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Communicating complexity: Integrated assessment of trade-offs concerning soil fertility management within African farming systems to support innovation and development

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African farming systems are highly heterogeneous: between agroecological and socioeconomic environments, in the wide variability in farmers' resource endowments and in farm management. This means that single solutions (or 'silver bullets') for improving farm productivity do not exist. Yet to date few approaches to understand constraints and explore options for change have tackled the bewildering complexity of African farming systems. In this paper we describe the Nutrient Use in Animal and Cropping systems – Efficiencies and Scales (NUANCES) framework. NUANCES offers a structured approach to unravel and understand the complexity of African farming to identify what we term 'best-fit' technologies – technologies targeted to specific types of farmers and to specific niches within their farms. The NUANCES framework is not 'just another computer model'! We combine the tools of systems analysis and experimentation, detailed field observations and surveys, incorporate expert knowledge (local knowledge and results of research), generate databases, and apply simulation models to analyse performance of farms, and the impacts of introducing new technologies. We have analysed and described complexity of farming systems, their external drivers and some of the mechanisms that result in (in)efficient use of scarce resources. Studying sites across sub-Saharan Africa has provided insights in the trajectories of change in farming systems in response to population growth, economic conditions and climate variability (cycles of drier and wetter years) and climate change. In regions where human population is dense and land scarce, farm typologies have proven useful to target technologies between farmers of different production objectives and resource endowment (notably in terms of land, labour and capacity for investment). In such regions we could categorise types of fields on the basis of their responsiveness to soil improving

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technologies along soil fertility gradients, relying on local indicators to differentiate those that may be managed through 'maintenance fertilization' from fields that are highly-responsive to fertilizers and fields that require rehabilitation before yields can improved. Where human population pressure on the land is less intense, farm and field types are harder to discern, without clear patterns. Nutrient cycling through livestock is in principle not efficient for increasing food production due to increased nutrient losses, but is attractive for farmers due to the multiple functions of livestock. We identified trade-offs between income generation, soil conservation and community agreements through optimising concurrent objectives at farm and village levels. These examples show that future analyses must focus at farm and farming system level and not at the level of individual fields to achieve appropriate targeting of technologies – both between locations and between farms at any given location. The approach for integrated assessment described here can be used *ex ante* to explore the potential of best-fit technologies and the ways they can be best combined at farm level. The dynamic and integrated nature of the framework allows the impact of changes in external drivers such as climate change or development policy to be analysed. Fundamental questions for integrated analysis relate to the site-specific knowledge and the simplification of processes required to integrate and move from one level to the next.

1. Introduction

Agricultural productivity in Africa must be increased to meet the demands of an increasingly urban population, as much as to support sustainable rural livelihoods (Andriesse et al., 2007). Poor soil fertility and the associated nutrient limitations for crop growth are highlighted as pervasive constraints in smallholder farming systems (Buresh et al., 1997; Sanchez, 2002; Sanchez and Swaminathan, 2005). Technologies or approaches for tackling resource constraints are invariably developed and tested for livestock or crops at animal, field or plot level – through the classic approaches of experimentation. Yet when farmers experiment with technologies they are often faced with constraints at the farm or higher levels – constraints that arise due to the lack of, or competing uses for – land, labour, cash or organic resources.

When analysing farming systems across Africa we faced a bewildering complexity. Closer examination led to the identification of recognisable patterns between farming systems, between farmers, their aspirations and their resource allocation strategies across the farms. This stimulated the exploration of possibilities to target technologies effectively to farm types, and the niches within farms where they may have greatest utility. Advances in our understanding of the constraints faced by farmers are important for guiding interventions and to create space for innovations. Deeper understanding of constraints is also needed to guide policy concerned with enhancing agricultural productivity and rural development. Thus findings of research need to be communicated to development agencies and extension services working in rural areas, and to government departments and international (donor) organizations to aid better targeting of policy at all levels.

In this article we describe an approach to unravel complexity in smallholder African farming systems. First, the approach is described, after which we present some of the major findings from comparative research across different countries in sub-Saharan Africa, with emphasis on use of organic resources and mineral fertilizers and on nutrient use efficiency. Maximizing the use efficiency of all inputs at the farm level is one of the underlying principles of the integrated soil fertility management (ISFM) approach, recently adopted by the Alliance for a Green Revolution in Africa (AGRA) (Vanlauwe et al., 2010). Our analysis builds on both published and unpublished research. We illustrate that – although repeating patterns can be found (Giller et al., 2006), and underlying drivers identified – the huge diversity between farming systems, between farms and between fields within farms necessitates a situated approach to 'best-fit' technologies and policies to the specific circumstances.

Although much of our work has focused on management of soil fertility, many of the key lessons learned have much broader applicability for integrated analysis of agricultural systems both in terms of methods and principles. The analyses focus initially on factors that lead to heterogeneity of farming systems, of farms and of fields. Understanding of the underlying causes of: (i) differences between the configuration of farms and fields within farms and (ii) long-term objectives, aspirations and strategies of farmers, allowed the analysis of trade-offs between immediate and long-term benefits to livelihoods of different farming activities. We conclude by reflecting on how best this complexity can be communicated to assist targeting of technologies in the field and to support innovation.

2. The NUANCES framework

The Nutrient Use in Animal and Cropping systems – Efficiencies and Scales (NUANCES) framework was developed to assess *ex ante* the feasibility, impact and trade-offs of changing agricultural management in the short- and long-term, with a focus on processes taking place at the farm rather than the single plot level (Giller et al., 2006). Different system-analytical methods are employed, combining participatory research, farm typologies, data-mining, experiments and modelling tools to identify intervention opportunities and pathways towards the sustainable intensification of smallholder farm systems. Steps in what we term the 'DEED' approach are to: 1. Describe current production systems and their constraints; 2. Explain the consequences of current farmers' decisions on resource allocation; 3. Explore options for agro-technological improvement for a range of possible future scenarios; 4. Design, together with the farmers, new management systems that contribute to the sustainable intensification of smallholder agriculture. Many of the protocols and analytical tools used in these four steps (surveys, models, databases) are described in working documents and papers (available on www.africanuances.nl). We describe each of these steps briefly below.

2.1. Describe

The first step at a location consists of collecting relevant background data: socioeconomic (including markets and infrastructure), institutional, agroecology (climate, soil descriptions and maps), farming systems descriptions and their major production/marketing constraints. A rapid survey is conducted in close collaboration with local researchers and development workers to capture the diversity of households. The sample size is typically of 50–100 farms which may represent all farms or only a small fraction of the farms in a village (or sub-location) depending on the local social organization. The farms are categorized into a small number (3–5) of groups according to main production objectives or orientation and resource constraints. Various approaches have been used to generate typologies in different study sites, using wealth classes identified by key informants and the farmers' themselves (Zingore et al., 2007b; Figueroa et al., 2008), by qualitative analysis based on detailed field work with farmers including farmers' production objectives (Tittonell et al., 2005a) or using multi-variate statistics including ordination and clustering methods (Sanogo et al., 2010; Tittonell et al., 2010). A small number of farms belonging to each class is selected purposively for quantitative characterization of production activities and main resource (cash, labour, nutrient) flows. Use of stratified sampling of an equal number of case study farms of each type ensures that diversity of the farming system is represented. Farms are randomly sampled from within each type but completely random sampling from the whole population of farms is not feasible given the intensity of data collection required for detailed system description. Resource flow mapping (Defoer et al., 2000) is used to collect detailed quantitative information on the configuration of the farm, field sizes and production units. Resource use calendars are developed using participatory budgeting tools to identify peak periods of demand for labour and other inputs (Galpin et al., 2000). Soils from different fields are sampled and analysed using rapid methods (Shepherd and Walsh, 2002; Tittonell et al., 2008c) and estimates of yields in the field are made to triangulate and confirm estimates made from farmers' recall. The characterization involves repeated visits to the farms, often over a whole year to ensure important events are captured.

