1.292	1.1	0.0
1	1986	255	22064.	11.9	30.0	0.785	1.6	0.0
1	1986	256	23980.	15.5	30.0	0.909	1.5	0.0
1	1986	257	16909.	15.2	29.0	0.863	1.2	0.0
1	1986	258	16466.	17.5	29.5	1.101	1.7	0.0
1	1986	259	9173.	17.5	26.5	1.383	0.9	0.0
1	1986	260	13410.	17.0	28.8	1.270	1.2	6.6
1	1986	261	20740.	14.9	29.5	1.039	1.2	5.5
1	1986	262	24642.	14.0	30.0	0.899	1.1	0.0
1	1986	263	19008.	17.0	29.0	1.051	1.4	9.0

Appendix 2.6.4 -III Weather data used in the simulation program (cont.)

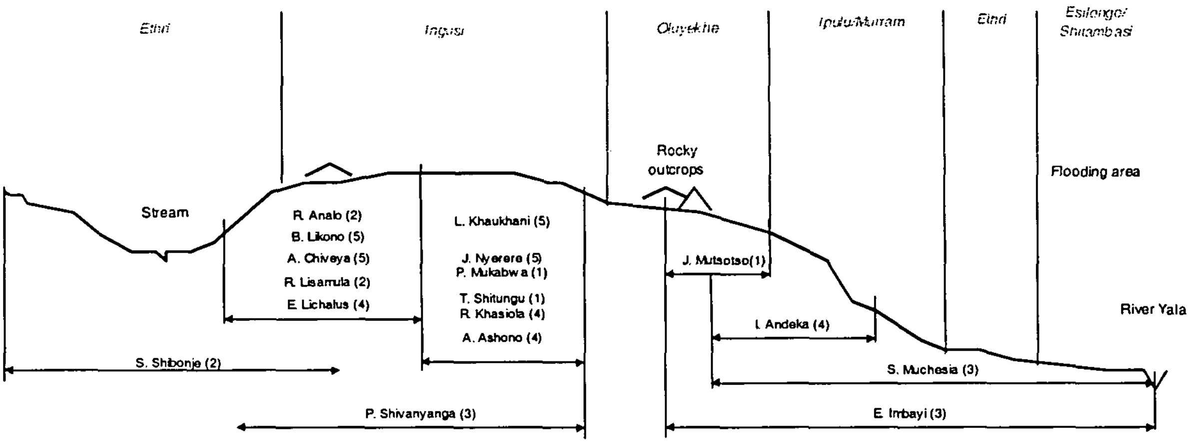
1	1986	264	20185.	17.0	29.0	1.264	1.2	0.0
1	1986	265	26816.	13.6	31.2	0.787	1.2	2.3
1	1986	266	22248.	14.2	31.9	0.762	1.1	0.0
1	1986	267	22136.	13.5	32.5	0.610	1.1	0.0
1	1986	268	24642.	13.5	33.0	0.627	1.2	0.0
1	1986	269	21845.	14.1	33.5	0.667	1.1	0.0
1	1986	270	23429.	13.5	32.5	0.633	1.2	0.0
1	1986	271	20038.	15.5	29.4	0.989	1.5	0.0
1	1986	272	24570.	13.5	29.9	0.773	0.9	0.0
1	1986	273	23022.	14.9	30.9	0.749	0.8	0.0
1	1986	274	25121.	13.9	31.5	0.772	1.3	0.0
1	1986	275	23242.	14.0	31.3	0.651	1.2	2.8
1	1986	276	24718.	13.3	31.5	0.752	0.9	0.0
1	1986	277	23573.	16.5	31.0	0.785	1.2	0.0
1	1986	278	21071.	15.5	31.2	0.858	1.1	0.0
1	1986	279	19670.	16.5	31.3	1.009	1.5	0.0
1	1986	280	23317.	15.9	30.9	0.871	1.2	38.0
1	1986	281	17644.	15.2	30.0	1.099	1.2	0.2
1	1986	282	24570.	17.5	31.0	1.067	1.2	0.0
1	1986	283	20333.	17.5	29.4	1.149	1.5	1.1
1	1986	284	17204.	16.5	28.5	1.229	1.1	17.0
1	1986	285	21881.	17.0	30.5	1.001	1.2	19.2
1	1986	286	24642.	16.9	30.0	1.197	1.2	0.0
1	1986	287	19008.	16.0	30.0	1.048	1.1	0.0
1	1986	288	24862.	14.9	31.2	0.748	0.9	0.0
1	1986	289	23796.	14.5	32.0	0.777	1.1	0.0
1	1986	290	25636.	14.6	32.3	0.740	1.3	0.0
1	1986	291	23944.	13.5	33.4	0.661	0.9	0.0
1	1986	292	22802.	14.0	32.5	0.744	1.4	0.8
1	1986	293	25049.	15.1	31.0	0.835	1.3	0.0
1	1986	294	21586.	15.5	30.9	0.828	1.1	0.0
1	1986	295	17388.	15.1	30.2	0.860	0.7	0.0
1	1986	296	17165.	15.8	30.0	1.013	0.9	1.4
1	1986	297	22360.	15.0	30.2	1.034	1.2	0.0
1	1986	298	19375.	15.8	30.0	1.006	1.3	11.1
1	1986	299	18565.	15.6	29.6	0.993	1.1	0.7
1	1986	300	22064.	17.1	28.2	1.204	1.2	0.0
1	1986	301	21881.	16.7	29.5	1.018	1.1	0.0
1	1986	302	18310.	16.0	30.5	1.050	1.3	26.1
1	1986	303	18270.	16.0	29.7	1.194	0.9	0.0
1	1986	304	24530.	16.0	27.0	1.063	1.9	0.0
1	1986	305	21586.	16.0	28.2	1.026	1.6	0.3
1	1986	306	16578.	18.0	28.5	1.363	0.8	0.0
1	1986	307	19746.	14.6	29.6	0.946	1.0	0.0
1	1986	308	23537.	15.5	29.3	1.168	1.7	26.0
1	1986	309	23904.	16.1	28.5	1.104	1.0	0.0
1	1986	310	15584.	16.5	29.0	1.234	1.5	2.6
1	1986	311	20923.	15.0	30.0	0.956	0.6	7.4
1	1986	312	20923.	16.5	32.0	1.268	1.1	31.4
1	1986	313	22543.	17.0	30.0	1.127	1.4	14.6
1	1986	314	22579.	16.0	29.5	1.174	1.5	1.5
1	1986	315	20776.	16.5	29.0	1.272	1.3	0.0
1	1986	316	20592.	16.0	29.0	1.305	0.9	1.5
1	1986	317	14958.	15.5	28.8	1.049	0.9	0.5
1	1986	318	12488.	16.0	28.0	1.170	0.8	0.0
1	1986	319	20333.	14.5	31.0	0.919	1.0	0.0
1	1986	320	21733.	16.5	29.5	1.306	1.2	4.8
1	1986	321	21881.	14.2	30.4	0.860	1.0	0.0
1	1986	322	20444.	15.5	30.0	0.997	0.9	0.0
1	1986	323	19966.	15.5	28.5	0.962	1.4	6.3
1	1986	324	24016.	13.5	30.2	0.824	1.1	0.0
1	1986	325	22028.	14.0	30.0	0.910	0.8	1.1
1	1986	326	18713.	14.3	30.0	0.912	1.1	2.0
1	1986	327	18310.	15.5	29.5	0.874	0.8	0.1
1	1986	328	20628.	15.0	31.0	0.775	1.0	0.0
1	1986	329	18454.	15.0	30.2	0.899	1.1	0.4
1	1986	330	22284.	16.6	31.0	0.994	1.2	3.4
1	1986	331	23537.	17.0	31.5	0.855	0.9	0.0
1	1986	332	20812.	15.0	30.5	0.932	1.2	0.0
1	1986	333	13558.	18.5	29.0	1.055	1.4	0.6
1	1986	334	18641.	14.0	31.5	0.841	0.8	0.2
1	1986	335	15584.	16.8	29.0	1.101	1.3	7.8
1	1986	336	14515.	16.5	-99.0	1.259	0.8	0.0
1	1986	337	23944.	-99.0	30.8	0.000	1.5	0.0
1	1986	338	20297.	15.9	29.5	1.130	1.9	42.2
1	1986	339	18122.	17.5	26.5	1.407	1.1	0.0
1	1986	340	17057.	16.5	25.5	1.157	0.9	2.9
1	1986	341	8363.	18.0	27.4	1.582	1.2	0.0
1	1986	342	17939.	16.6	28.8	1.204	0.8	0.0
1	1986	343	21438.	15.0	29.5	0.983	1.7	45.0
1	1986	344	20408.	17.5	26.5	1.363	1.5	5.7
1	1986	345	19854.	16.9	27.5	1.307	1.0	0.0
1	1986	346	26298.	16.5	28.5	1.088	1.4	3.2
1	1986	347	21992.	15.6	29.5	0.906	1.2	1.6
1	1986	348	20923.	18.0	28.0	1.405	1.6	1.3
1	1986	349	23980.	15.0	28.5	0.986	1.6	0.0
1	1986	350	22691.	14.5	30.0	0.767	1.2	0.0
1	1986	351	19080.	15.0	30.0	0.932	1.1	1.1
1	1986	352	20812.	16.0	29.5	0.990	1.1	7.8
1	1986	353	20369.	15.5	28.4	1.151	1.3	13.6
1	1986	354	22615.	16.0	28.5	1.132	1.5	0.0
1	1986	355	21550.	15.4	28.4	1.098	1.5	1.8
1	1986	356	19375.	18.6	29.5	1.542	1.1	0.6
1	1986	357	22176.	17.7	30.0	1.224	1.1	0.0
1	1986	358	21254.	18.5	30.5	1.172	1.1	0.0
1	1986	359	21992.	16.7	30.7	1.263	1.2	0.0
1	1986	360	23242.	19.0	29.5	1.073	1.5	0.0
1	1986	361	23796.	18.5	29.6	1.094	1.5	0.0
1	1986	362	22986.	14.2	29.5	0.817	1.7	0.0
1	1986	363	23501.	13.8	30.2	0.812	1.5	0.0
1	1986	364	23832.	16.7	31.3	0.921	1.4	2.1
1	1986	365	22507.	16.3	31.5	0.970	1.3	0.0

Appendix to Chapter 3

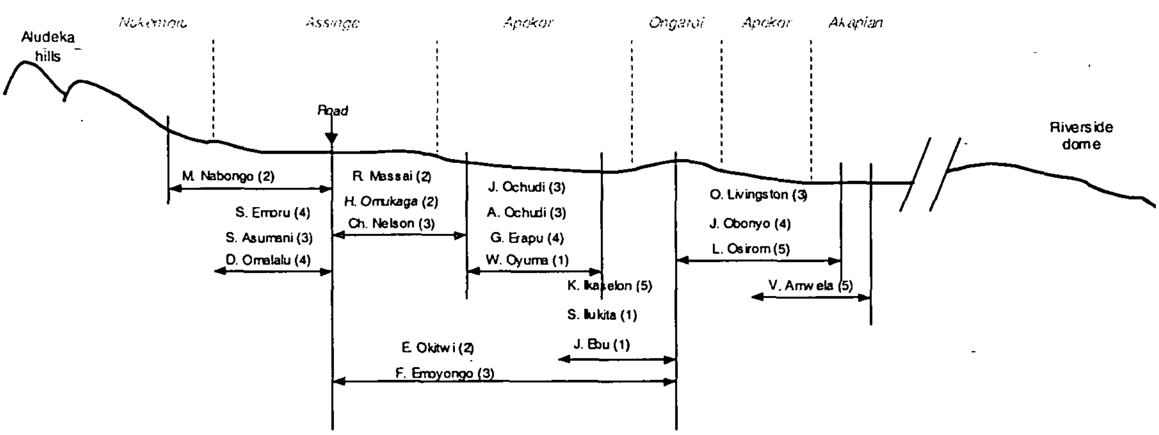
Contents | No.

Appendix 3.1.1 Distribution of farms along the landscape

A



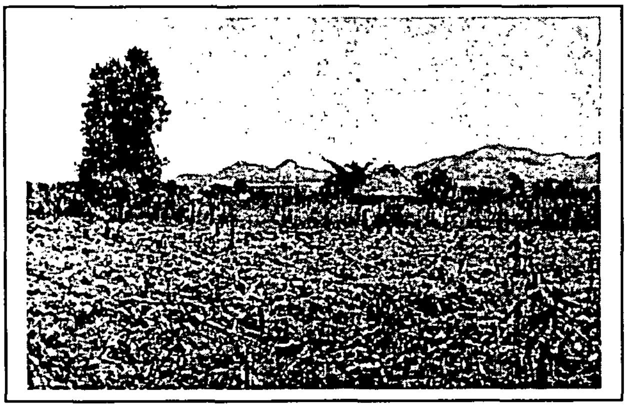
B



Distribution along the landscape of the interviewed and sampled farms in Shinyalu (A) and in Aludeka (B), western Kenya. The distribution of farms in Emuhaia resembles that of Shinyalu. Names in italics indicate local terms for soil/landscape units (in Figure A, the names given to a certain unit in Shinyalu and Emuhaia are both shown when they are different). The names of the farmers are followed by the farm type to which they below, into brackets. The arrows below the farmers' names indicate the soilscape units on which the sampled farms are placed (e.g. Mr. E. Okitwi's farm, which belongs to the type 2, includes *Assinge*, *Apokor* and *Ongaroi* soils within its area). Figure A represents a section of about 2 to 5 km of distance from valley to valley; in Figure B the distance from the hills to the river ranges between 5 to 10 km.

