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Resource use dynamics and interactions in the tropics: Scaling up in space and time

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Abstract

We discuss the temporal and spatial dynamics of nutrient resources and water within cropping and livestock systems, their interactions and those with other resources such as labour. Short-term dynamics (within season) revolve around nutrient availability and losses as a function of soil moisture dynamics. Longer-term effects (multiple seasons and years) are related to residual effects of crop management in successive seasons and to changes in soil organic matter contents.

Spatial patterns of resource use are consistent across different tropical farming systems. Farmers preferentially allocate manure, mineral fertilizers and labour to fields close to the homestead, resulting in strong negative soil fertility gradients away from the homestead. Livestock are the central means of concentration of nutrients within farming systems, resulting in their inequitable redistribution from common lands and poorer households to richer households. Productivity gains achieved by concentration on home plots are at the expense of long-term declining productivity on remote fields. Restricted availability of inputs leads to a form of self-organization resulting in repeating patterns of farm organization that are recognisable across sub-Saharan Africa.

Principles for enhancing allocation efficiency of scarce resources are required that address the dynamics of interacting temporal and spatial scales. Managed variability that creates gradients of soil fertility can have major effects on resource use efficiency of both nutrients and water, necessitating analysis of trade-offs at farm scale. Investment decisions of farming

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families are shaped through complex interactions among competing demands for investment of cash and labour within and beyond farm boundaries. Combinations of socio-economic and agro-ecological conditions can provide windows of opportunity in both time and space that favour investment in particular forms of management.

Past research provides a vast array of technologies to improve agricultural production, and understanding of the underlying processes. A research framework is proposed representing farm systems as sets of interacting components. This framework can be used ex-ante, to assist in targeting technologies to specific types of farmers, and for identification of more appropriate technologies. It can be used to explore short and long-term trade-offs of management strategies and to evaluate effects of policy on farms varying in resource endowment.

Keywords: Crop/livestock systems; Spatial dynamics; Self-organization; Whole farm analysis; Scaling up

1. Introduction

Much of our understanding of the utilization of resources for agricultural production in the tropics is based on a single crop and often a single resource, either water or one of the macronutrients. In reality agricultural production suffers from multiple constraints, so the interactions between resources are often critical in determining overall productivity. Smallholder farms consist of several fields that are managed differently, but because of limited availability of key resources such as labour and nutrients, highly interdependently. Smallholder agriculture in the tropics is typified by multiple cropping, with several crops intercropped together, within which competition for resources is determined by the temporal dynamics of their availability in relation to the growth patterns of the different species (Trenbath, 1976). Livestock plays a major role in concentration and redistribution of nutrient resources both within and between farms, and in harvesting of forage (and nutrients) from areas of common land (Powell et al., 2004).

Poor soil fertility is regarded as the underlying factor limiting productivity in African agriculture. Substantial knowledge has been accumulated on different approaches to manage soil fertility in smallholder farms in Africa (see for example Buresh et al., 1997; Waddington et al., 1998). Nevertheless, the lack of adoption of various technologies, or the absence of widespread testing and experimentation by farmers, are disappointing. Reasons underlying the lack of impact of much agricultural research are undoubtedly complex and include, in addition to technical factors, a host of socio-economic and political factors. However, a fundamental problem that lies at the door of the scientific community is the lack of integration of available knowledge. Essentially, research has been driven by a 'commodity'-based, plot or field scale approach, despite the increasing realization that natural resource management has to be tackled at the scale of the farming system, including the common lands. For example, various projects have explored the potential of grain legumes, herbaceous green manures, multi-purpose trees in agroforestry or management of animal manures or mineral fertilizers for improving soil fertility.

But virtually no studies exist where the potential of all of these technologies has been compared within a single study at farm scale. Management of production systems is often a compromise between the potential for short-term maximization of crop and livestock production and investment for sustainable production in the long term. Thus, assessment of the use efficiency and dynamics of natural resources and their interactions requires analysis at a variety of spatial and temporal scales.