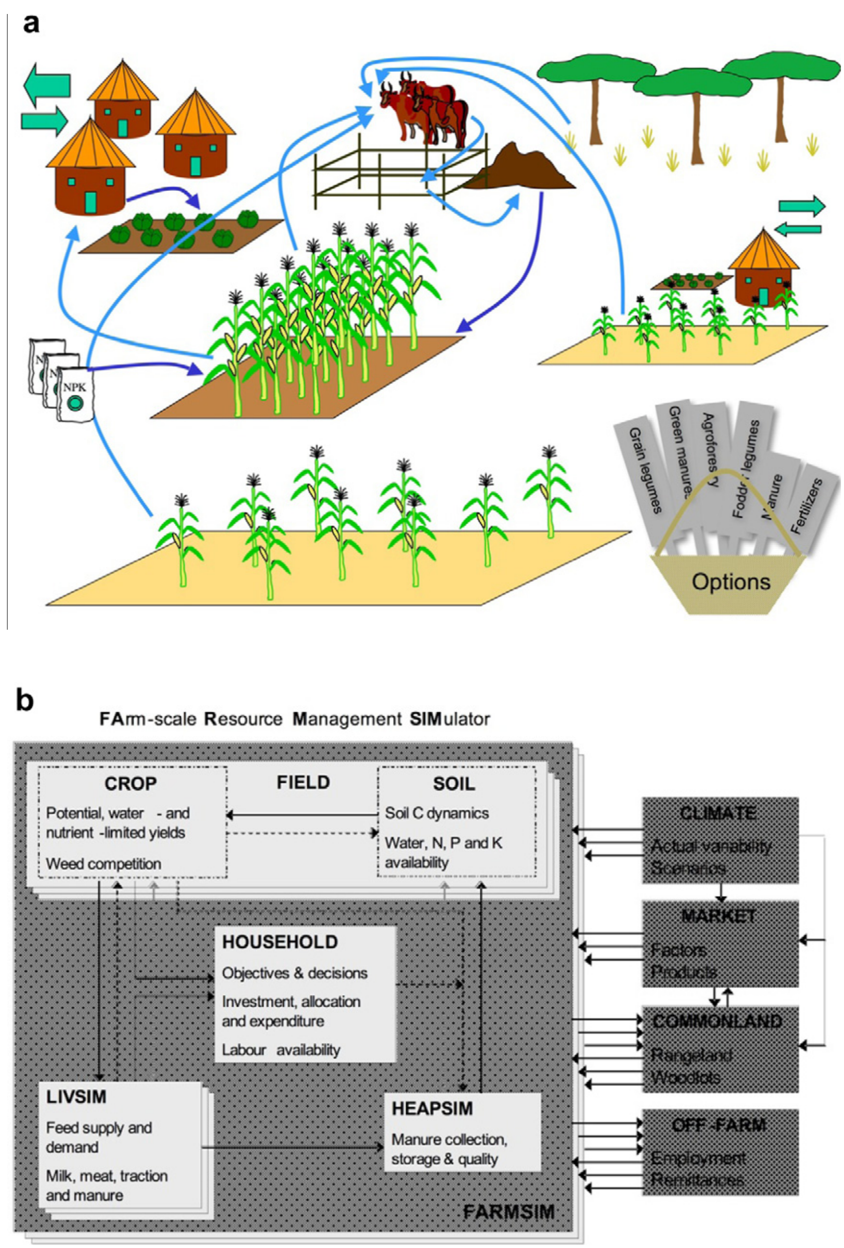

Fig. 1. (a) A representation of the key components of smallholder farming systems in sub-Saharan Africa that forms the core of the NUANCES framework (adapted from Giller et al., 2006). The 'basket of options' needs to fit to specific socio-ecological niches within diverse farming systems. See text for further explanation. (b) Schematic representation of the relationships between different modules of the model FArm-scale Resource Management SIMulator (FARMSIM). Crop and soil models are combined within the FIELD module; different instances of FIELD represent the various field plots of a farm. Different instances of LIVSIM (the LIVestock SIMulator) represent different herds of cattle, sheep, goats or individual animals. Different instances of FARMSIM represent different farm types in the community. Weather conditions, markets, common resources and income from employment and remittances are driving variables to the farm system.

2.2. Explain

The detailed characterizations described above are simplified to 'virtual' farms as no analysis can encompass all farming activities. Virtual farms constitute the basis for the dynamic simulation of the farm system, coupling soil/crop, grassland, livestock, manure and household models. The scheme in Fig. 1a illustrates how diverse, complex smallholder farming systems can be understood as a limited set of interacting components. Although the cartoon of the farming system (Fig. 1a) was originally drawn for a crop–livestock system in Zimbabwe, it has features that are readily recognised by researchers and farmers from other regions and countries. The scheme is translated into a model of the farming system, NUANCES–FARMSIM (FARM SIMulator Tittonell et al., 2008a; van Wijk et al., 2009) (Fig. 1b). We use component subsystem models that are as simple as possible to avoid being overwhelmed by detail, but to include all major activities to allow scenario analysis. Agricultural fields are represented by the FIELD model that contains linked crop and soil models (Tittonell et al., 2010), livestock production (milk, meat and manure) and reproduction are represented by LIVSIM (Rufino et al., 2009), an individual based model, and manure and organic residue management by HEAPSIM (Rufino et al., 2007). Each of the component models can have multiple instances depending on the configuration of the farm studied. NUANCES–FARMSIM and the component models are used together with secondary data, expert knowledge and empirical agronomic experiments or feeding experiments to generate understanding of the key processes that control farm performance. Farmers' decisions on resource allocation are represented in the model based on farmers' responses during the detailed system characterization and observations in the field. Discussions with key informants and farmers are conducted, both individually and in groups, to understand farmers' objectives and aspirations and the major constraints faced (Misiko, 2007; Misiko et al., 2008). These discussions feed into the choice of future scenarios to be explored.

2.3. Explore

Once confidence has been gained that the component models capture the essential behaviour of the productivity responses, these are used to explore scenarios of allocation of resources, based either on current or increased availability, depending on the question being asked. In reality, exploration of scenarios takes place iteratively with the previous 'explain' step as it is part and parcel of the validation and testing of the models. Availability of the primary resources for farming of land, labour and cash also act to constrain farm performance. Concurrently, based on literature and previous research in the area (or similar areas) a series of 'best-bet' technologies (a basket of options) to enhance productivity is identified (e.g. Waddington et al., 1998). The major external influences that have been studied to date are effects of climate, investment of nutrient resources and availability of common grazing lands (Rufino et al., 2010; Tittonell et al., 2009; van Wijk et al., 2009), but the models can potentially be used to explore effects of other drivers such as availability of labour or effects of changing farm size. Key questions on trade-offs between resource allocation or prioritising of different farm activities require analysis at farm level, including the dynamic feedbacks between different parts of the farm (Tittonell et al., 2007a).