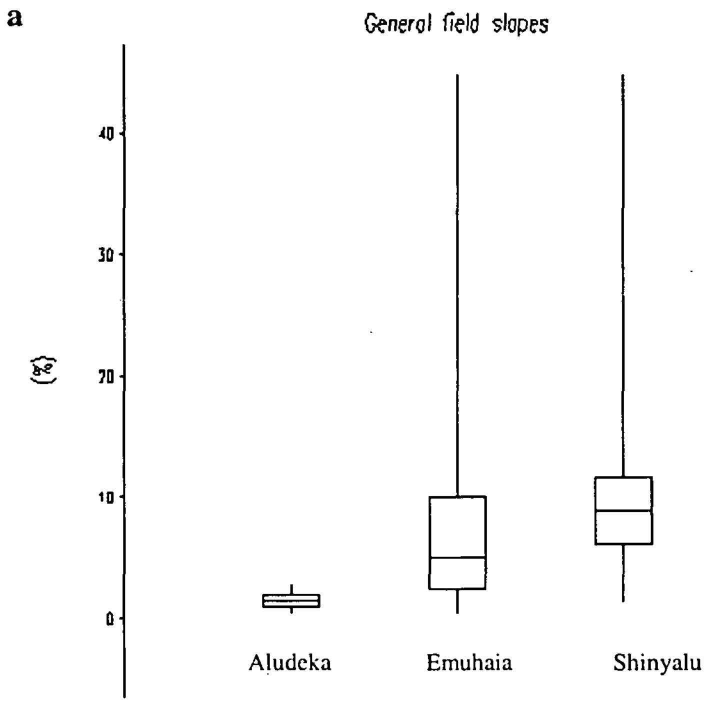
Appendix 3.1.4 – I Reconnaissance of common features during the transect walks across the farms

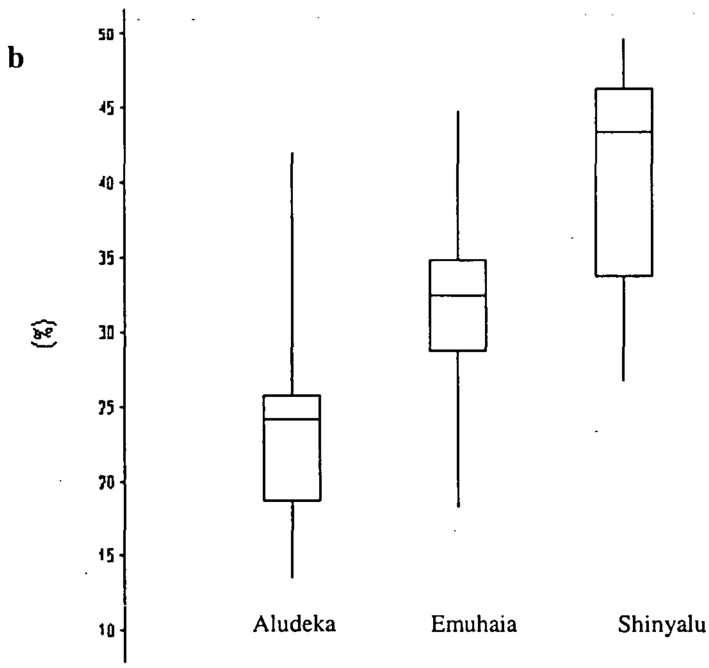
The relatively intensive livestock system in Emuhaia: *Above*, a compound where cattle are tethered and fed cut grass; *Right*, cattle manure collected from a zero grazing unit



The high variability in soil types in Aludeka: *Above left*, a fertile swampy area sporadically used for cultivation and/or for cutting roofing grass; *Above right*, a general view of an area of sandy soils (behind, the hills around Tororo, Uganda); *Right*, the surface appearance of a 'murram' field (laterite concretions). The three pictures were taken at no more than 1.5 km away from each other.

Appendix 3.1.5 - I Range of soil properties at site scale (slope and clay)

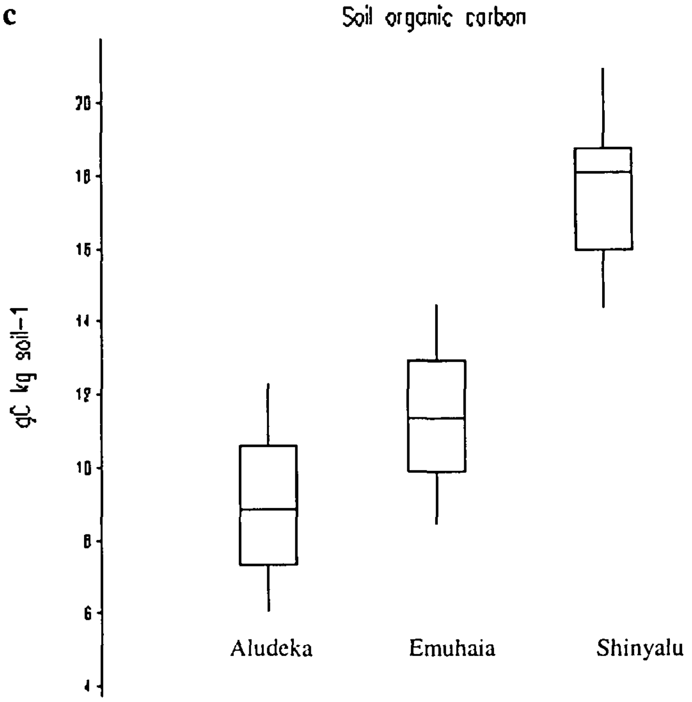




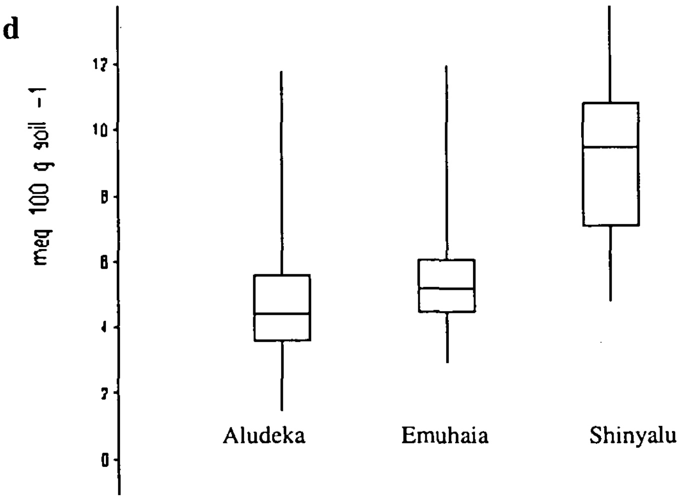
Range of relevant soil and landscape properties for the farm samples from Aludeka, Emuhaia and Shinyalu, western Kenya. (a) field slope [%]; (b) clay content [%]. The box-and-whisker diagrams include the range of 50% of the samples (rectangle), the median (cross bar) and the maximum and minimum values (extreme of the lines). Sample sizes 53 (Aludeka), 55 (Emuhaia), 53 (Shinyalu).

Appendix 3.1.5 - II Range of soil properties at site scale (organic carbon and cation exchange capacity)

c



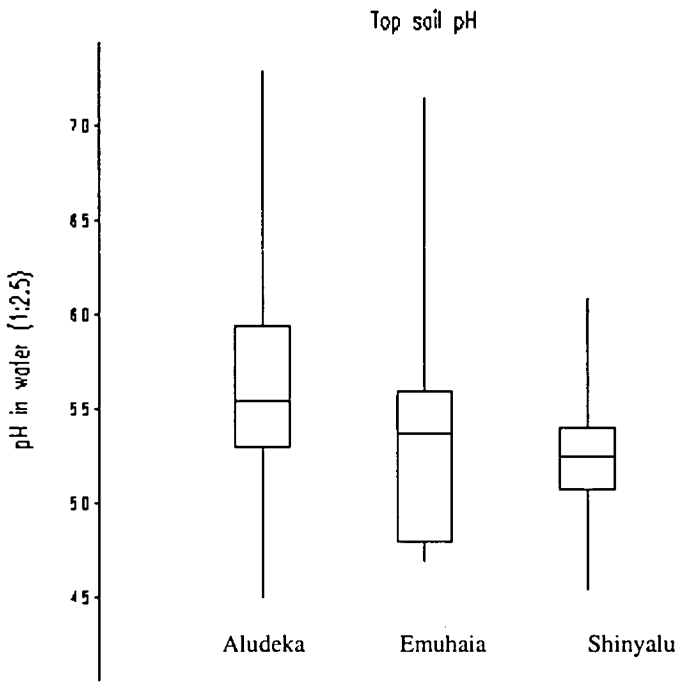
d



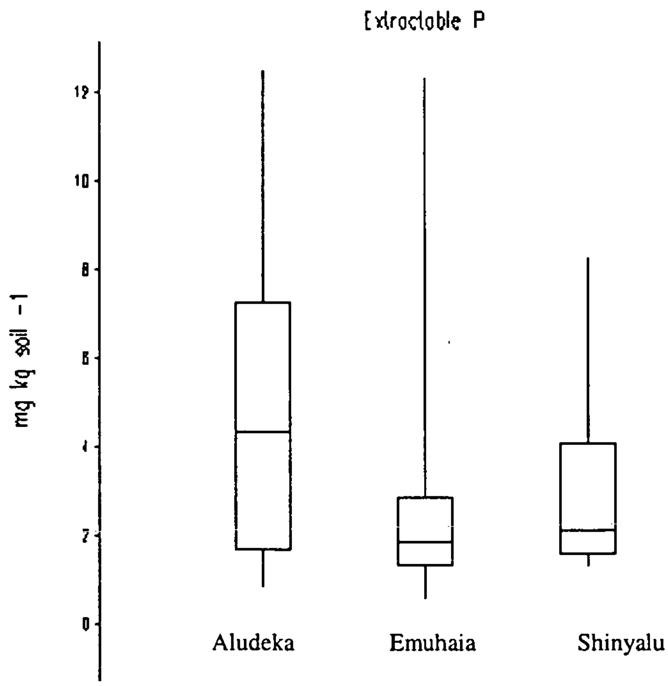
Range of relevant soil and landscape properties for the farm samples from Aludeka, Emuhaia and Shinyalu, western Kenya. (c) soil organic carbon [g kg^{-1}]; (d) effective cation exchange capacity [meq 100 g $^{-1}$]. For explanation see Figures a and b.

Appendix 3.1.5 - III Range of soil properties at site scale (pH and extractable P)

e



f



Range of relevant soil and landscape properties for the farm samples from Aludeka, Emuhaia and Shinyalu, western Kenya. (e) topsoil pH; (f) extractable P (modified Olsen) [mg kg^{-1}]. For explanation see Figures a and b.

Appendix 3.1.2 Between-sites variability: Family, labour and income

Table a

Characteristics of the household heads	% of farms Emuhaia	Shinyalu	Aludeka
Gender			
Male	50	63	95
Female	50	37	11
Marital status			
Married	70	68	89
Single	5	5	0
Widow	25	26	16
Educational level			
Primary	25	47	53
Secondary	40	26	21
Tertiary	5	0	0
None	30	21	26

Table b

Activity for which labour is hired	% of farms Emuhaia	Shinyalu	Aludeka
Land preparation*	45	53	42
Planting/sowing	20	47	21
Weeding	40	68	58
Harvesting	0	47	16
Tea planking	5	16	n/a
Farming in general	10	11	16
Livestock feeding	15	0	0
House Keeping	10	5	0

(*) in Shinyalu and Aludeka it also includes oxen hiring

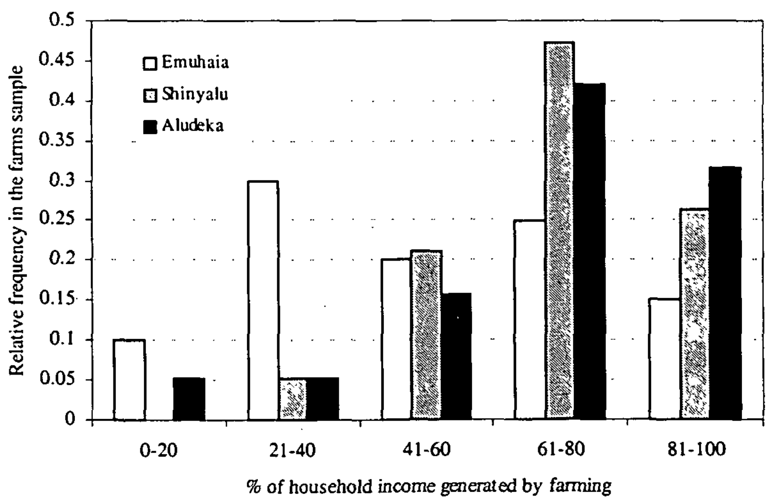


Figure c: Relative importance of on-farm income at Emuhaia, Shinyalu and Aludeka

Appendix 3.1.3: Between-sites variability: production activities

Table a

Production activities	% of farms		
	Emuhaia	Shinyalu	Aludeka
Grain crops			
Maize	100	100	100
Sorghum	15	11	42
Finger millet	5	0	74
Rice	0	0	21
Beans	95	100	68
Ground nuts	5	5	53
Root/tuber crops			
Cassava	25	26	100
Sweet potato	20	26	16
Jam	10	16	0
Fruits and vegetables			
Banana	95	68	89
Mango	5	0	47
Avocado	30	42	5
Local vegetables	35	26	0
Kales/cabbages	60	58	11
Cowpea*	40	47	21
Pastures and forages			
Natural grassland	35	42	63
Napier grass	65	37	5
Strictly cash crops			
Tea	10	21	0
Sugar cane	15	16	26
Cotton	0	0	16
Tobacco	5	0	21
*Livestock produce***			
Milk	40	32	16
Eggs	80	63	84

(*) cowpea is mainly grown as a vegetable, its green leaves are consumed
(**) meat production is not included because chickens, piglets, cows and calves are sold sporadically.