We are developing an integrated analytical framework (The NUANCES (**N**utrient **U**se in **AN**imal and **C**ropping systems – **E**fficiency and **S**cales) Framework) with the aim of embedding analyses of the potential for different soil improving technologies in the context of farmers' strategies. The analysis presented here is a necessary step in the synthesis of knowledge to allow the comparative analysis of farming strategies and efficient targeting of resources within a farm-livelihood system. Our focus in this article is on integrated use of resources for soil fertility improvement within farms. In Section 2, we describe the essential features of the NUANCES framework; Section 3 focuses on the key concept of resource use efficiency and Sections 4 and 5 discuss the initial results derived using the framework. In the final Sections 6 and 7, we discuss how the scope of NUANCES can be widened.

2. Moving from field to farm scale

2.1. Repeating patterns of land use within smallholder farms in Africa

Strong gradients of or zones different in soil fertility exist in many smallholder farming systems in Africa (Hilhorst and Muchena, 2000). Variability in soil fertility is partly inherent, arising from differences in parent material and position in the landscape. Heterogeneity in soil fertility is also created by management. Wood-ash, organic waste and composts tend to be added to home-gardens close to the homestead, which consequently often have higher pH and fertility than cropped fields further away (Chikuvire, 2000). In livestock-based systems the animals concentrate nutrients at sites where they are stalled overnight. A well-known example is the 'ring' management system in West Africa (Ruthenberg, 1980). Fields close to the village are much more fertile than the 'bush' fields some 0.5–2 km away (Prudencio, 1993). In smallholder farms in East and southern Africa, large differences in soil fertility status are found among fields even within small farms of less than 1.5 ha (Tittonell et al., 2005). The manure collected from 'kraals' or 'bomas' is often applied to specific crops or fields within the farm, again preferentially to fields closer to the homestead (Mapfumo and Giller, 2001). Fields further away from the homestead often receive no organic amendments and little mineral fertilizer.

Some of the nutrient flows and transfers that result in gradients in soil fertility vary strongly among farmers of different social status; notably between cattle owners and non-cattle owners. Common lands are mined for browse and grazing by cattle, as are crop residues in most fields after harvest. A large proportion of the nutrients contained in the forage is concentrated into the manure (Powell and Williams, 1993). Manure is a major nutrient resource in many tropical farming

Table 1
Key issues relating to resource use efficiency that need to be considered at different scales of analysis

Hierachical level	Time scale		
	Short term (1 season)	Medium term (1–5 years)	Long term (5–50 years)
Key issues			
Field/common land	Production efficiencies Fodder production Fuelwood availability	Production efficiencies of rotations Rangeland improvement	Soil erosion Soil carbon contents Yield stability Livestock carrying capacity
Farm	Resource tradeoffs Farm scale efficiency Labour allocation between fields	Risk avoidance Allocation of crops in rotation between fields	Livelihood stability
Village	Product prices Labour markets	Institutional development (input/output markets)	Social institutions, infrastructure (roads, etc.)

systems, but the quantities of manure are limited and represent a transfer of resources to wealthier farmers (Achard and Banoin, 2003). Access to external inputs, such as mineral fertilizers, as well as labour availability, is also highly dependent on the size and resource endowment of the farming household. Thus, different issues emerge at different scales or hierarchical levels within the farming systems (Table 1).

Although the relative sizes of fields and the crops grown on different fields within the farms vary, repeating patterns of land use can be identified that are remarkably similar among smallholder farming systems across Africa. The pictorial representation of a smallholder farming system in Fig. 1(a) was drawn to represent smallholder farms in *Shona* villages in Zimbabwe, but has been shown to capture the essential features of farming systems throughout sub-Saharan Africa. We suggest that the repeating patterns of land use across smallholder farms represents a form of 'self-organization' of pattern within the farming systems in the face of restricted resources of land, labour and nutrient inputs. The example in Fig. 2 from western Kenya demonstrates the differences in resource allocation among farms of different resource endowment. All farmers, irrespective of resource endowment, apply organic manures preferentially to fields close to the homestead. Wealthier farmers who use more mineral fertilizers are able to apply them across the different fields, but other farmers have restricted access to fertilizers. This preferential use of organic manures close to the homestead leads to development of soil fertility gradients even in farms as small as 0.45 ha.