2.4. Design

Once detailed understanding of the short- and long-term implications of different interventions, changes in farm management or in configuration of the farm has been gained, this is used to feed discussion and feedback with development agents and farmers (Misiko, 2007). A number of iterative cycles of modelling and discussion with farmers may be needed. We have experienced this as an essential step in our research, providing a reality check for the researchers, and also providing new ideas and inputs to refine or alter the scenarios explored. The discussions support co-learning with stakeholders, and it has been interesting to see how the simple concept of trade-offs has raised considerable interest and debate with farmers (e.g. Tittonell et al., 2008b). The exploration of future scenarios is done together with farmer groups using participatory methods through action research to test the applicability of the alternative 'best-fit' technologies (e.g. Baijukya, 2006) or institutional arrangements to enable change in farming (e.g. Adjei-Nsiah et al., 2008).

3. Key lessons learned

In this section we present some of the insights gained from a comparative analysis of smallholder African farming systems.

3.1. Describing the diversity and dynamics of African farming (describe)

We have analysed the diversity of farming systems and farm types in regions of high agricultural potential with better and more reliable rainfall in East and Central Africa (Kenya (Tittonell et al., 2005a,b, 2010), Rwanda, Tanzania (Baijukya et al., 2005; Mwijage et al., 2009), Uganda (Fermont et al., 2008; Ebanyat et al., 2010)), West Africa (Cameroon, Ghana (Adjei-Nsiah et al., 2004), Mali (Sanogo et al., 2010) and Southern Africa (Zambia, Zimbabwe (Zingore et al., 2007b)). This information is stored in databases that serve as a baseline for monitoring and evaluation of change at farm and farming system level (Herrero et al., 2007). Development of a standard approach for characterization of the farming systems proved more problematic than anticipated. The large differences between farming systems that ranged from shifting cultivation with perennial tree crops in humid forest (Cameroon) to crop–livestock farming in semi-arid savanna (Mali and Zimbabwe) meant that consistent sets of variables could not be used across all sites. Nevertheless, the comparisons between the farming systems revealed important similarities as well as the expected differences, which are described below.

A rural family that can be considered as 'poor' in one village or country may be seen as 'wealthy' in another. Criteria for defining a household as 'wealthy' range from having sufficient food for 10 months in a year in central Malawi, to owning a motor bike or television in Central Kenya. In each location there was a wide variability in resource endowment and production objectives – with highly-skewed distributions between the groups. The poorest and most disadvantaged households typically cultivated only small areas, due to lack of land or labour and owned little or no livestock. Such households were rarely self-sufficient in food, and were often delayed in cultivating, planting and weeding due to their need to earn their food by working for better-resourced farmers. Across sites, education was considered a priority for investment – so that their children would not have to be farmers. The typologies can be translated into simple cartoons for communication with farmers and development workers (Fig. 2).

Although we tend to regard smallholder farms as stable systems, both farms and farming systems are moving targets. Intensive farming involving continuous cropping on small areas of land is a relatively new phenomenon in Africa, having started within the past 50–100 years in most countries. This, together with other factors such as rapid demographic changes (in many cases population densities have doubled twice in the past 50 years),

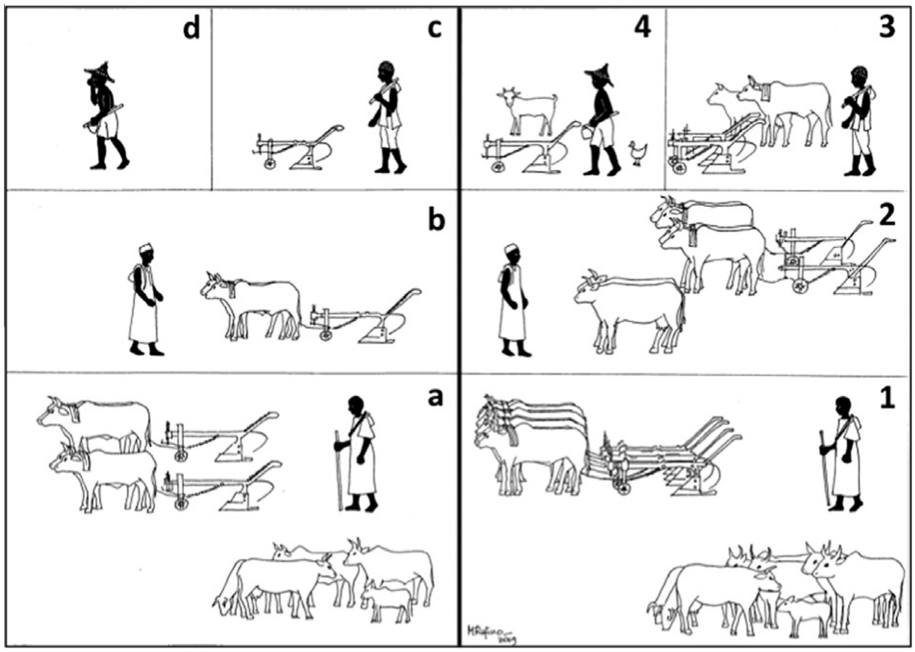

Fig. 2. Cartoon illustrating the main features of different farm types identified based largely on traction and livestock ownership in Koutiala, Mali. The left-hand panel illustrates a typology used in 1980 (IER, 1988), and the right-hand panel a typology developed in 2007. In 1980, the main distinguishing features were: Group a – two span of oxen, herd size >10 heads; Group b – one span of oxen, herd size <10 heads; Group c – one ox or a plough (insufficient to make a span with plough); Group d – only manual labour. In 2007, the main distinguishing features were: Group 1 – four span of oxen, herd size >20 heads including four cows; Group 2 – two span of oxen, herd size <20 heads including 2 cows; Group 3 – few cattle, of which at least one span of oxen; Group 4 – one plough, no oxen only small ruminants and chicken. Roughly 70% of the farmers belonged to Group b in 1980 and Group 2 in 2007 (based on Sanogo et al., 2010).

means that smallholder farming systems are highly dynamic. In many parts of Africa traditional crops, notably the small grains such as finger-millet (*Eleusine coracana* L.), pearl millet (*Pennisetum glaucum* (L.) R.Br.) and sorghum (*Sorghum bicolor* (L.) Moench) are increasingly replaced by other staple foods such as maize (*Zea mays* L.) and cassava (*Manihot esculenta* Crantz). This is often due to a change in preferences, the extra labour required to process small grains, and damage by birds. Highland banana is rapidly being replaced by maize and root crops (cassava and sweet potato [*Ipomoea batatas* L.]) in western Tanzania (Baijukya et al., 2005). In mid-altitude zones of East Africa the area of farms cropped with cassava increased from 1–11% to up to 55% within four decades (Fig. 3, Fermont et al., 2008). The changes in farming systems in both of these latter cases seem to be driven by increasing population pressure and declining soil fertility.