Appendix 3.2.2 – I Between farm variability: labour, income and land for different wealth classes

Table a: Comparative labour, income and wealth indicators for different wealth classes at the three sites (cf. Table 3.2.2 in main text)

Site	Wealth Class	Labour variables: Family size	Family members working on farm	Family members working off farm	Hired labour (man-days)	Income from farming (%)	Self sufficiency of maize (months)	Livestock ownership (heads)
Emuhaia	HRE	5.1	3.3	1.3	5.6	46	8.7	3.9
	MRE	6.9	3.7	0.7	1.6	68	6.7	3.4
	LRE	5.3	2.7	0.7	0.2	55	3.2	0.8
SED		*1.5*	*1.1*	*0.4*	*0.6*	*14*	*1.6*	*0.91*
Shinyalu	HRE	6.0	3.4	0.6	6.7	64	10.0	3.6
	MRE	7.5	4.1	0.7	4.3	82	9.5	3.9
	LRE	5.2	2.5	0.6	1.0	80	7.1	1.8
SED		*1.9*	*1.1*	*0.5*	*1.1*	*10*	*1.3*	*1.6*
Aludeka	HRE	7.1	4.7	0.4	6.7	73	6.3	2.4
	MRE	7.6	3.4	0.4	4.3	77	7.0	6.6
	LRE	6.3	3.1	0.3	0.2	72	4.3	1.0
SED		*1.8*	*0.9*	*0.4*	*0.9*	*13*	*2.4*	*1.9*

HRE, MRE and LRE: high, medium and low resource endowment, respectively. SED: standard error of the differences

Table b: Comparative land size and land distribution indicators for different wealth classes at the three sites (cf. Table 3.2.3 in main text)

Site	Wealth class	Land use intensity: Farm size (ha)	Cropped area (ha)	Number of production units*	Land availability (ha): Per family member	Per family labour	Per labour unit **
Emuhaia	HRE	1.3	1.4	5.1	0.29	0.42	0.13
	MRE	0.6	0.6	6.0	0.13	0.20	0.12
	LRE	0.4	0.4	4.3	0.07	0.20	0.20
SED		*0.16*	*0.15*	*0.67*	*0.04*	*0.06*	*0.03*
Shinyalu	HRE	1.1	1.0	6.2	0.19	0.36	0.10
	MRE	1.1	1.0	6.8	0.18	0.36	0.14
	LRE	0.9	0.7	6.2	0.23	0.39	0.29
SED		*0.21*	*0.12*	*0.85*	*0.04*	*0.07*	*0.03*
Aludeka	HRE	2.7	2.0	7.0	0.38	0.56	0.22
	MRE	2.0	1.9	8.3	0.38	0.68	0.27
	LRE	0.9	0.8	5.7	0.18	0.30	0.30
SED		*0.6*	*0.5*	*1.6*	*0.14*	*0.16*	*0.07*

HRE, MRE and LRE: high, medium and low resource endowment, respectively. SED: standard error of the differences

Appendix 3.2.2 – II Between farm variability: management practices

Production structure and management practices across sites and farm types

Site	Farm type	Livestock ownership (% of farms)		Production of cash crops	Firewood source		Management practices (% of farms)				Fertilisers use (% of farms)		Use of legumes*
		All kinds	Cattle	(% of farms)	Own woodlots (% of farms)	Acquired from off farm (%)	Fallow	Fallow rotation	Crops rotation	Compost	Cattle manure	Inorganic	(% of farms)
Emuhaia	1	100	100	60	40	52	20	n/a	20	100	100	100	75
	2	100	100	100	100	5	33	n/a	33	67	100	67	66
	3	100	100	100	80	21	40	n/a	60	100	100	100	80
	4	80	67	50	67	56	33	n/a	66	100	100	67	67
	5	50	50	33	25	68	25	n/a	0	75	75	0	75
Shinyalu	1	67	67	33	100	57	0	0	33	67	100	100	67
	2	100	100	100	100	4	67	0	67	67	100	100	67
	3	100	80	100	100	16	60	60	60	80	80	80	80
	4	100	100	50	100	32	25	0	0	75	100	100	75
	5	25	0	50	100	37	25	0	50	50	50	75	50
Aludeka	1	67	0	100	100	36	33	33	100	33	67	0	67
	2	80	0	60	100	9	100	60	100	60	20	60	40
	3	100	80	100	80	16	80	60	100	60	80	20	80
	4	50	50	100	25	28	50	25	100	0	0	25	50
	5	33	0	33	100	43	33	33	100	0	33	0	33

*excluding beans and groundnuts
n/a: not applicable

Appendix 3.2.2 – III Between farm variability: management practices

Production structure and management practices across sites and wealth classes

Site	Farm Type	Livestock ownership		Production of	Firewood source		Management practices (% of farms)				Fertilisers use (% of farms)		Use of
		All kinds (% of farms)	Cattle (% of farms)	cash crops (% of farms)	Own woodlots (% of farms)	Acquired from off farm (%)	fallow	fallow rotation	crops rotation	composting	cattle manure	inorganic	legumes* (% of farms)
Emuhaia	HRE	100	100	71	71	28	14	n/a	14	86	100	86	71
	MRE	100	100	86	71	36	57	n/a	71	100	100	86	86
	LRE	65	50	50	33	61	17	n/a	17	83	83	33	67
Shinyalu	HRE	80	80	60	100	31	20	0	40	80	100	100	60
	MRE	100	88	100	100	24	38	37.5	50	75	88	88	88
	LRE	50	33	33	100	36	33	0	33	50	67	83	50
Aludeka	HRE	57	0	71	100	26	71	71	100	43	43	57	71
	MRE	100	71	100	71	21	86	57	100	43	57	0	71
	LRE	33	17	67	67	32	33	17	100	0	17	17	33

*excluding beans and groundnuts
n/a: not applicable

Appendix 3.2.3 – I Results of the resource flow maps at farm scale

Table a

Site	Farm Type	Area under crops (ha) Home stead	Area under crops (ha) Total cropped	Total food* production (t)	Food produced per capita (t)	Sold on the market (t)	Sold on the market (%)	Average food yield (t ha^{-1}) Home stead	Average food yield (t ha^{-1}) Total cropped
Emuhaia	T1	0.3	0.4	0.9	0.2	0.1	9	1.8	1.6
	T2	1.8	2.5	2.8	0.4	1.2	45	1.5	1.1
	T3	0.6	3.5	6.0	0.6	3.3	56	2.3	1.7
	T4	0.5	0.5	1.0	0.2	0.2	16	2.0	2.0
	T5	0.6	0.9	0.6	0.1	0.1	14	0.5	0.6
Shinyalu	T1	0.8	0.8	1.9	0.3	0.0	2	1.2	1.2
	T2	2.9	2.9	3.6	0.4	1.5	43	1.2	1.2
	T3	2.0	2.0	6.3	1.3	3.3	52	3.1	2.8
	T4	1.1	1.1	1.9	0.5	0.6	29	1.7	1.7
	T5	0.9	0.9	0.6	0.1	0.0	7	0.7	0.7
Aludeka	T1	1.1	1.1	1.4	0.5	0.4	32	1.3	1.3
	T2	3.3	3.3	4.9	0.6	1.5	31	1.5	1.5
	T3	1.0	8.4	9.0	1.1	6.0	67	2.1	1.1
	T4	0.9	1.4	1.4	0.3	0.3	22	1.2	1.0
	T5	0.9	0.9	0.7	0.1	0.0	6	0.7	0.7

*including grain, tuber, fruit and leaf crops

Table b

Site	Farm type	Grain production Area (ha)	Grain production Total (t)	Grain production Yield (t ha^{-1})	Proportion shared of Area (%)	Proportion shared of Production (%)	Maize yield (t ha^{-1}) Best field	Maize yield (t ha^{-1}) Worst field
Emuhaia	T1	0.1	0.2	1.3	33	18	1.2	0.9
	T2	0.8	1.1	1.3	32	39	0.8	0.0
	T3	1.9	4.8	2.5	53	80	3.0	0.3
	T4	0.3	0.3	1.1	55	30	1.2	0.7
	T5	0.4	0.2	0.6	41	38	0.7	0.0
Shinyalu	T1	0.8	1.1	1.4	73	58	1.0	0.1
	T2	1.3	1.5	1.2	43	43	1.9	0.1
	T3	1.1	1.3	1.2	53	21	1.8	0.3
	T4	0.8	0.6	0.7	73	32	2.9	0.1
	T5	0.8	0.3	0.4	93	55	0.5	0.1
Aludeka	T1	0.7	0.6	0.8	69	44	0.8	0.4
	T2	1.3	1.3	1.0	41	26	2.0	0.5
	T3	7.3	5.6	0.8	86	62	1.3	0.3
	T4	0.7	0.3	0.4	48	20	1.5	0.4
	T5	0.2	0.1	0.5	22	14	0.7	0.2

Appendix 3.2.3 – II Results of the resource flow maps at farm scale

Table a: Seasonal land, labour and input use, gross production and consumption for different activities estimated from the resource flow map drawn at John Mutsotso's farm (case study farm type 1, Shinyalu)

Activity	Land allocated (ha)	Labour allocated (mandays)	Fertilisers use (kg) Inorganic	Fertilisers use (kg) Organic	Gross production (unit per farm)	Gross consumption (unit per farm)	Marketed (%)
Grain crops	0.78	32	27	600	1858 Kg	1768 kg	5
Root/tuber crops	0	0	0	0	0	90 kg	0
Fruits/vegetables	0.26	20	13	180	2971 kg	2931 kg	1
Pastures/forages	0	0	0	0	0 kg	480 kg	0
Strictly cash crops	0	0	0	0	0	n/a	0
Livestock in general	0.02	52	n/a	n/a	n/a	n/a	n/a
Milk	0	0	n/a	n/a	0	50 kg	0
Wood	0.01	n/a	n/a	n/a	0	44 bundles	0

Table b: Seasonal land, labour and input use, gross production and consumption for different activities estimated from the resource flow map drawn at Shiboko Shivonje's farm (case study farm type 2, Shinyalu)

Activity	Land allocated (ha)	Labour allocated (mandays)	Fertilisers use (kg) Inorganic	Fertilisers use (kg) Organic	Gross production (unit per farm)	Gross consumption (unit per farm)	Marketed (%)
Grain crops	1.26	60	81	200	1550 kg	990 kg	36
Root/tuber crops	0.26	9	0	0	480 kg	420 kg	13
Fruits/vegetables	0.66	42	14	40	2540 kg	780 kg	69
Pastures/forages	0.25	68	0	0	6600 kg	3200 kg	52
Strictly cash crops	0.71	122	150	0	910 kg	0 kg	100
Livestock in general	0.14	52	n/a	n/a	n/a	n/a	n/a
Milk	0.14	n/a	n/a	n/a	680 kg	160 kg	76
Wood	0.11	n/a	n/a	n/a	78 bundles	78 bundles	0

Table c: Seasonal land, labour and input use, gross production and consumption for different activities estimated from the resource flow map drawn at Peter Shivanyanga's farm (case study farm type 3, Shinyalu)

Activity	Land allocated (ha)	Labour allocated (mandays)	Fertilisers use (kg) Inorganic	Fertilisers use (kg) Organic	Gross production (unit per farm)	Gross consumption (unit per farm)	Marketed (%)
Grain crops	1.07	58	13.5	0	1298 kg	404 kg	69
Root/tuber crops	0.09	4	0	0	240 kg	240 kg	0
Fruits/vegetables	0.28	21	5	0	2320 kg	400 kg	83
Pastures/forages	0.32	26	0	0	3250 kg	650 kg	80
Strictly cash crops	0.07	2	0	0	22 bundles	3 bundles	86
Livestock in general	0.49	46	n/a	n/a	n/a	n/a	n/a
Milk	0.24	n/a	n/a	n/a	375 kg	75 kg	80
Wood	0.08	n/a	n/a	n/a	60 bundles	60 bundles	0
Other enterprises*	0.01	6	n/a	n/a	78 kg	4 kg	95

*honey bees

Appendix 3.2.3 – II (cont.) Results of the resource flow maps at farm scale

Table d: Seasonal land, labour and input use, gross production and consumption for different activities estimated from the resource flow map drawn at Elphas Lichalus' farm (case study farm type 4, Shinyalu)

Activity	Land allocated (ha)	Labour allocated (mandays)	Fertilisers use (kg) Inorganic	Fertilisers use (kg) Organic	Gross production (unit per farm)	Gross consumption (unit per farm)	Marketed (%)
Grain crops	0.825	34	20	140	615 kg	892 kg	0
Root/tuber crops	0.08	3	0	0	10 kg	80 kg	0
Fruits/vegetables	0.505	12	0	100	160 kg	360 kg	0
Pastures/forages	0	0	0	0	0	400 kg	0
Strictly cash crops	0	0	0	0	0	n/a	0
Livestock in general	0.09	46	n/a	n/a	n/a	n/a	n/a
Milk	0.09	n/a	n/a	n/a	280 kg	60 kg	79
Wood	0.08	n/a	n/a	n/a	22 bundles	48 bundles	0
Other enterprises*	n/a	56	n/a	n/a	n/a	n/a	n/a

*oxen services

Table e: Seasonal land, labour and input use, gross production and consumption for different activities estimated from the resource flow map drawn at Lucia Khaukhani's farm (case study farm type 5, Shinyalu)

Activity	Land allocated (ha)	Labour allocated (mandays)	Fertilisers use (kg) Inorganic	Fertilisers use (kg) Organic	Gross production (unit per farm)	Gross consumption (unit per farm)	Marketed (%)
Grain crops	0.821	30	4	0	334 kg	600 kg	0
Root/tuber crops	0.14	5	0	0	80 kg	120 kg	0
Fruits/vegetables	0.429	16	0.75	0	880 kg	820 kg	6.8
Pastures/forages	0	0	0	0	0	n/a	0
Strictly cash crops	0	0	0	0	0	n/a	0
Livestock in general	0	0	n/a	n/a	n/a	n/a	n/a
Milk	0	0	n/a	n/a	0	120 kg	0
Wood	0	0	n/a	n/a	0	42 bundles	0

Appendix 3.2.3 – III Results of the resource flow maps at farm scale

Table a: Nutrient application rates under different forms for different farm types across sites. Estimations from the results of the resource flow maps.

Site	Farm type	C application rate (kg ha^{-1})	Total nutrients applied (kg ha^{-1})		
			N	P	K
Emuhaia	T1	4416	116	58	118
	T2	509	27	25	14
	T3	3146	72	34	84
	T4	1825	44	25	49
	T5	2774	58	24	74
Shinyalu	T1	664	26	19	18
	T2	144	26	18	4
	T3	526	24	12	14
	T4	322	14	10	9
	T5	0	3	3	0
Aludeka	T1	0	3	7	0
	T2	0	1	2	0
	T3	0	0	0	0
	T4	0	0	0	0
	T5	0	0	0	0

Table b: Labour requirements for a maize/beans intercrop during the long rains season at Shinyalu, West Kenya. Mean values followed by standard deviations.

Activity	Number of labourers employed		Number of days working		Labour requirement (man-days ha^{-1})	
Land preparation						
1st ploughing	3.9	*+/- 1.4*	2.4	*+/- 0.9*	10.4	*+/- 3.8*
2nd ploughing and planting	5.1	*+/- 2.1*	1.6	*+/- 0.6*	9.2	*+/- 2.3*
Weeding	9.7	*+/- 2.3*	1.3	*+/- 0.6*	14.2	*+/- 6.0*
Harvesting	10.1	*+/- 6.0*	1.1	*+/- 0.3*	13.6	*+/- 9.0*

Appendix 3.2.3 – IV Results of the resource flow maps at farm scale

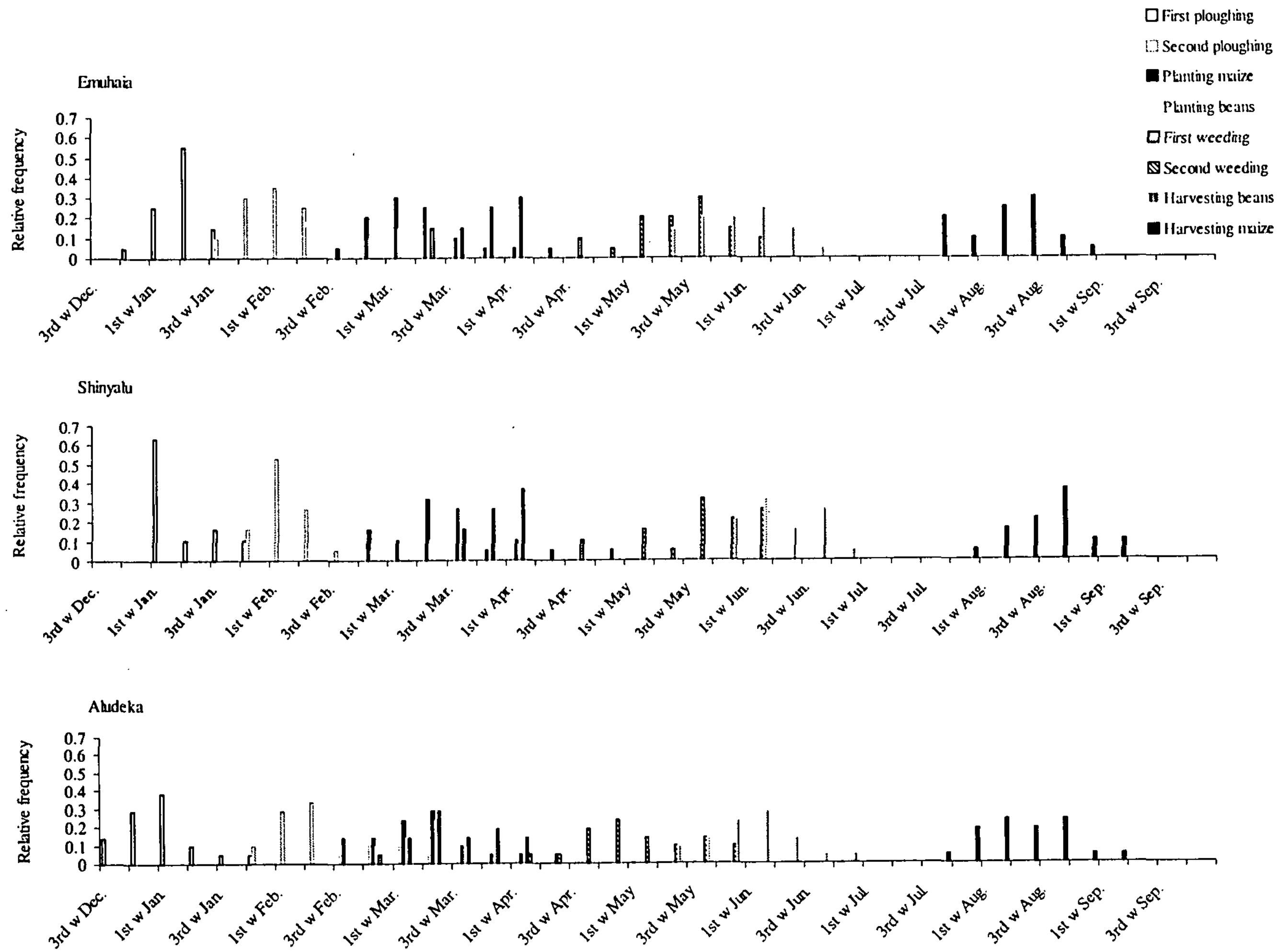


Figure a: Timing of different farm activities during the long rains season. Frequency indicates the relative number of farmers that gave certain answer.

Appendix 3.3.2 Farmers' land quality classification

Table a

Site	Wealth class	Total area* (ha)	Land quality (%)			Land quality (ha)		
			Fertile	Regular	Poor	Fertile	Regular	Poor
Emuhaia	HRE	1.4	50	29	19	0.6	0.5	0.3
	MRE	0.8	51	27	23	0.4	0.2	0.2
	LRE	0.5	35	27	39	0.1	0.1	0.2
Shinyalu	HRE	1.5	44	34	22	0.7	0.4	0.4
	MRE	1.3	55	23	22	0.4	0.3	0.2
	LRE	1.0	38	27	35	0.3	0.3	0.4
Aludeka	HRE	2.6	46	34	20	1.2	0.9	0.4
	MRE	1.6	32	29	39	0.5	0.5	0.7
	LRE	1.0	17	30	53	0.2	0.3	0.5

*Total area might not coincide with previous figures because is calculated for a sub-sample of 15 farms out of 20.

Table b

	Relative frequency %		
Criteria for land quality classification	Emuhaia	Shinyalu	Aludeka
Soil type	40	33	67
Texture	20	7	53
Water holding capacity	20	7	27
Fertility	13	40	33
Slope	53	73	0
Weed type	27	0	0
Distance from homestead	0	7	20
Others	0	7	7
Reasons for differences in yields among fields			
Water logging	0	0	7
Erosion	73	93	13
Declining soil fertility	60	40	27
Weeds, pests or diseases	47	7	0
Management inputs	40	20	13
Use of different varieties	27	47	0

Appendix to Chapter 4

Contents No.

Appendix 4.1.1 ANOVA tables for selected soil properties

a) Soil organic carbon

Analysis of an unbalanced design using GenStat regression

Change	d.f.	s.s.	m.s.	v.r.	F pr.
+ Site	2	2143.681	1071.841	294.71	<.001
+ Farmty	4	95.887	23.972	6.59	<.001
+ Site.Farmty	8	103.361	12.920	3.55	0.002
+ Fieldty	5	49.525	9.905	2.72	0.026
+ Farmty.Fieldty	20	39.096	1.955	0.54	0.940
+ Site.Fieldty	8	26.486	3.311	0.91	0.513
+ Site.Farmty.Fieldty	22	60.545	2.752	0.76	0.765
Residual	71	258.224	3.637		
Total	140	2776.806	19.834		

b) Total soil nitrogen

Analysis of an unbalanced design using GenStat regression

Change	d.f.	s.s.	m.s.	v.r.	F pr.
+ Site	2	25.31827	12.65913	140.26	<.001
+ Farmty	4	3.96629	0.99157	10.99	<.001
+ Site.Farmty	8	2.59988	0.32499	3.60	0.001
+ Fieldty	5	0.68288	0.13658	1.51	0.197
+ Farmty.Fieldty	20	1.86787	0.09339	1.03	0.436
+ Site.Fieldty	8	1.12318	0.14040	1.56	0.154
+ Site.Farmty.Fieldty	22	2.39267	0.10876	1.20	0.272
Residual	71	6.40825	0.09026		
Total	140	44.35930	0.31685		

c) Extractable P

Analysis of an unbalanced design using GenStat regression

Change	d.f.	s.s.	m.s.	v.r.	F pr.
+ Site	2	229.8	114.9	0.72	0.490
+ Farmty	4	845.4	211.3	1.33	0.269
+ Site.Farmty	8	2998.3	374.8	2.35	0.027
+ Fieldty	5	2815.4	563.1	3.53	0.007
+ Farmty.Fieldty	20	3562.7	178.1	1.12	0.353
+ Site.Fieldty	8	943.7	118.0	0.74	0.656
+ Site.Farmty.Fieldty	22	7652.7	347.8	2.18	0.007
Residual	71	11321.1	159.5		
Total	140	30369.0	216.9		

d) Exchangeable K^+

Analysis of an unbalanced design using GenStat regression

Change	d.f.	s.s.	m.s.	v.r.	F pr.
+ Site	2	0.10445	0.05223	1.75	0.181
+ Farmty	4	2.46095	0.61524	20.62	<.001
+ Site.Farmty	8	1.11905	0.13988	4.69	<.001
+ Fieldty	5	4.43591	0.88718	29.73	<.001
+ Farmty.Fieldty	20	1.86542	0.09327	3.13	<.001
+ Site.Fieldty	8	2.25622	0.28203	9.45	<.001
+ Site.Farmty.Fieldty	22	3.02269	0.13740	4.60	<.001
Residual	71	2.11854	0.02984		
Total	140	17.38323	0.12417		

e) Effective cation exchange capacity

Analysis of an unbalanced design using GenStat regression

Change	d.f.	s.s.	m.s.	v.r.	F pr.
+ Site	2	555.4823	277.7411	347.51	<.001
+ Farmty	4	42.4746	10.6187	13.29	<.001
+ Site.Farmty	8	62.7195	7.8399	9.81	<.001
+ Fieldty	5	7.0714	1.4143	1.77	0.141
+ Farmty.Fieldty	17	34.2277	2.0134	2.52	0.008
+ Site.Fieldty	5	12.1806	2.4361	3.05	0.020
+ Site.Farmty.Fieldty	6	38.7690	6.4615	8.08	<.001
Residual	41	32.7687	0.7992		
Total	88	785.6939	8.9283		

Appendix 4.1.2 Validation of yield estimates against RFM results

Yields obtained by means of the allometric models were in reasonable agreement with those calculated from the results of the resource flow maps, as illustrated in Figure a. In all sites, the divergence between yields estimated by both ways increased as the yields increased. Yields estimated from the resource flow maps were more variable (CV around 35 %) due to the various sources of error faced during their calculation (see chapter 2, Resource flow maps, Data processing). Nevertheless, the agreement shown by both ways of estimation is acceptable and reinforces the assumption of accuracy that their use implies.

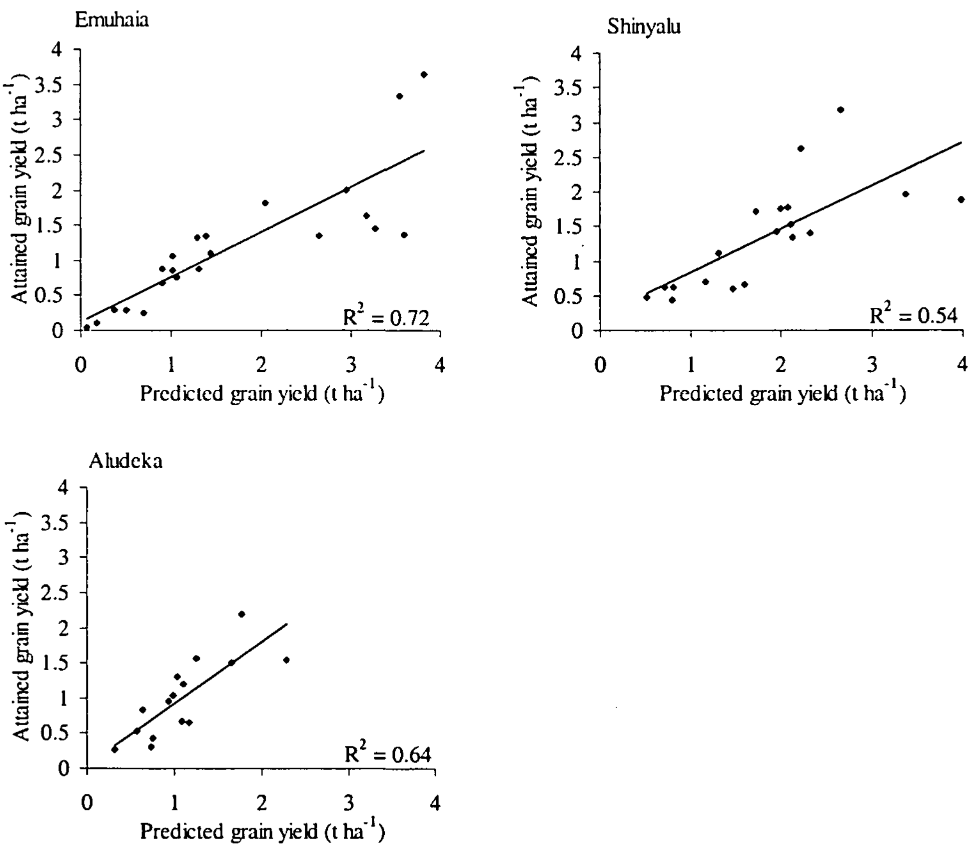


Figure a: Relationship between estimated maize yields by means of allometric models (predicted) and yields calculated from the amounts harvested according to farmers estimations during the resource-flow map exercise (attained), for three working sites in Western Kenya during the long rains season of 2002.