Next to inherent variability of soil types in the landscape, management decisions on the allocation of (scarce) resources generate gradients of soil fertility around villages (Prudencio, 1993) or within individual farms (Carter and Murwira, 1995). Livestock are a central means of concentration of nutrients, resulting in inequitable redistribution of nutrients from common to cultivated lands and from poorer households to farms of richer households (Ramisch,

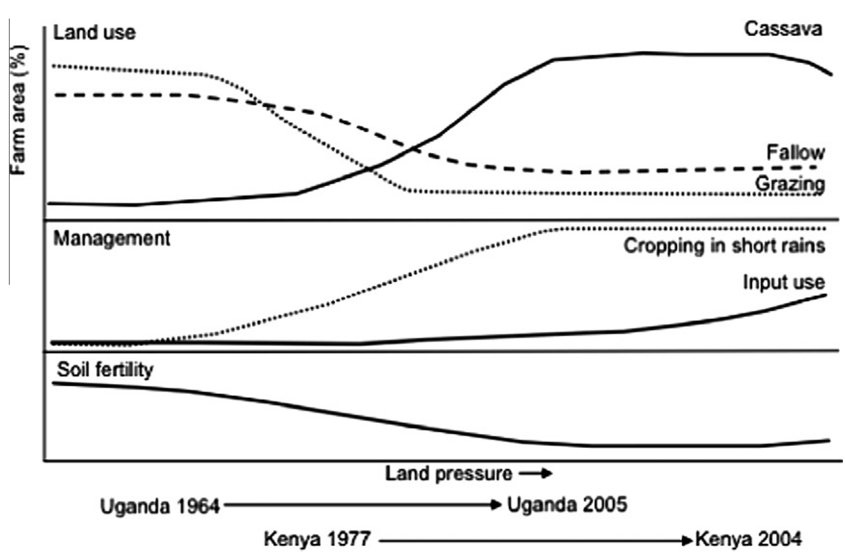

Fig. 3. Changes in cropping patterns in eastern Uganda and western Kenya over the past 40 years showing the increase in the land area cropped with cassava (modified from Fermont et al., 2008).

2005; Schlecht et al., 2006). Farmers preferentially allocate manure, compost, mineral fertilizers and labour to fields close to their homesteads (infields) resulting in strong gradients of soil fertility decline with increasing distance from the homestead as this provides the highest returns (Tittonell et al., 2005a, 2005b; Zingore et al., 2007b). The resulting differences in soil fertility between fields within a single farm may be as wide as those found between agro-ecological zones. Productivity gains are achieved by concentration of nutrients from the common lands, or concentration to infields, at the long-term expense of declining productivity in remote fields and common lands. This is particularly problematic due to the shrinkage of common lands resulting from agricultural expansion due to increased population pressure. In undulating landscapes, the fields that are farther from the homestead are often also located on steeper slopes with thinner soils and more erosion risk. If productivity in these fields is poor, other factors exacerbate the differences in yield compared with manured fields: farmers tend to plant later, more sparsely and to weed later in the poor fields (Tittonell et al., 2007b). The resulting lack of crop cover leads to more intense erosion that increases the rate of degradation.

Clear gradients of soil fertility decline with increasing distance from the homestead are not a universal feature of African farming systems. In densely populated areas with few livestock and sparse use of manure or mineral fertilizers, variability in soil fertility is mainly governed by position in the catena or soilscape. For example, in the finger-millet based systems of Pallisa, Uganda the fertility of farmers' fields is largely governed by their location along a toposequence (Ebanyat, 2009). In areas where the population density is relatively small and land use less intense no clear spatial patterns in soil fertility are observed. In the humid forest of Cameroon (Fig. 4) and the forest/Guinea savanna transition of Ghana the houses are clustered along roads, and farmers use little or no manure or fertilizers (Adjei-Nsiah et al., 2004, 2007). In such areas, the intensity of cropping close to the village leads to reductions in soil fertility whereas the 'bush' fields further away remain more fertile (Adjei-Nsiah, 2008).

The key drivers that result in management-induced variations in soil fertility are the intensity of land use and the spatial allocation of animal manure and compost. An interesting challenge is to identify thresholds of population and livestock density at which these effects become apparent. Such thresholds will undoubtedly differ with agroecology: with the favourable bimodal rainfall and deep heavy soils of western Kenya 'dense' populations are >1000 people per km^2, whereas on inherently poor granite sand with unimodal rainfall in Zimbabwe >80 people per km^2 is considered to be a dense population.

3.2. Explaining the consequences of human-induced soil fertility differences (explain)

Understanding the underlying causes of 'management-created' spatial heterogeneity, and their consequences for crop growth is key to understanding the productivity of the intensive farming systems. On sandy soils in Zimbabwe, Rowe et al. (2006) calculated that spatial allocation of a limited amount of cattle manure across three fields of a small farm could create a strong gradient in yield and soil C within only 5 years. This heterogeneity in soil fertility has strong effects on resource use efficiency i.e. returns to nutrient and water inputs, land and labour (Vanlauwe et al., 2006; Tittonell et al., 2008d). In western Kenya experiments on a large number of smallholder farms clearly show that a large part of the shortfall from potential yield or 'yield gap' is due to constraints associated with poor soil fertility (Fig. 5a). Farmers' maize yields, including fields that may have received manure and fertilizers under farmers' management, were 2–3 times larger in fields closer to the homesteads, compared with mid-distance or remote fields. Yields in experimental plots that received NPK fertilizers yielded 2–3 t ha^{-1} more than under farmers' management (i.e., yields were 2–4 times larger). Gap 1 represents the increase in productivity that can be achieved by better agronomic management (e.g. more timely planting and weeding) that increases the efficiency with which the land, and available nutrients and water and labour is used. Although farmers recognise the importance of timely management labour shortage often prevents this. Gap 2 represents the additional yield increase that can be achieved with mineral fertilizer (Fig. 5a). This example clearly demonstrates large differences in resource use efficiency across distances that can be as small as 50–100 m, with much larger yield responses to fertilizer addition in the outfields.

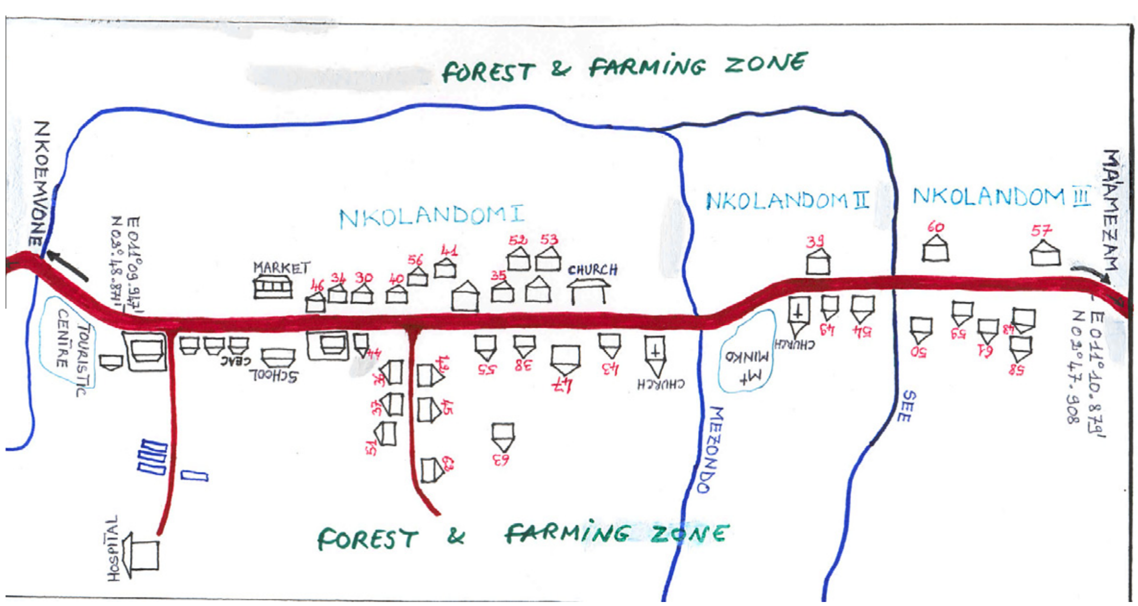

Fig. 4. A village map of Nkolandom in the humid forest of Cameroon were the population is sparse (<5 people/km^2) but clustered into villages. The map shows the linear arrangement of the village along a road and the surrounding farming zone. More intensive cropping in the fields close to the village leads to decreased soil fertility compared with 'bush' fields at a greater distance.