Appendix 4.2.1 Maize yield variability explained by single-factor, non-linear regression models

Table a: Determination coefficients of the best non-linear regression model to explain maize yield variability at each site with single soil and management factors.

Explanatory variable	Site	Non linear regression	
		Type	r^2
SOC	Emuhaia	Exponential	0.13
	Shinyalu	Exponential	0.23
	Aludeka	Exponential	0.33
Total N	Emuhaia	Polynomial 2nd order	0.21
	Shinyalu	Polynomial 2nd order	0.30
	Aludeka	Exponential	0.24
Extr. P	Emuhaia	Polynomial 2nd order	0.54
	Shinyalu	Polynomial 2nd order	0.43
	Aludeka	Polynomial 3rd order	0.69
DHI	Emuhaia	Polynomial 2nd order	0.20
	Shinyalu	Polynomial 2nd order	0.24
	Aludeka	Polynomial 2nd order	0.35
PDI	Emuhaia	Exponential	0.21
	Shinyalu	Exponential	0.24
	Aludeka	Exponential	0.37
Plant density	Emuhaia	Polynomial 2nd order	0.33
	Shinyalu	Polynomial 3rd order	0.19
	Aludeka	Polynomial 3rd order	0.20
Weeds	Emuhaia	Exponential	0.29
	Shinyalu	Exponential	0.17
	Aludeka	Exponential	0.17

Appendix 4.2.2 – I Correlation between variables used for the multiple regression models

Table a: Correlation matrix for the selected soil fertility and management variables used to build multiple regression models to explain maize yield variability at Emuhaia

	Total P	Striga	pH	Extr. P	Exch. Ca	C:N ratio	Exch. Bases	Exch. H+	Clay	Clay + Silt	DHI	ECEC	Exch. K	Exch. Mg	Total N	PDI	Plant density	Field slope	SOC	Weed
Total P	1.00																			
Striga	-0.21	1.00																		
pH	0.27	-0.31	1.00																	
Extr. P	0.44	-0.33	0.78	1.00																
Exch. Ca	0.52	-0.26	0.90	0.84	1.00															
C:N ratio	0.03	-0.02	0.10	0.03	-0.05	1.00														
Exch. Bases	0.47	-0.30	0.89	0.77	0.97	-0.03	1.00													
Ecxch. H+	-0.19	0.35	-0.65	-0.34	-0.53	0.02	-0.59	1.00												
Clay	0.08	0.21	-0.36	-0.25	-0.09	-0.52	-0.01	0.29	1.00											
Clay + Silt	0.33	0.07	0.03	0.03	0.31	-0.49	0.39	0.01	0.87	1.00										
DHI	-0.42	0.10	-0.46	-0.45	-0.51	0.06	-0.48	0.37	-0.06	-0.22	1.00									
ECEC	0.48	-0.27	0.86	0.78	0.96	-0.03	0.99	-0.46	0.04	0.43	-0.46	1.00								
Exch. K	0.20	-0.26	0.60	0.56	0.49	0.30	0.61	-0.37	-0.12	0.05	-0.43	0.60	1.00							
Exch. Mg	-0.02	-0.23	0.23	-0.08	0.20	-0.03	0.44	-0.42	0.34	0.48	0.01	0.41	0.46	1.00						
Total N	0.28	-0.20	0.16	0.17	0.29	-0.71	0.28	-0.23	0.27	0.40	-0.33	0.27	0.03	0.12	1.00					
PDI	-0.07	0.50	-0.18	-0.09	-0.20	0.55	-0.29	0.52	-0.25	-0.37	0.11	-0.22	-0.08	-0.49	-0.43	1.00				
Pl. density	0.31	-0.54	0.09	0.16	0.12	-0.28	0.18	-0.49	-0.04	-0.01	-0.14	0.10	0.13	0.28	0.43	-0.60	1.00			
Field slope	-0.12	0.26	-0.35	-0.21	-0.32	0.31	-0.30	0.63	0.17	0.04	0.22	-0.21	0.07	-0.07	-0.22	0.60	-0.54	1.00		
SOC	0.60	-0.27	0.46	0.41	0.53	0.36	0.51	-0.21	-0.23	0.07	-0.50	0.53	0.43	0.05	0.31	0.21	0.04	0.12	1.00	
Weed	-0.54	0.52	-0.51	-0.45	-0.58	0.25	-0.59	0.53	-0.04	-0.31	0.49	-0.54	-0.33	-0.23	-0.53	0.39	-0.55	0.42	-0.52	1.00

PDI: planting date index; DHI: distance from the homestead index; ECEC: effective cation exchange capacity; SOC: soil organic carbon

Appendix 4.2.2 – I (cont.) Correlation between variables used for the multiple regression models

Table b: Correlation matrix for the selected soil fertility and management variables used to build multiple regression models to explain maize yield variability at Shinyalu

	PDI	Extr. P	Exch. K	DHI	Exch. Ca	Total N	SOC	Exch. H+	Exch. Bases	C:N ratio	Clay	Clay + Silt	ECEC	Exch. Mg	pH	Plant density	Field slope	Total P	Weed
PDI	1.00																		
Extr. P	-0.25	1.00																	
Exch. K	-0.23	0.13	1.00																
DHI	0.01	0.00	-0.11	1.00															
Exch. Ca	-0.12	-0.04	0.50	0.04	1.00														
Total N	-0.24	0.43	0.29	-0.44	0.18	1.00													
SOC	-0.32	0.19	0.37	-0.39	0.46	0.78	1.00												
Exch. H+	0.46	-0.25	-0.52	-0.04	-0.77	-0.29	-0.47	1.00											
Exch. Bases	0.03	-0.12	0.43	0.12	0.93	0.08	0.31	-0.57	1.00										
C:N ratio	0.14	-0.33	-0.19	0.41	-0.18	-0.84	-0.62	0.26	-0.15	1.00									
Clay	-0.24	-0.02	0.28	-0.20	-0.10	0.07	0.18	0.19	-0.20	0.21	1.00								
Clay + Silt	0.31	-0.05	-0.11	-0.02	0.25	-0.06	0.17	0.14	0.26	0.17	0.35	1.00							
ECEC	0.09	-0.16	0.40	0.12	0.90	0.05	0.27	-0.49	1.00	-0.12	-0.19	0.29	1.00						
Exch. Mg	0.27	-0.23	0.11	0.23	0.57	-0.12	-0.01	-0.10	0.83	-0.04	-0.33	0.23	0.87	1.00					
pH	-0.06	0.03	0.53	-0.15	0.86	0.21	0.46	-0.80	0.74	-0.13	-0.20	0.05	0.69	0.34	1.00				
Pl. density	0.02	-0.18	-0.21	-0.22	-0.44	-0.32	-0.30	0.19	-0.52	0.35	0.08	-0.16	-0.53	-0.50	-0.29	1.00			
Field slope	0.33	-0.04	-0.21	0.51	0.14	-0.21	-0.25	0.25	0.44	0.05	-0.33	0.26	0.49	0.79	-0.12	-0.49	1.00		
Total P	0.02	0.10	0.16	-0.49	0.04	0.74	0.79	0.10	0.00	-0.59	0.33	0.24	0.01	-0.08	0.04	-0.17	-0.12	1.00	
Weed	0.09	-0.11	-0.09	0.36	-0.35	-0.54	-0.36	0.34	-0.30	0.74	0.30	0.25	-0.28	-0.15	-0.28	0.36	0.11	-0.20	1.00

PDI: planting date index; DHI: distance from the homestead index; ECEC: effective cation exchange capacity; SOC: soil organic carbon

Appendix 4.2.2 – I (cont.) Correlation between variables used for the multiple regression models

Table c: Correlation matrix for the selected soil fertility and management variables used to build multiple regression models to explain maize yield variability at Aludeka

	DHI	ECEC	Exch. Ca	Exch. K	Extr. P	PDI	pH	Plant density	SOC	Weed	Field slope	Total N	Exch. Mg	Clay + Silt	Clay	C:N ratio	Exch. Bases	Exch. H+
DHI	1.00																	
ECEC	0.12	1.00																
Exch. Ca	0.04	0.90	1.00															
Exch. K	-0.11	0.40	0.50	1.00														
Extr. P	-0.05	0.58	0.59	-0.05	1.00													
PDI	0.01	0.09	-0.12	-0.23	0.05	1.00												
pH	-0.15	0.69	0.86	0.53	0.35	-0.06	1.00											
Pl. density	-0.22	-0.53	-0.44	-0.21	-0.30	0.02	-0.29	1.00										
SOC	0.03	0.35	0.31	0.30	0.24	-0.21	0.24	-0.48	1.00									
Weed	0.36	-0.28	-0.35	-0.09	-0.41	0.09	-0.28	0.36	0.04	1.00								
Field slope	0.51	0.49	0.14	-0.21	0.25	0.33	-0.12	-0.49	0.27	0.11	1.00							
Total N	0.22	-0.11	0.02	-0.08	-0.03	-0.18	-0.02	-0.21	0.38	0.02	0.01	1.00						
Exch. Mg	0.23	0.87	0.57	0.11	0.45	0.27	0.34	-0.50	0.30	-0.15	0.79	-0.18	1.00					
Clay + Silt	0.22	-0.04	0.06	-0.04	0.09	-0.29	0.06	-0.18	0.59	0.32	-0.05	0.52	-0.13	1.00				
Clay	0.28	-0.13	-0.01	-0.10	0.04	-0.08	0.01	-0.03	0.40	0.39	-0.14	0.50	-0.23	0.90	1.00			
C:N ratio	-0.09	0.34	0.17	0.27	0.08	0.11	0.12	-0.06	0.14	0.00	0.27	-0.77	0.42	-0.36	-0.40	1.00		
Exch. Bases	0.12	1.00	0.93	0.43	0.58	0.03	0.74	-0.52	0.36	-0.30	0.44	-0.08	0.83	-0.03	-0.12	0.32	1.00	
Exch. H+	-0.04	-0.49	-0.77	-0.52	-0.25	0.46	-0.80	0.19	-0.25	0.34	0.25	-0.22	-0.10	-0.13	-0.08	0.04	-0.57	1.00

PDI: planting date index; DHI: distance from the homestead index; ECEC: effective cation exchange capacity; SOC: soil organic carbon

Appendix 4.2.2 – II Multiple regression models to explain maize yield for Emuhaia

a) Management factors

```
Response variate: GDW
    Forced terms: Constant
       Forced df: 1
      Free terms: pl_density + Striga + Weed + PDI + DHI

      Free terms: (1)  pl_density       (4)  PDI
                  (2)  Striga           (5)  DHI
                  (3)  Weed
```

Best subsets with 1 term

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)
45.52	9.18	2	-	-	-	.000	-
36.58	13.64	2	.002	-	-	-	-
35.04	14.40	2	-	.002	-	-	-
29.99	16.93	2	-	-	.005	-	-
11.48	26.15	2	-	-	-	-	.068

Best subsets with 2 terms

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)
55.02	5.32	3	-	-	.034	.002	-
54.08	5.76	3	-	-	-	.000	.043
53.42	6.07	3	-	.050	-	.008	-
50.46	7.47	3	.100	-	-	.019	-
45.40	9.88	3	.041	.054	-	-	-
44.15	10.46	3	-	.002	-	-	.053
43.93	10.57	3	.002	-	-	-	.072
41.75	11.60	3	.037	-	.112	-	-

Best subsets with 3 terms

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)
61.76	3.17	4	-	.042	-	.006	.036
58.08	4.82	4	.111	-	-	.014	.049
56.86	5.37	4	-	.195	.130	.012	-
56.33	5.60	4	-	-	.176	.002	.226
54.67	6.35	4	.368	-	.114	.021	-
54.19	6.57	4	.266	.128	-	.045	-
52.98	7.11	4	.047	.045	-	-	.059
46.22	10.14	4	.123	.126	.271	-	-

Best subsets with 4 terms

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)
62.13	4.06	5	.294	.106	-	.034	.043
60.34	4.82	5	-	.112	.560	.009	.127
57.10	6.19	5	.266	-	.453	.018	.173
55.53	6.86	5	.507	.261	.231	.043	-
50.33	9.06	5	.081	.075	.850	-	.133

Best subsets with 5 terms

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)
59.91	6.00	6	.379	.158	.813	.039	.110

b) Inherent properties

```
Response variate: GDW
    Forced terms: Constant
       Forced df: 1
      Free terms: Slope2 + Clay_% + Sand_%
```

Best subsets with 1 term

Adjusted	Cp	Df	Slope2	Clay_%	Sand_%
12.44	2.61	2	.060	-	-
0.91	5.32	2	-	-	.288
<0.00	6.65	2	-	.817	-

Best subsets with 2 terms

Adjusted	Cp	Df	Slope2	Clay_%	Sand_%
14.86	3.04	3	.053	-	.226
9.57	4.22	3	.056	.553	-
6.91	4.82	3	-	.147	.077

Best subsets with 3 terms

Adjusted	Cp	Df	Slope2	Clay_%	Sand_%
15.03	4.00	4	.111	.322	.154

Appendix 4.2.2 – II Multiple regression models to explain maize yield for Emuhaia

c) Soil fertility variables

```
 Response variate: GDW
     Forced terms: Constant
        Forced df: 1
       Free terms: Acidity_cmolc_kg + Bases + C_N_tio + C_P_tio +
                   ExCa_cmolc_kg + ExK_cmolc_kg + ExP_mg_P_kg +
                   Nt_g_kg + pH_water + SOC_g_kg + Total_P

* MESSAGE: The FREE and FORCED formula are modified in the following way(s):
  - The following FREE model terms are completely aliased and are dropped:
      ECEC + ExMg_cmolc_kg

*** All possible subset selection ***
        Free terms: (1)  Acidity_cmolc_kg      (7)  ExP_mg_P_kg
                   (2)  Bases                (8)  Nt_g_kg
                   (3)  C_N_tio              (9)  pH_water
                   (4)  C_P_tio             (10)  SOC_g_kg
                   (5)  ExCa_cmolc_kg       (11)  Total_P
                   (6)  ExK_cmolc_kg
* MESSAGE: Probabilities are based on F-statistics, i.e. on variance ratios
```

Best subsets with 1 term

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
35.10	28.18	2	.002	-	-	-	-	-	-	-	-	-	-
33.11	29.59	2	-	.003	-	-	-	-	-	-	-	-	-
27.55	33.55	2	-	-	-	-	-	.007	-	-	-	-	-
25.82	34.78	2	-	-	-	-	-	-	-	-	.009	-	-
24.23	35.91	2	-	-	-	-	-	-	.012	-	-	-	-
23.07	36.73	2	-	-	-	-	.014	-	-	-	-	-	-
18.87	39.72	2	-	-	-	-	-	-	-	.025	-	-	-
8.99	46.75	2	-	-	-	.095	-	-	-	-	-	-	-

Best subsets with 2 terms

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
53.44	15.47	3	-	-	.002	-	-	.000	-	-	-	-	-
47.13	19.74	3	-	-	-	-	-	.003	-	.009	-	-	-
45.55	20.81	3	.012	-	-	-	-	.040	-	-	-	-	-
44.89	21.25	3	.004	-	-	-	-	-	-	.046	-	-	-
44.26	21.68	3	.010	-	-	-	-	-	.052	-	-	-	-
42.90	22.59	3	.001	-	.068	-	-	-	-	-	-	-	-
41.29	23.68	3	.067	.094	-	-	-	-	-	-	-	-	-
40.89	23.96	3	.003	-	-	.102	-	-	-	-	-	-	-

Best subsets with 3 terms

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
67.13	7.05	4	.008	-	.002	-	-	.001	-	-	-	-	-
59.58	11.89	4	-	-	.001	.064	-	.000	-	-	-	-	-
58.24	12.74	4	.024	-	-	-	-	.016	-	.018	-	-	-
55.87	14.26	4	-	-	.003	-	-	.009	-	-	.170	-	-
55.51	14.49	4	-	-	.002	-	-	.000	-	-	-	-	.187
55.18	14.70	4	-	.204	.007	-	-	.015	-	-	-	-	-
54.32	15.25	4	-	-	.004	-	-	.006	.258	-	-	-	-
53.91	15.51	4	.006	-	.039	-	-	-	.030	-	-	-	-

Best subsets with 4 terms

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
72.89	4.39	5	.006	-	.001	.042	-	.001	-	-	-	-	-
68.22	7.22	5	.011	-	.002	-	-	.002	-	-	-	-	.221
66.87	8.04	5	.012	-	.003	-	-	.011	.367	-	-	-	-
65.37	8.94	5	.012	-	.044	-	-	.002	-	.773	-	-	-
65.23	9.03	5	.023	.905	.003	-	-	.007	-	-	-	-	-
65.21	9.04	5	.018	-	.003	-	.956	.003	-	-	-	-	-
65.20	9.04	5	.027	-	.002	-	-	.004	-	-	.962	-	-
65.20	9.05	5	.010	-	.003	-	-	.002	-	-	-	.982	-

Appendix 4.2.2 – II Emuhaia (c) Cont.

Best subsets with 5 terms

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
73.72	4.96	6	.011	-	-	.015	-	.001	-	.001	-	.010	-
73.07	5.33	6	.011	.002	.003	-	.001	-	.002	-	-	-	-
71.89	6.00	6	.009	.540	.001	.040	-	.003	-	-	-	-	-
71.79	6.06	6	.008	-	.001	.041	.570	.002	-	-	-	-	-
71.74	6.09	6	.009	-	.001	.065	-	.008	.589	-	-	-	-
71.72	6.10	6	.007	-	.002	.041	-	.001	-	-	-	.593	-
71.31	6.33	6	.017	-	.001	.047	-	.003	-	-	.808	-	-
71.30	6.33	6	.008	-	.001	.112	-	.002	-	-	-	-	.811

Best subsets with 6 terms

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
76.98	4.28	7	.005	.001	.001	-	.000	-	.001	-	-	-	.073
76.62	4.48	7	.005	.003	.001	.084	.001	-	.001	-	-	-	-
75.20	5.23	7	-	.000	.000	-	.000	-	.006	-	.010	-	.009
74.84	5.43	7	.003	-	.001	.030	.105	.006	.107	-	-	-	-
74.45	5.64	7	.015	-	-	.024	-	.008	.246	.001	-	.007	-
73.72	6.03	7	.008	.002	.002	-	.001	-	.001	-	-	.257	-
72.92	6.45	7	.015	.003	.106	-	.002	-	.002	.355	-	-	-
72.77	6.53	7	.005	.224	.001	.038	-	.004	.236	-	-	-	-

Best subsets with 7 terms

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
79.37	4.28	8	.064	.001	.001	-	.000	-	.002	-	.120	-	.020
76.61	5.65	8	.007	.004	.069	.088	.001	-	.001	.336	-	-	-
76.58	5.67	8	.005	.003	.002	.115	.001	-	.001	-	-	.341	-
76.13	5.89	8	.006	.004	.002	.507	.002	-	.001	-	-	-	.420
76.06	5.92	8	.006	.205	.002	.070	.102	.433	.046	-	-	-	-
75.72	6.09	8	.025	.006	.002	.074	.002	-	.003	-	.517	-	-
75.64	6.13	8	.008	.001	.044	-	.001	-	.001	.684	-	-	.124
75.62	6.14	8	.007	.001	.003	-	.001	-	.001	-	-	.692	.163

Best subsets with 8 terms

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
78.05	6.15	9	.099	.019	.001	-	.008	.694	.010	-	.128	-	.024
78.00	6.18	9	.070	.002	.001	.727	.001	-	.003	-	.163	-	.142
77.84	6.25	9	.075	.001	.002	-	.000	-	.003	-	.145	.859	.049
77.81	6.26	9	.075	.001	.016	-	.000	-	.003	.891	.147	-	.039
75.98	7.11	9	.023	.005	.002	.091	.001	-	.003	-	.434	.302	-
75.79	7.20	9	.034	.007	.061	.074	.002	-	.003	.326	.482	-	-
75.35	7.40	9	.008	.173	.076	.085	.085	.604	.041	.455	-	-	-
75.15	7.49	9	.009	.007	.075	.410	.003	-	.002	.514	-	-	.681

Best subsets with 9 terms

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
76.46	8.05	10	.107	.024	.002	-	.012	.634	.016	-	.142	.736	.053
76.35	8.09	10	.079	.004	.002	.674	.002	-	.004	-	.214	.760	.294
76.33	8.10	10	.079	.005	.036	.674	.003	-	.004	.774	.223	-	.277
76.33	8.10	10	.117	.023	.033	-	.010	.674	.013	.821	.149	-	.043
76.28	8.13	10	.124	.076	.002	.871	.045	.812	.025	-	.211	-	.194
75.99	8.25	10	.105	.002	.218	-	.001	-	.006	.969	.164	.909	.061
74.04	9.08	10	.030	.146	.003	.106	.081	.875	.045	-	.513	.421	-
74.01	9.09	10	.043	.010	.299	.107	.006	-	.006	.902	.468	.742	-

Best subsets with 10 terms

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
74.44	10.00	11	.131	.083	.004	.825	.051	.758	.032	-	.240	.720	.299
74.36	10.03	11	.133	.035	.212	-	.023	.636	.028	.892	.160	.784	.066
74.32	10.05	11	.138	.095	.050	.811	.060	.812	.031	.777	.265	-	.308
74.21	10.09	11	.110	.008	.267	.688	.006	-	.009	.965	.244	.912	.319
71.75	11.05	11	.052	.215	.355	.125	.161	.849	.088	.868	.569	.845	-
71.11	11.30	11	.029	.247	.453	.396	.186	.683	.101	.757	-	.950	.765
71.01	11.34	11	.204	.221	-	.605	.187	.967	.109	.007	.468	.110	.444
68.40	12.37	11	-	.058	.401	.807	.049	.521	.075	.825	.050	.885	.107

Best subsets with 11 terms

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
71.89	12.00	12	.155	.126	.273	.860	.099	.767	.062	.950	.280	.828	.329

Appendix 4.2.2 – III Multiple regression models to explain maize yield for Shinyalu

a) Management factors

```
Response variate: GDW
     Forced terms: Constant
        Forced df: 1
       Free terms: PDI + pl_density + Weed + DHI

* MESSAGE: The FREE and FORCED formula are modified in the following way(s):
  - The following FREE model terms are completely aliased and are dropped:
      Striga

       Free terms: (1)  PDI              (3)  Weed
                   (2)  pl_density       (4)  DHI
```

Best subsets with 1 term

Adjusted	Cp	Df	(1)	(2)	(3)	(4)
31.36	2.75	2	-	-	-	.007
8.61	8.63	2	.119	-	-	-
1.94	10.35	2	-	-	.260	-
<0.00	12.24	2	-	.769	-	-

Best subsets with 2 terms

Adjusted	Cp	Df	(1)	(2)	(3)	(4)
42.16	1.08	3	.058	-	-	.005
27.52	4.64	3	-	-	.756	.018
27.47	4.65	3	-	.770	-	.009
9.28	9.08	3	.143	-	.305	-
3.58	10.47	3	.128	.740	-	-
<0.00	11.43	3	-	.448	.194	-

Best subsets with 3 terms

Adjusted	Cp	Df	(1)	(2)	(3)	(4)
38.64	3.00	4	.067	.778	-	.006
38.39	3.06	4	.069	-	.883	.010
22.82	6.61	4	-	.876	.851	.029
6.99	10.22	4	.153	.448	.227	-

Best subsets with 4 terms

Adjusted	Cp	Df	(1)	(2)	(3)	(4)
34.26	5.00	5	.078	.816	.991	.018

b) Inherent properties

```
Response variate: GDW
    Forced terms: Constant
       Forced df: 1
      Free terms: Clay_% + Sand_% + Slope2

*** All possible subset selection ***
```

Best subsets with 1 term

Adjusted	Cp	Df	Clay_%	Sand_%	Slope2
6.50	0.44	2	-	-	.152
<0.00	2.30	2	-	.674	-
<0.00	2.47	2	.920	-	-

Best subsets with 2 terms

Adjusted	Cp	Df	Clay_%	Sand_%	Slope2
3.03	2.07	3	.540	-	.130
0.68	2.43	3	-	.952	.184
<0.00	4.29	3	.960	.690	-

Best subsets with 3 terms

Adjusted	Cp	Df	Clay_%	Sand_%	Slope2
<0.00	4.00	4	.520	.795	.151

Appendix 4.2.2 – III Multiple regression models to explain maize yield for Shinyalu

c) Soil fertility variables

```
Response variate: GDW
    Forced terms: Constant
       Forced df: 1
      Free terms: Acidity_cmolc_kg + Bases + C_N_tio + C_P_tio +
                  ExCa_cmolc_kg + ExK_cmolc_kg + ExP_mg_P_kg +
                  Nt_g_kg + pH_water + SOC_g_kg + Total_P
* MESSAGE: The FREE and FORCED formula are modified in the following way(s):
  - The following FREE model terms are completely aliased and are dropped:
      ECEC + ExMg_cmolc_kg

      Free terms: (1)  Acidity_cmolc_kg      (7)  ExP_mg_P_kg
                  (2)  Bases                 (8)  Nt_g_kg
                  (3)  C_N_tio               (9)  pH_water
                  (4)  C_P_tio              (10)  SOC_g_kg
                  (5)  ExCa_cmolc_kg        (11)  Total_P
                  (6)  ExK_cmolc_kg
```

Best subsets with 1 term

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
22.12	-1.81	2	-	-	-	-	-	-	-	.024	-	-	-
15.86	-0.75	2	-	-	.051	-	-	-	-	-	-	-	-
12.71	-0.22	2	-	-	-	-	-	-	.074	-	-	-	-
10.04	0.24	2	-	-	-	-	-	-	-	-	-	.101	-
8.30	0.53	2	-	-	-	-	-	-	-	-	-	-	.123
8.20	0.55	2	-	-	-	.125	-	-	-	-	-	-	-
3.76	1.30	2	-	.209	-	-	-	-	-	-	-	-	-
<0.00	2.03	2	-	-	-	-	.356	-	-	-	-	-	-

Best subsets with 2 terms

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
30.55	-1.93	3	-	.099	-	-	-	-	-	.014	-	-	-
29.61	-1.78	3	-	-	-	-	-	.113	-	.009	-	-	-
28.81	-1.65	3	-	-	-	-	.127	-	-	.012	-	-	-
27.38	-1.43	3	-	-	-	-	.039	-	-	-	-	.014	-
26.68	-1.31	3	-	.042	-	-	-	-	-	-	-	.023	-
26.13	-1.23	3	-	.085	.025	-	-	-	-	-	-	-	-
23.11	-0.75	3	-	-	-	.088	-	-	.055	-	-	-	-
22.63	-0.67	3	-	-	-	-	-	-	.308	.094	-	-	-

Best subsets with 3 terms

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
32.53	-0.92	4	-	-	-	-	.053	-	.157	-	-	.029	-
30.87	-0.67	4	-	.273	-	-	-	.316	-	.010	-	-	-
30.71	-0.65	4	-	-	-	-	-	.111	.280	.039	-	-	-
30.45	-0.61	4	-	.070	-	-	-	-	.192	-	-	.047	-
29.95	-0.53	4	-	.130	-	.050	-	-	.068	-	-	-	-
29.04	-0.40	4	-	.139	-	-	-	-	.429	.056	-	-	-
29.00	-0.39	4	-	-	-	-	.367	.323	-	.009	-	-	-
29.00	-0.39	4	-	.047	.236	-	-	-	-	-	-	.219	-

Best subsets with 4 terms

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
33.33	0.30	5	-	-	-	-	.164	.296	.126	-	-	.022	-
32.28	0.44	5	-	.189	-	-	-	.256	.146	-	-	.030	-
30.57	0.68	5	-	-	-	-	.054	-	.223	-	-	.089	.460
30.42	0.70	5	-	-	-	-	.042	-	-	.227	-	.156	.225
30.38	0.71	5	-	-	.228	-	.028	-	-	-	-	.072	.234
30.24	0.73	5	-	-	.488	-	.068	-	.239	-	-	.149	-
30.10	0.75	5	-	.367	-	-	-	.287	.376	.039	-	-	-
29.62	0.82	5	-	.074	.379	-	-	-	.305	-	-	.234	-

Best subsets with 5 terms

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
32.01	1.80	6	-	-	-	.275	.043	-	.141	-	-	.112	.200
31.19	1.91	6	-	-	-	-	.108	.302	-	.179	-	.150	.213
31.05	1.93	6	-	-	-	-	.133	.314	.182	-	-	.082	.476
30.78	1.96	6	-	.191	.419	-	-	.287	.239	-	-	.162	-
30.72	1.97	6	-	-	.504	-	.192	.314	.196	-	-	.120	-
30.67	1.98	6	-	.050	-	.182	-	-	.128	-	-	.231	.235
30.20	2.04	6	-	-	-	-	.193	.267	.144	-	.552	.030	-
29.88	2.08	6	-	-	-	-	.254	.287	.251	.586	-	.291	-

Appendix 4.2.2 – III Shinyalu (c) Cont.