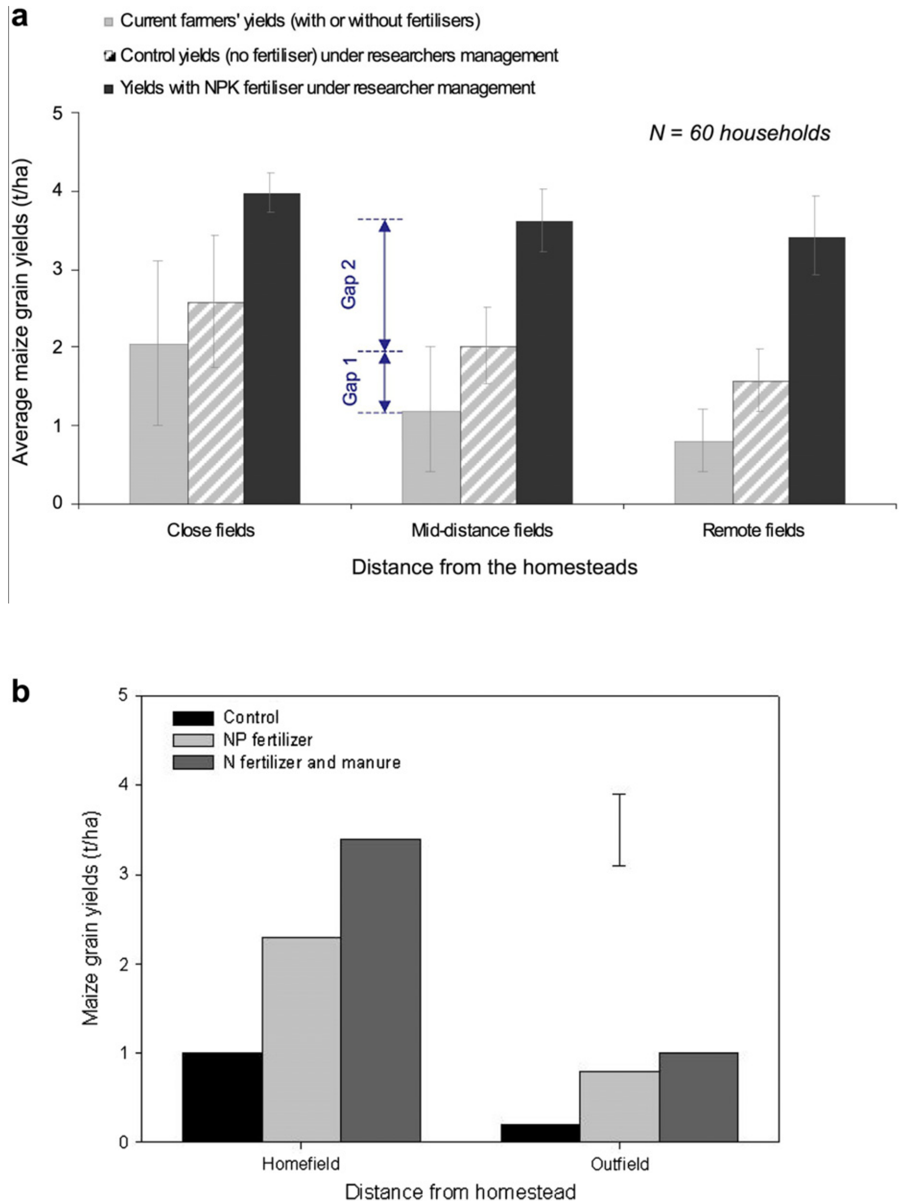

Fig. 5. (a) Yield gaps measured in farmers' field across soil fertility gradients in western Kenya, demonstrating the essential role of good agronomic management and additional nutrients (as fertilizers) in achieving increases in productivity. Yields of maize were measured on a sample of 160 farmers' fields (60 households) under farmers' and researchers' management in three villages of western Kenya. In the same season, experimental plots were established on the same fields, employing improved varieties and crop husbandry (e.g., early planting, weeding, etc.). The experimental plots with no fertilizers (control yields) but better management, yielded between 0.5 and 1 t ha^{-1} more than under farmers' management (even though some farmers applied fertilizers). This difference represents the *yield gap 1*, due to crop management and is attributable largely to labour shortages on-farm. Experimental plots that received NPK fertilizers (black bars) at a rate of 100 N, 100 P and 100 kg Kha^{-1}, yielded 2–3 t ha^{-1} more than under farmers' management. The size of *yield gap 2*, or fertilizer response under researchers' management, differed between fields at varying distances from the homestead. The sum of the yield gaps represents the yield improvement that can be achieved through proper management and fertilizer use (from Tittonell et al., 2008d). (b) Maize yields in unamended control plots and in response to N and P fertilizer (100 kg N ha^{-1} and 30 kg P ha^{-1}) or N fertilizer applied with manure (100 kg N ha^{-1} and 30 kg P ha^{-1} in manure) in a home field and an outfield on sandy granitic soils in Murewa, Zimbabwe (from Zingore et al., 2007a). Yields are averaged over 3 years. Vertical bar is the SED.

On-farm field experimentation in Zimbabwe showed even more extreme effects of soil fertility gradients on crop response to mineral fertilizers and organic manure on sandy granitic soils (Fig. 5b). Maize yields in unamended control plots were 1 t ha^{-1} larger in fields closest to homesteads than in outfields which produced less than 0.2 t ha^{-1}. It is unclear why farmers invest labour in outfields that give such small returns: interviews with farmers suggest that such fields are cultivated in the hope fertilizers may become available, and due to social pressure to maintain tidy fields. Application of mineral N in combination with P fertilizer or manure increased maize yields on the home fields on sandy soils by as much as 3.4 t ha^{-1} in the first year. In contrast, on sandy nutrient depleted outfields, maize did not respond to addition of mineral N and P over three seasons (Zingore et al., 2007a). Responses to combined applications of manure and mineral N were also poor in the first two seasons (maximum yields <1 t ha^{-1}). Substantial responses to mineral fertilizers were only observed after 3 years of manure addition, and further investigation revealed that the lack of response to fertilizers in degraded soils was due to deficiencies of Ca and Zn on top of the N + P deficiencies (Zingore et al., 2008). These results illustrate the need for local adaptation of agronomic recommendations and targeting of nutrient resources between fields.

Apart from the insights into crop management and responses, our understanding of the diversity of households and their access to markets allows us to place these results in context. In western Kenya, poorer farmers in need of cash are forced to sell their maize immediately after harvest, when maize is abundant on the market (Table 1). These farmers often buy (locally retailed) maize during the rest of the year and when they buy fertilizers they do it in small amounts, experiencing the most unfavourable fertilizer:maize price ratios. The opposite is true for wealthier farmers, who can buy fertilizers in bags and store their maize to wait for better prices before selling.

3.3. Exploring strategies for allocation of scarce resources (explore)

Farmers' allocation of scarce resources – organic manures, mineral fertilizers and labour for weeding – results in large differences in soil fertility and in yield between different fields in the farm. The component simulation models of NUANCES described above provide a means to explore the effects of alternative allocation of resources on productivity in the short- and long-term. Model-based analysis in crop–livestock farming systems in north-east Zimbabwe revealed that maize productivity and response to application of mineral and cattle manure decreased substantially with decreasing soil fertility (Rowe et al., 2006; Tittonell et al., 2007c; Zingore et al., 2007b). Limited nutrient resources were used most efficiently at the farm level by targeting nutrients to the fields of higher fertility, but limiting application rates to less than the farmers were adding to avoid decreasing marginal responses. However, the increase in crop productivity achieved by reallocating a limited amount of resources within the farm from one field to another was not sustained on the sandy soil, due to changes in soil fertility over time. On such soils, increased investment in organic nutrient resources is necessary to ensure efficient use of fertilizers and sustainably increase crop productivity. Both experimental data and modelling showed that, in the long-term, exclusive use of fertilizer without paying attention to soil organic matter resulted in a sharp decline in maize productivity. The model analysis indicated that N is the major nutrient that limits productivity when woodlands are cleared for maize production. Decline in soil fertility with continuous cropping induces deficiencies of P and other nutrients, making it necessary to apply multiple nutrients to increase maize yields in depleted fields.

Further investigations suggest that there is scope to improve productivity of smallholder farms by targeted application of limited mineral and organic nutrient resources to fields varying in soil fertility, although this has greater impact on wealthier farmers who have more fertile soils and greater access to fertilizer and manure (Zingore, 2006). In the case of Zimbabwe referred to above, targeting manure applications >5 t ha^{-1} y^{-1} for about 10 years was required to restore soil organic matter in depleted fields to about 60% and 50% of contents under native woodlands; this was required to increase productivity to 90% of attainable yields. But even small amounts of poor quality manure in combination with mineral fertilizers may contribute to increased productivity and fertilizer use efficiency, as shown in a model-based analysis of allocation strategies of manure of varying quality (as derived from farm surveying/ sampling) across soil fertility gradients (Tittonell et al., 2008a). Such management options, although technically feasible, may still be hampered by other constraints or priorities that emerge when considering the farm level. For example, Tittonell et al. (2007a) used inverse modelling to analyse trade-offs in allocating cash and labour to crop husbandry and soil erosion control across fields of a typical farm in an undulating landscape. The analysis revealed important trade-offs between increasing food production and reducing soil and nutrient losses, and indicated that investments in nutrients were only justified when basic crop management was ensured (e.g. weeding, early planting). Since labour-constrained this farm household most seriously, fertilizer use turned out to be uneconomic under most price scenarios explored.

Recommended fertilizer rates as derived from on-farm experimentation often translate into small total quantities required at farm scale. Fig. 6 was constructed with outputs of a NUANCES–FARMSIM modelling study in which all the model components have been thoroughly tested for farming systems under intense demographic pressure in western Kenya, and considering the climatic variability registered in the last decade. Repeated 10-year explorations performed with all the models coupled, keeping labour availability and nutrient recycling at observed (surveyed) levels on small farms <0.8 ha in area, indicate that substantial increases in overall food production could be achieved with small investments in fertilizers – as little as 30 kg N and 15 kg P per farm in each season (Tittonell et al., 2009). Wide variability in crop responses and in nutrient retention within the farm system was simulated in response to variability in rainfall. Such small application rates allow the farm soil stock of P, a critical nutrient in the area, to be replenished at a rate of 1–2% per season, contributing to the long-term sustainability of the system. Further explorations indicated that fertilizer use could be made yet more efficient at farm system level through parallel increases in livestock productivity through improved feeding strategies (Tittonell et al., 2009).

3.4. Designing systems for sustainable intensification (design)

In many smallholder farming systems the amount of nutrients available (in either organic or inorganic form) is insufficient to boost productivity of all fields in the farm. A crop–livestock farmer who grows part of the fodder for his/her cattle faces the choice of whether to allocate scarce nutrients preferentially to the food crops (e.g. maize in many systems in SSA) or to the fodder crops

Table 1
Fertilizer:maize price ratios (kg of maize necessary to pay for 1 kg N fertilizer) for different purchasers and at different times of the year and in western Kenya (adapted from Tittonell et al., 2008d).

Price per kg N fertilizer	Maize sold in 90-kg bags		Maize retailed in 2-kg tins	
	Before harvest	After harvest	Before harvest	After harvest
78 KSh (agro dealer)	3.9	9.0	2.6	7.8
130 KSh (local retailer)	6.5	15.1	4.3	13.0

1 Euro = 99 KSh (September 2008).

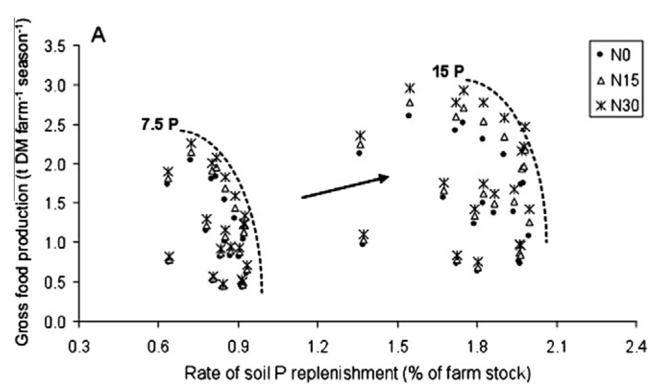

Fig. 6. Simulation results from the 10-year scenario of N and P fertilizer use. Gross food production plotted against the rate of farm-scale soil P replenishment with mineral fertilizer when 7.5 and 15 kg P $season^{-1}$ are used in a case study farm, without or with application of N at 15 and 30 kg farm $season^{-1}$, and with 'hand-drawn' lines illustrating P-limitation to farm productivity (from Tittonell et al., 2009).

(e.g. Napier grass). A sensitivity analysis of management strategies in a crop–livestock farm in western Kenya, revealed a strong negative correlation between simulated productivity of Napier grass and maize (van Wijk et al., 2009). This negative correlation was caused by different nutrient allocation strategies as the farms were highly nutrient-limited. Strong trade-offs exist between food and milk production due to allocation of the available nutrients to maize or to Napier. They show the importance of a whole farm perspective, because although these soils are responsive to organic inputs (e.g. Kapkiyai et al., 1999) potential productivity of the farm is strongly limited by the small amounts of inputs available. Once the trade-offs are known, new farming strategies under current or increased access to resources can be designed using participatory approaches. Farmers' objectives will determine which outputs of the system are weighed more heavily than others, and therefore which farming strategies will result in the preferred development of the farm.

Using livestock to recycle nutrients on-farm increases nutrient losses and diminishes the nutrient capture efficiency (Rufino et al., 2006, 2007). Livestock manure is, however, a better source of nutrients than plant materials used as green manures (Mtambanengwe and Mapfumo, 2006), and especially effective when it is combined with mineral fertilizers (Tittonell et al., 2008a).

Increasing manure availability may appear as a promising solution to soil fertility problems. This availability depends largely on fodder production at farm level and, in grazing systems, on the productivity of the rangelands and agreements and rights to use them. Livestock not only produce physical products but also play an important role in accumulation of wealth, insurance and display of status (Moll, 2005). These functions are especially important where they are not fulfilled by other means. Where rainfall is erratic livestock are perceived by farmers as a means to reducing income variability through the sales of animals (Dercon, 2002), but the capacity of livestock to smooth food consumption appears to be limited (Fafchamps et al., 1998; Hoddinott, 2006). Where there are market opportunities farmers may invest their savings in purchasing a dairy cow (Staal et al., 2002), or to buy oxen for ploughing. The development of dairy allows farmers to benefit from the generation of daily cash. Farmers believe that by producing milk they can improve substantially their income and educate their children (Bebe et al., 2003).