Best subsets with 6 terms

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
31.78	3.15	7	.292	.141	-	.180	-	-	.080	-	-	.136	.122
31.69	3.17	7	-	-	-	.311	.108	.352	.123	-	-	.105	.228
31.00	3.25	7	-	.117	-	.226	-	.323	.112	-	-	.173	.254
29.80	3.39	7	-	-	.398	-	.126	.333	.310	-	-	.111	.380
29.51	3.43	7	.215	.220	.233	-	-	-	.246	-	-	.106	.192
29.37	3.44	7	-	-	-	-	.156	.287	.431	.422	-	.172	.360
29.02	3.48	7	.514	-	-	.274	.191	-	.120	-	-	.143	.183
28.41	3.56	7	-	-	.427	-	.176	.269	.237	-	.461	.173	-

Best subsets with 7 terms

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
29.17	4.76	8	.216	.117	-	.150	-	-	.070	-	.471	.127	.102
28.32	4.85	8	.474	.193	-	.223	-	.531	.094	-	-	.198	.208
28.09	4.88	8	.254	.204	-	.309	-	-	.220	.548	-	.144	.115
27.64	4.93	8	.153	.156	.174	-	-	-	.223	-	.424	.092	.149
27.62	4.93	8	-	-	-	.298	.133	.322	.132	-	.580	.167	.263
27.06	4.99	8	-	-	-	.448	.138	.341	.313	.635	-	.178	.247
26.38	5.07	8	.720	-	-	.318	.235	.466	.136	-	-	.214	.291
26.09	5.10	8	.360	.484	-	.208	.789	-	.102	-	-	.149	.147

Best subsets with 8 terms

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
25.38	6.43	9	.188	.155	-	.260	-	-	.191	.521	.456	.134	.096
25.38	6.43	9	.337	.152	-	.187	-	.522	.082	-	.469	.186	.172
24.15	6.56	9	.413	.271	-	.371	-	.527	.249	.543	-	.210	.195
23.74	6.60	9	.257	.196	.215	-	-	.524	.231	-	.428	.144	.241
23.22	6.65	9	.439	-	.280	-	.205	.457	.261	-	.424	.161	.307
23.13	6.66	9	.222	.144	.721	.565	-	-	.205	-	.451	.135	.141
22.96	6.67	9	.575	-	-	.287	.186	.445	.125	-	.491	.205	.258
22.26	6.74	9	.295	.481	-	.193	.884	-	.097	-	.514	.145	.133

Best subsets with 9 terms

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
21.09	8.07	10	.292	.201	-	.314	-	.517	.217	.516	.454	.196	.160
18.06	8.35	10	.338	.184	.751	.593	-	.552	.222	-	.458	.197	.220
17.97	8.35	10	.489	-	-	.434	.253	.450	.273	.547	.488	.217	.236
17.65	8.38	10	.251	.463	-	.281	.811	-	.209	.524	.508	.153	.123
17.45	8.40	10	.499	.275	.675	.414	-	.516	.243	.485	-	.304	.203
17.32	8.41	10	.250	.179	.878	.464	-	-	.228	.598	.522	.191	.140
17.09	8.43	10	.462	.602	-	.259	.988	.555	.123	-	.502	.212	.234
16.27	8.51	10	.474	.581	-	.387	.814	.586	.267	.544	-	.228	.234

Best subsets with 10 terms

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
11.80	10.03	11	.381	.230	.825	.471	-	.527	.246	.564	.533	.279	.197
11.36	10.06	11	.395	.582	-	.361	.914	.564	.252	.536	.499	.223	.214
8.35	10.30	11	.498	.537	.650	.407	.753	.580	.256	.473	-	.327	.235
7.94	10.34	11	.289	.470	.826	.459	.780	-	.247	.577	.601	.224	.176
7.87	10.34	11	.554	-	.909	.619	.291	.472	.320	.642	.558	.288	.293
7.82	10.35	11	.454	.646	.766	.639	.994	.583	.281	-	.492	.226	.294
5.80	10.51	11	.455	.777	.540	-	.874	.540	.375	.810	.488	.212	.326
3.87	10.66	11	-	.861	.737	.525	.731	.372	.347	.621	.752	.475	.376

Best subsets with 11 terms

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
<0.00	12.00	12	.443	.577	.808	.499	.870	.580	.286	.575	.598	.313	.260

Appendix 4.2.2 – IV Multiple regression models to explain maize yield for Aludeka

a) Management factors

```
Response variate: GDW
    Forced terms: Constant
       Forced df: 1
      Free terms: PDI + pl_density + Striga + Weed + DHI

      Free terms: (1)  PDI              (4)  Weed
                  (2)  pl_density       (5)  DHI
                  (3)  Striga
```

Best subsets with 1 term

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)
50.85	5.36	2	-	.000	-	-	-
24.86	16.12	2	-	-	-	-	.017
24.12	16.43	2	-	-	-	.019	-
11.41	21.69	2	.086	-	-	-	-
5.06	24.32	2	-	-	.180	-	-

Best subsets with 2 terms

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)
63.05	1.40	3	-	.001	-	-	.020
50.09	6.46	3	.402	.002	-	-	-
49.89	6.53	3	-	.007	-	.423	-
48.55	7.06	3	-	.001	.630	-	-
30.13	14.24	3	-	-	-	.150	.136
23.05	17.00	3	.450	-	-	-	.077
20.23	18.10	3	-	-	.911	-	.056
20.18	18.12	3	.694	-	-	.110	-

Best subsets with 3 terms

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)
64.17	2.09	4	-	.000	.239	-	.013
60.78	3.33	4	-	.002	-	.790	.034
60.65	3.38	4	.882	.001	-	-	.036
47.33	8.25	4	.644	.008	-	.693	-
46.80	8.44	4	.502	.003	.922	-	-
46.70	8.48	4	-	.009	.839	.515	-
26.48	15.87	4	-	-	.656	.145	.143
25.48	16.23	4	.969	-	-	.236	.164

Best subsets with 4 terms

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)
61.72	4.06	5	.846	.001	.253	-	.020
61.67	4.08	5	-	.002	.265	.893	.020
57.98	5.33	5	.974	.003	-	.829	.046
43.58	10.25	5	.687	.011	.965	.710	-
21.38	17.82	5	.873	-	.647	.240	.162

Best subsets with 5 terms

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)
58.96	6.00	6	.788	.003	.269	.815	.027

Appendix 4.2.2 – IV Multiple regression models to explain maize yield for Aludeka

b) Inherent properties

Response variate: GDW
Forced terms: Constant
Forced df: 1
Free terms: Clay_% + Claysilt + Slope1

* MESSAGE: The FREE and FORCED formula are modified in the following way(s):
- The following FREE model terms are completely aliased and are dropped:
Sand_% + Silt_% + Slope2

* MESSAGE: Probabilities are based on F-statistics, i.e. on variance ratios

Best subsets with 1 term

Adjusted	Cp	Df	Clay_%	Claysilt	Slope1
1.91	0.79	2	-	-	.261
0.22	1.06	2	-	.322	-
<0.00	1.60	2	.509	-	-

Best subsets with 2 terms

Adjusted	Cp	Df	Clay_%	Claysilt	Slope1
<0.00	2.30	3	-	.485	.386
<0.00	2.65	3	.706	-	.338
<0.00	2.79	3	.604	.377	-

Best subsets with 3 terms

Adjusted	Cp	Df	Clay_%	Claysilt	Slope1
<0.00	4.00	4	.591	.434	.389

c) Soil fertility variables

Response variate: GDW
Forced terms: Constant
Forced df: 1
Free terms: SOC_g_kg + pH_water + Nt_g_kg + ECEC + ExCa_cmolc_kg +
ExK_cmolc_kg + ExMg_cmolc_kg + ExP_mg_P_kg +
C_N_tio

* MESSAGE: The FREE and FORCED formula are modified in the following way(s):
- The following FREE model terms are completely aliased and are dropped:
Acidity_cmolc_kg + Bases

Free terms:
(1) SOC_g_kg
(2) pH_water
(3) Nt_g_kg
(4) ECEC
(5) ExCa_cmolc_kg
(6) ExK_cmolc_kg
(7) ExMg_cmolc_kg
(8) ExP_mg_P_kg
(9) C_N_tio

Best subsets with 1 term

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
51.94	0.97	2	-	-	-	-	-	-	-	.000	-
27.13	9.21	2	.013	-	-	-	-	-	-	-	-
15.90	12.94	2	-	-	-	-	.051	-	-	-	-
14.01	13.57	2	-	-	-	.064	-	-	-	-	-
11.06	14.55	2	-	.090	-	-	-	-	-	-	-
<0.00	19.36	2	-	-	.532	-	-	-	-	-	-
<0.00	19.49	2	-	-	-	-	-	.566	-	-	-
<0.00	19.71	2	-	-	-	-	-	-	.635	-	-

Best subsets with 2 terms

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
66.10	-2.40	3	.012	-	-	-	-	-	-	.000	-
55.22	1.00	3	-	-	-	.153	-	-	-	.001	-
55.00	1.07	3	-	-	-	-	-	-	.161	.000	-
54.53	1.22	3	-	-	-	-	.180	-	-	.001	-
52.25	1.93	3	-	-	.307	-	-	-	-	.000	-
51.91	2.04	3	-	.334	-	-	-	-	-	.001	-
49.36	2.83	3	-	-	-	-	-	.717	-	.001	-
48.95	2.97	3	-	-	-	-	-	-	-	.000	.948

Appendix 4.2.2 – IV Aludeka (c) Cont.

Best subsets with 3 terms

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
64.79	-0.68	4	.013	-	-	-	-	.534	-	.000	-
64.24	-0.52	4	.035	-	-	-	.686	-	-	.001	-
64.07	-0.47	4	.040	-	-	-	-	-	.759	.001	-
64.00	-0.45	4	.014	-	-	-	-	-	-	.001	.796
63.94	-0.43	4	.043	-	-	.839	-	-	-	.001	-
63.87	-0.41	4	.026	-	.909	-	-	-	-	.001	-
63.84	-0.40	4	.024	.956	-	-	-	-	-	.001	-
55.16	2.15	4	-	-	.093	-	-	-	-	.000	.174

Best subsets with 4 terms

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
63.50	0.99	5	.033	-	-	.418	.380	-	-	.002	-
63.11	1.09	5	.034	.474	-	-	.416	-	-	.001	-
62.98	1.13	5	.014	-	-	-	-	.456	-	.001	.611
62.98	1.13	5	.032	-	-	-	.612	.496	-	.001	-
62.79	1.18	5	.040	-	-	.664	-	.475	-	.001	-
62.59	1.24	5	.024	-	.735	-	-	.496	-	.001	-
62.39	1.29	5	.024	.834	-	-	-	.527	-	.001	-
62.29	1.32	5	.044	-	-	-	-	.596	.929	.002	-

Best subsets with 5 terms

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
61.70	2.73	6	.038	.569	-	.499	.346	-	-	.003	-
61.26	2.84	6	.064	-	-	.409	.380	-	.671	.003	-
60.89	2.94	6	.041	.416	-	-	.406	-	-	.001	.660
60.79	2.96	6	.046	-	-	.427	.398	-	-	.003	.862
60.71	2.98	6	.052	-	-	.669	.619	.942	-	.004	-
60.70	2.98	6	.039	.671	-	-	.539	.713	-	.002	-
60.70	2.99	6	.042	-	.989	.436	.398	-	-	.004	-
60.52	3.03	6	.071	.504	-	-	.434	-	.782	.004	-

Best subsets with 6 terms

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
59.26	4.55	7	.044	.488	-	.501	.345	-	-	.004	.647
58.98	4.62	7	.071	.607	-	.487	.380	-	.717	.004	-
58.85	4.65	7	.050	.534	-	.532	.454	.760	-	.006	-
58.68	4.69	7	.052	.557	.829	.513	.361	-	-	.005	-
58.26	4.79	7	.073	-	-	.536	.513	.801	.635	.006	-
58.26	4.79	7	.046	.582	-	-	.534	.678	-	.002	.634
58.09	4.83	7	.087	-	-	.427	.405	-	.694	.005	.898
58.04	4.84	7	.080	-	.969	.428	.399	-	.682	.006	-