In a simulation exercise to assess the impact of integrated soil fertility management at village scale (Rufino et al., 2010), information from experimentation, soil types, livestock feeding and manure management was combined and used to design a strategy to restore the fertility of unproductive soils and improve livestock nutrition in a village in north-east Zimbabwe. Most mineral and organic fertilizers were currently applied to the home fields covering approximately 30% of 116 ha of cropland and producing about 85% of the food grain within the village. As earlier work had shown that mineral N and P fertilizers alone could not enhance yields due to deficiencies of Ca, Zn and other nutrients (Zingore et al., 2008) at least some manure is needed combined with fertilizer N and P. In a baseline scenario which represented current management with small amounts of NP fertilizers (between 5–50 kg N ha^{-1} y^{-1} and 2–17 kg P ha^{-1} y^{-1}), the village reached food self-sufficiency for its 66 households (about 330 people) only in years of good rainfall, while most of the cropland produced little grain and feed for the livestock. In an alternative scenario, small rates of fertilizers (30 kg N and 15 kg P ha^{-1} y^{-1}) were applied to the home fields

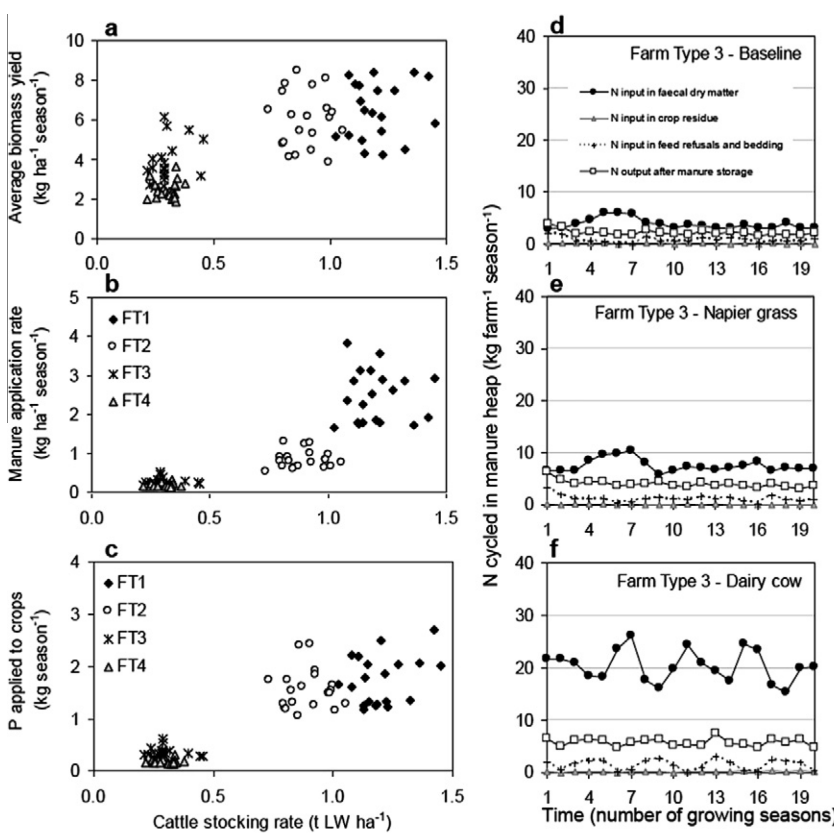

Fig. 7. Farm-scale indicators of the degree of crop–livestock interaction derived from a 10-year baseline simulation for four case study farms owning livestock: FT1, FT2, FT3 and FT4, farm types 1–4, respectively. (a) Average biomass yields of food and fodder crops, (b) Average manure application rates and (c) Total amount of P applied to crops in manure plotted against cattle stocking rates expressed as live weight per area of each farm. (d–f) Seasonal amount of N cycled in the manure heap of farm type 3 (FT3) under different scenarios, indicating inputs of N in faecal dry matter, crop residue, feed refusals and bedding materials added to the heap and N coming out of the heap after storage; scenario description in text (from Tittonell et al., 2009c).

and crop residues were incorporated. Mid- and outfields received a full NP fertilizer rate (60 kg N and 30 kg P ha^{-1} y^{-1}), and all of the available manure (2–4 t ha^{-1} y^{-1}). This continuous addition of small amounts of manure (2–4 t ha^{-1} y^{-1}) and fertilizers increased maize yields in the mid- and outfields from 0–0.5 to 1–3 t ha^{-1} at the end of the 10 year simulation. At the village scale, more than double the amount of grain needed for food self-sufficiency was produced plus extra feed for the livestock of the village. Although this would require a twofold increase in fertilizer use, the amount required is less than half that needed to meet the blanket recommendations for N for the whole cropland of the village. Following this strategy, 27% of the land would remain unproductive because of the lack of animal manure, although this land might be targeted in a restoration programme. This example clearly indicates the advantages of best-fit approaches over blanket recommendations.

A modelling exercise at farm level in western Kenya (Tittonell et al., 2009) confirms that the number of livestock in the system increases the amount of nutrients being recycled within the farm, but also increases the losses. The analysis of four smallholder farms owning livestock but differing in the number and type of animals and feeding/stalling strategies shows that higher stocking rates were associated with greater primary productivity on farm through increased C and nutrient application rates to crops in manure (Fig. 7a–c). The amount of N recycled through manure in each farm was also quantified for different step-wise intensification scenarios simulated with NUANCES–FARMSIM. Fig. 7d–e illustrate the increase in the magnitude of N inputs to the manure storage heap in faecal dry matter, in crop residues, in feed refusals and bedding materials, and the amount of N coming out of the heap after storage when part of the area of farm type 3 was allocated to fodder production (Napier grass scenario), and when an improved dairy cattle breed was brought into the farm to replace the local breed (Dairy cow scenario). These extra nutrients circulating within the farm would not been brought into the system through other means if livestock were not a key livelihood activity. Thus, although greater losses of N may be associated with increasing livestock stocking rates, these may be seen as a 'cost' of increasing primary productivity, as is common in highly intensified crop-livestock systems in Europe (e.g. van Keulen et al., 2000).

4. Communicating complex outcomes for targeting technologies within smallholder farms

Throughout Africa, recommendations for technologies on nutrient management remain rooted in outdated knowledge – often recommending too much fertilizer in relation to potential crop demand on a blanket (uniform) basis. When we raise the need for differentiated approaches a common response is "*But this is too complicated. It isn't possible to derive recommendations for every field of every farm*". Here we discuss some simple concepts and approaches that can assist in finding a way through this maze to derive rules-of-thumb for targeting technologies and to guide development interventions.

4.1. Developing decision rules for targeting technologies

Rather than referring to 'best-bet' technologies, which are a selection of approaches to improving productivity that show promise for a given agroecological environment, there is a need for 'best-fit' technologies targeted to different types of farms and to specific socio-ecological niches within farms. Indeed, it is neither desirable nor possible to derive 'recommendations' for each field in each farm, but the repeating patterns that are observed allow this concept to be put into action. Ojiem et al. (2006) developed the concept of the socio-ecological niche, recognizing that the windows of opportunity for different technologies are defined by both agroecological and socioeconomic variables. Options for integrated management of resources by smallholder farmers must be targeted to: (i) the specific context in which farming takes place; (ii) particular types of households pursuing different livelihood strategies; and (iii) spatio-temporal 'niches' within the farming system.