Best subsets with 7 terms

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
57.93	6.04	8	.062	.362	-	.313	.284	.421	.408	.007	-
56.06	6.45	8	.097	.485	.729	.510	.355	-	-	.007	.604
55.90	6.48	8	.082	.538	-	.528	.411	-	.775	.006	.696
55.77	6.51	8	.057	.493	-	.580	.497	.823	-	.009	.692
55.46	6.58	8	.093	.592	.826	.501	.395	-	.723	.007	-
55.19	6.63	8	.071	.542	.889	.576	.498	.804	-	.011	-
54.91	6.69	8	.139	.430	.685	-	.426	-	.688	.009	.569
54.81	6.72	8	.118	.574	.776	-	.536	.710	-	.004	.635

Best subsets with 8 terms

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
53.75	8.04	9	.090	.384	-	.394	.362	.501	.487	.011	.945
53.73	8.04	9	.081	.387	.967	.350	.322	.460	.437	.013	-
52.09	8.36	9	.114	.473	.701	.553	.475	.772	-	.016	.602
51.82	8.42	9	.180	.535	.799	.600	.474	-	.863	.012	.689
50.67	8.64	9	.169	.565	.735	-	.532	.821	.787	.013	.609
50.11	8.75	9	.171	.624	.739	.595	-	.671	.723	.013	.608
50.00	8.77	9	.244	-	.901	.653	.640	.861	.744	.017	.921
44.41	9.87	9	-	.553	.288	.385	.358	.511	.298	.008	.255

Best subsets with 9 terms

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
48.84	10.00	10	.205	.402	.846	.444	.409	.535	.562	.019	.841

Appendix 4.3 - I Relationship between the resource use intensity and maize yield

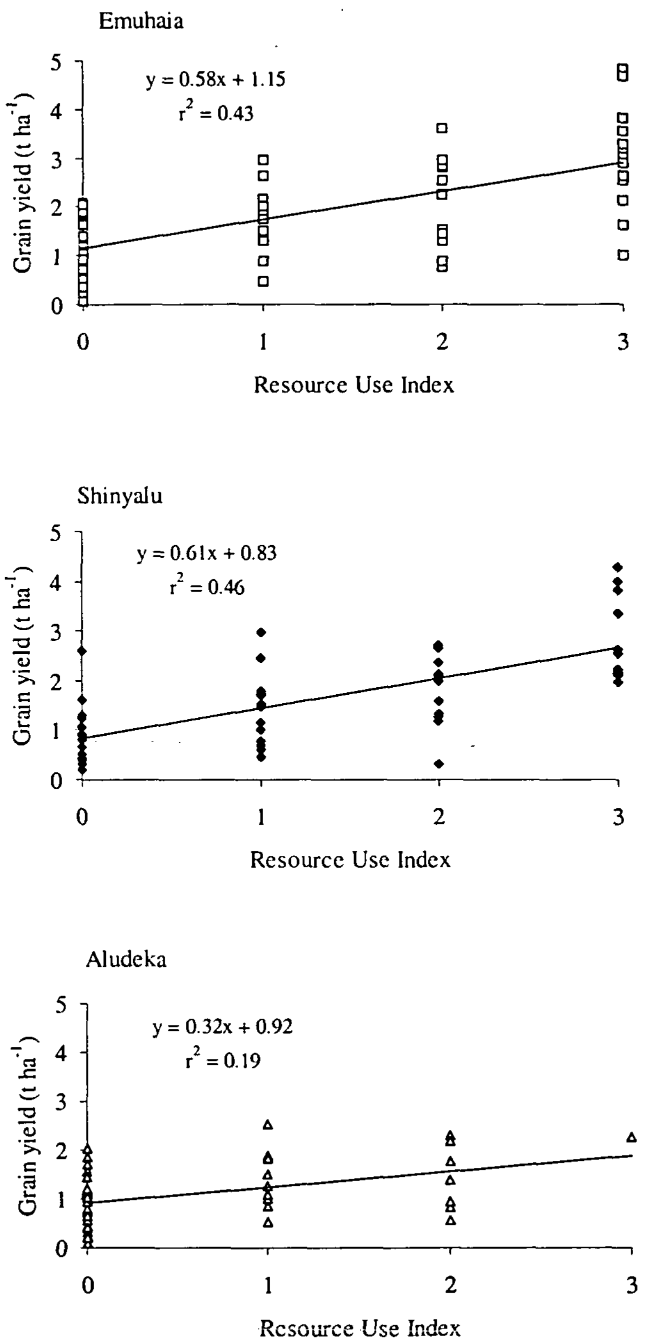


Figure 4.3 – I: Relationship between the resource use index (RUI) and the grain yield of maize crops at farmer fields in the three working sites. The resource use intensity was assessed through a score (0= no use; 3 = high use).

Appendix 4.3 – II Range of values for the soil fertility index at site scale

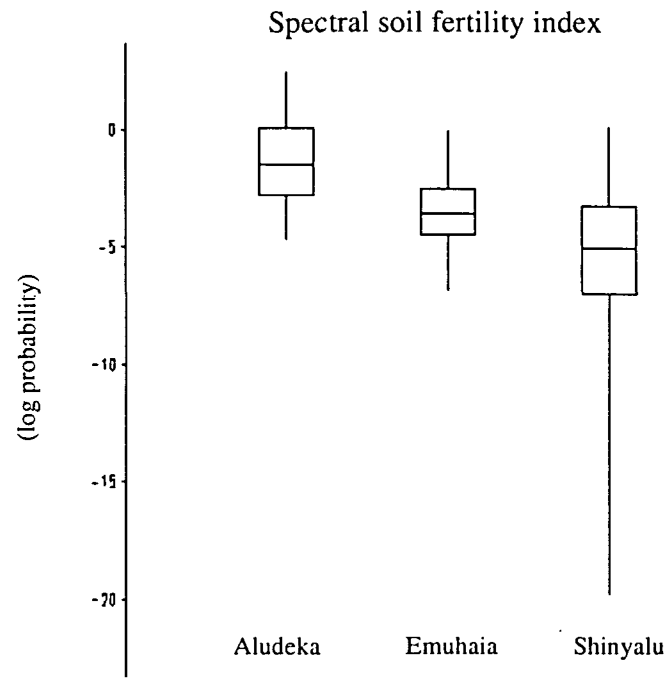


Figure 4.3 – II: Range of soil fertility indexes for the soil samples from the different sites. The soil fertility index is the log probability of a soil sample to fall into the fertile class. The box-and-whisker diagrams include the range of 50% of the samples (rectangle), the median (cross bar) and the maximum and minimum values (extreme of the lines). Sample sizes 53 (Aludeka), 55 (Emuhaia), 53 (Shinyalu).

Appendix 4.3 – III Relationship between the soil fertility index and maize yield

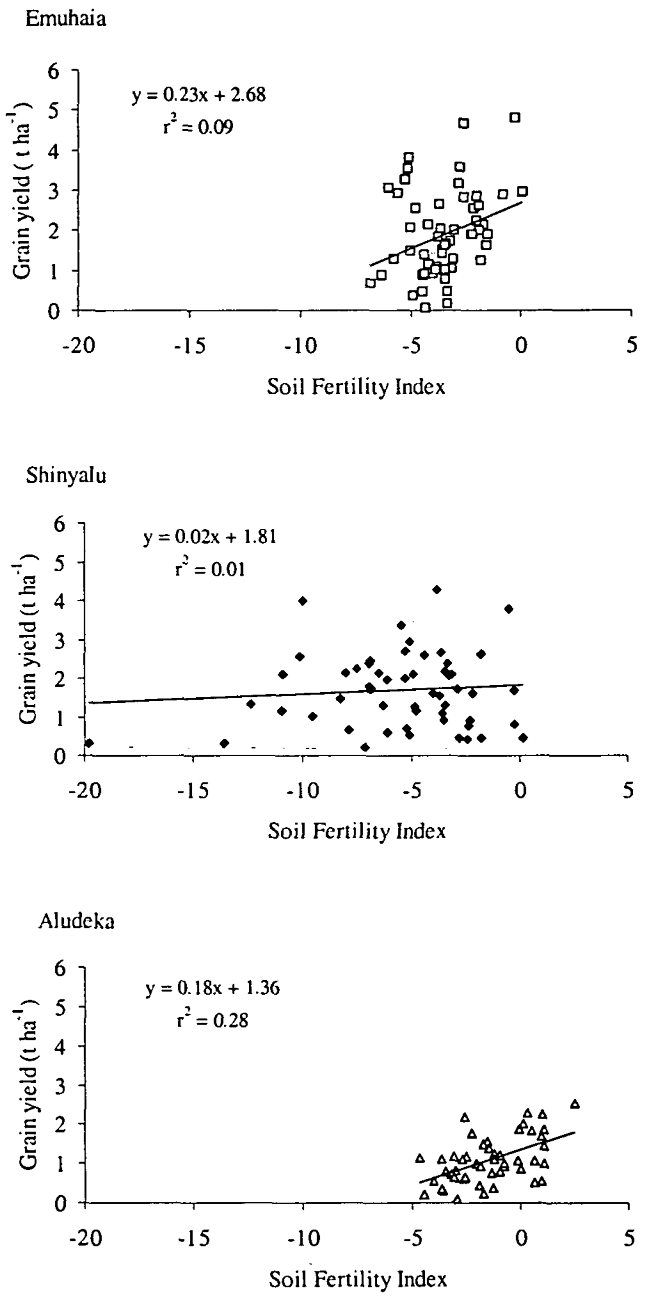


Figure 4.3 – III: Relationship between maize yields and the spectral soil fertility index for the three working sites. The soil fertility index is the log probability of a soil sample to fall into the fertile class.

Appendix to Chapter 5

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Appendix 5.2 Parameters used in different simulations

Table a: Soil properties corresponding to the examples used to study the sensitivity of the simulation model to changes in soil clay content

Soil parameters	Unit	Range* High	Range* Normal	Range* Low
Clay	%	54	44	28
Silt	%	21	26	42
Sand	%	25	30	32
Bulk density**	kg m^{-3}	1200	1000	1120
Volumetric water content at:	m^3 m^{-3}			
Saturation		50	62	52
Field capacity		38	42	41
Wilting point		26	23	23
Soil erodibility (factor K)	-	0.08	0.12	0.24

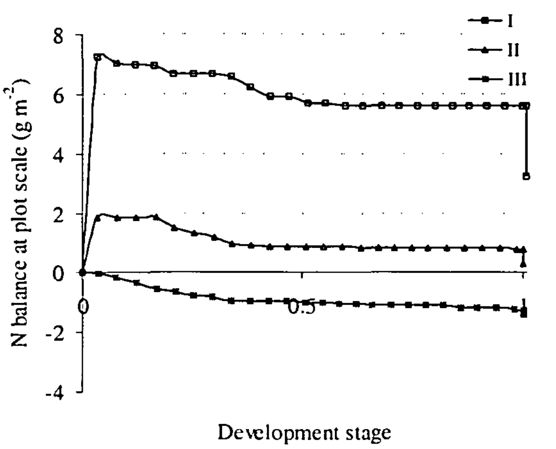
*High, normal and low refer to the range of soil clay contents in the set of samples from Emuhaia and Shinyalu
**Considering only situations where no signs of soil compaction were observed

Table b: Parameters used to characterise the close and remote fields included in the simulation of alternative soil fertility management practices. Values taken from own measurements except *, from literature (FURP, 1994).

Parameter	Unit	Case study** Close field	Case study** Remote field
Field slope	%	5	9
Clay content	%	43	35
SOC	g kg^{-1}	1.5	0.55
C:N ratio of soil OM	-	15	16
pH water (1: 2.5)	-	5.7	5.3
Volumetric water content at:	m^3 m^{-3}		
Saturation*		0.56	0.52
Field capacity*		0.44	0.38
Wilting point*		0.23	0.22
Residues incorporated	kg ha^{-1}	2000	500
Plant density	plants m^{-2}	5.1	3.5

**Shiboka Shivonje's farm
SOC: soil organic carbon; OM: organic matter

Appendix 5.3 Simulation results



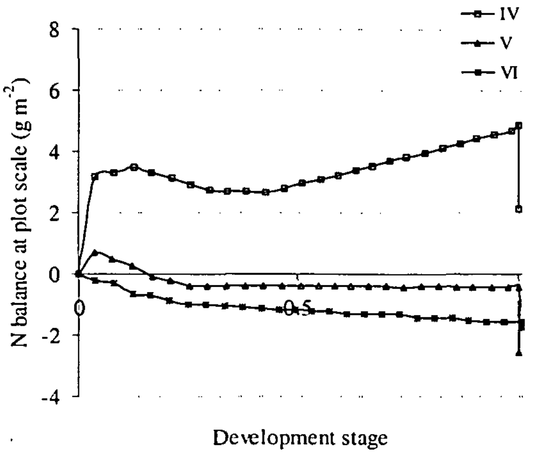


Figure a: Time course of the N balance at plot scale for the different simulation scenarios (I to VI). The final drop in the N balance indicates the N removal by harvests. The increase in the N balance for scenario IV (home garden) corresponds to the daily additions of household wastes and chicken manure to those fields. The N balances in the remote fields (scenarios III and VI) are negative even if no output is harvested from the plot.

Table b: Simulated N balances at plot scale with increasing application rates of inorganic N fertilisers (urea 46: 0: 0), combined with application of organic fertilisers of good and poor quality in the different fields of a case study farm.

N balance at plot scale (kg N ha^{-1})	N fertilisation rate (kg urea ha^{-1})					
	0	50	75	100	150	200
No application of organic fertiliser						
Close field	18.5	16.9	12.5	7.9	1.1	-5.3
Remote field	-6.2	-9.3	-13.1	-16.5	-21.7	-11.9
Good quality OF application (1 t ha^{-1})						
Close field	36.6	45.7	41.1	36.5	29.7	23.1
Remote field	24.0	23.1	19.5	16.2	9.4	18.9
Poor quality OF application (1 t ha^{-1})						
Close field	23.3	29.6	27.6	23.3	16.3	10.4
Remote field	1.4	8.6	5.7	2.6	-3.0	-1.4

OF stands for organic fertiliser. Organic materials of different quality had N contents of 3% (good) and 0.7% (poor).