We demonstrate above that a systems approach is required to identify best-fit technologies, as when farm level constraints are not taken into account misleading conclusions on the sustainability of interventions may be drawn. Dynamic analysis at farm-level reveals the trade-offs associated with alternative management strategies over time. The repeating patterns that can be discerned across farming systems allow simple classifications to be derived. By distinguishing types of farms that differ in resource endowment and production objectives, appropriate technologies can be targeted to farmers. For example, conservation agriculture can reduce soil erosion and enhance infiltration of rainfall, but is being promoted throughout Africa without thorough analysis of labour constraints or competing uses for crop residues for livestock feed that may limit adoption (Giller et al., 2009). A thorough *ex ante* analysis could assist development agencies in understanding what proportion of households can utilise a given intervention such as conservation agriculture.

Simple typologies can also be derived in terms of field responses. For example, in both Kenya and Zimbabwe the broad heterogeneity of fields can be reduced and summarized across farm types into three categories: (1) fertile fields unresponsive to fertilizer applications; (2) intermediate fields, highly-responsive to fertilizers; and (3) infertile fields unresponsive to fertilizers. Recommendations for ISFM technologies can be derived for each of the field types (Tittonell et al., 2007c; Zingore et al., 2007a, 2008d). Category 1, fertile unresponsive fields require only maintenance fertilization; Category 2 fields can be targeted with many different technologies, using fertilizers efficiently and managing grain legume–cereal intercrops for instance; Category 3 fields need interventions aimed at restoration or rehabilitation to bring them back into productive use. Fertilizer recommendations can then be derived for these categories of fields based on simple rule-based approaches for a given agroecology, relying on local indicators of soil fertility/productivity.

We do not aim to develop a 'decision support system' in the form of computer-based software that would be used directly by farmers or extension/NGOs. The NUANCES framework combines empirical knowledge, databases and modelling tools that help to advance understanding. This is done by a team of researchers, and the relevance of the analyses is ensured by frequent contact with farmer groups and development workers. By engaging with farmers through participatory action research we gain a better insight into farmers constraints and understand how technologies need to be locally adapted (Defoer et al., 1998). This allows 'ground rules' to be distilled that form the basis for development of extension materials in each of the target areas. A major issue in this context is the diagnosis of soil fertility constraints by farmers in order for them to engage in site-specific nutrient management practices using such ground rules.

4.2. Supporting the innovation and development agendas

A meta-analysis of reports concerning the first Millennium Development Goal – to eradicate hunger and poverty – demonstrated consensus on the need to increase agricultural productivity, but there is a dearth of ideas on how this might be achieved (Andriesse et al., 2007). Development policy often claims to address the needs of the 'poorest of the poor'. There is increasing demand from local and international NGOs for advice and information on potential ways to increase agricultural productivity, particularly relating to soil fertility. Potential technology interventions are generally tested by trial and error, and applied uniformly across broad regions with little insight into whom is likely to benefit. *Ex-ante* integrated assessment tools such as NUANCES can help in identifying the most promising options for intensification (at farm level and in the short- and long-term) before they are promoted among farmers. This is of particular importance in face of the major investments in smallholder agriculture currently made in sub-Saharan Africa (e.g. www.agra-alliance.org).

A focus is to identify windows of opportunity that favour particular forms of management, recognizing that the attractiveness of technologies grows, and wanes, as intensity of land use and links to urban markets for both produce and employment develop (de Ridder et al., 2004). For a given combination of agroecological and socioeconomic conditions, a multitude of different combinations and trajectories of response by farmers may be equally productive. Farmers who have ready access to mineral fertilizers have less interest in labour-demanding soil improving technologies. Equally, poor households that are often labour-constrained are unlikely to be able to invest in labour-demanding technologies due to the need to use their labour to generate income. Technology development specifically for the poorest farmers needs to target labour-saving approaches: in Zimbabwe management to increase the abundance of leguminous weeds (indifallows) in farmers' fallow fields shows promise in raising base yields of maize, marginally in absolute terms, but significantly in terms of food provision for poor households (Mapfumo et al., 2005).

Although our analyses indicate that farmers often are doing the best they can with available resources, we find that farmers often lack a good understanding of how best to manage resources when they become available. The recent investment in fertilizer in Malawi under the national subsidy programme resulted in substantial increases in food production but with a N use efficiency of only 14 kg grain kg^{-1} fertilizer overall (Malawi Government, 2008) – less than half the efficiency that can be achieved with good management. The poor efficiency of fertilizer use was partly due to problems in timely-delivery of the inputs, but poor targeting of fertilizers to fields with different soil fertility constraints was a major problem.

A particular problem farmers face is when and how to rehabilitate degraded soils. Our analyses demonstrate that this takes considerable time and capital investment often beyond the reach of rural households. The clear need for external investment to enable farmers to rehabilitate land is a key message for development policy that quantitative analyses can underscore. A broader issue is how we can move forward from considering only the best 'system responses' under current farm structure and functioning to designing farms and farming systems that can evolve under new circumstances – perhaps with phased-investment-plans in a 'stepping-up' progression (Dorward, 2009).

Discussions with advisors within international and local NGOs have stimulated strong interest in the NUANCES framework. These interactions have highlighted the need for tailored options and institution building, in contrast to global interventions and technology development, as we often find now. Indeed the term 'best-fits' was first used in relation to agricultural advisory services (Birner et al., 2006). Tailoring of options and institutions necessitates the involvement of stakeholders at local and national level. The 'learning centres' approach (http://sofecsa.org/) brings together farmers, their organizations, extension workers, NGOs, private sector, policy makers and researchers in an alliance. The aim is to take advantage of the strengths of all partners to help farmers select and combine the most appropriate technology elements from a basket of options. Supporting innovation often requires direct intervention to create the necessary conditions and to make technologies available to farmers. An enabling policy environment is essential to create the conditions for success through (i) more favourable input/output prices or specific subsidies, e.g. 'fertilizer and seeds', in the short to medium terms, or (ii) reinforcement of agricultural extension services and market access in the long-term.

Our work demonstrates the power of comparative analysis for understanding complex systems: by contrasting farming systems across several countries we gain insights into the drivers that determine their functioning. Previous research at farm level using tools such as NUTMON has been instrumental in highlighting the critical lack of nutrient inputs in African smallholder farms (Smaling and Fresco, 1993; de Jager et al., 1998). The simple simulation approach of the NUANCES framework builds on these earlier studies and allows analysis of the interactions and dynamics of smallholder farming. To date our research has not addressed detailed economic analyses of options, but ongoing work is focused on incorporating into the framework the capacity to evaluate labour constraints and cash budgets. We have focused on areas of relatively better rainfall and high agricultural potential and techniques for water management such as rainwater harvesting would undoubtedly be more important in areas where water is more limiting.

Most research and development projects or interventions deal with singular approaches, and do not assist in selecting from the broader basket of options. The approach for integrated assessment described here can be used *ex ante* to explore the potential of several different options for productivity improvement and the ways they can be best combined at farm level. In response to the dynamic nature of smallholder farming systems, recommendations and extension materials need to be flexible to be able to respond to the changing circumstances of farming. Both at local and international level, policy advice needs to move towards more strategic thinking and decision-making, and escape the allure of simple 'silver bullet' solutions. Robust advice should be based on principles and processes, recognizing the need for local experimentation and adaptation and taking into account the trade-offs relating to adoption of new approaches that arise from the constrained settings within which smallholder farmers operate.

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