The existence of such repeating patterns across farming systems represents the basis for development of an analytical framework to examine, describe, and explore the dynamics of resource use at farm scale. The scheme in Fig. 1(b) illustrates how diverse, complex smallholder farming systems can be understood as a limited set of

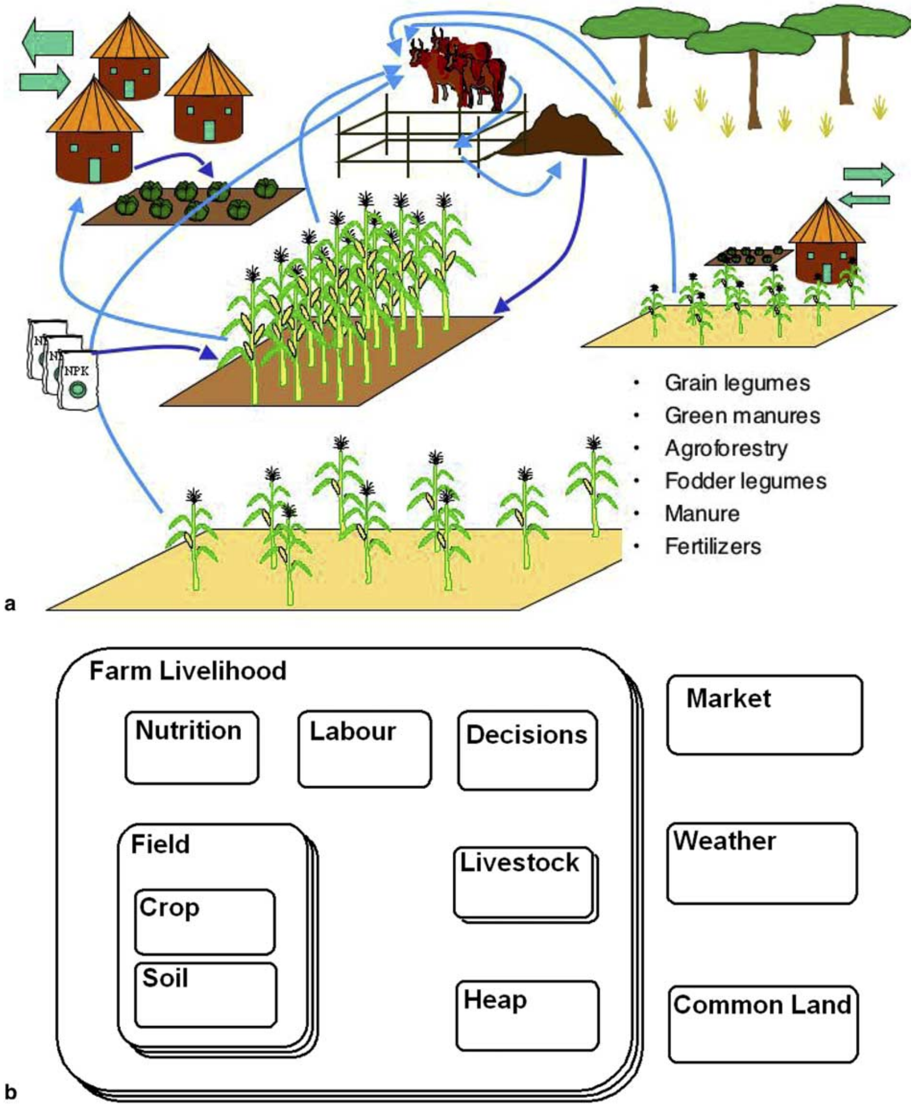

Fig. 1. (a) A representation of the key components of the farming system typical to smallholder farming systems in sub-Saharan Africa, that forms the core of the NUANCES framework. See text for further explanation. (b) The essential components required to conduct an analysis at farm scale. The 'stacks' of components for farm, field and livestock represent multiple instances of these components.

interacting components. In order to understand the essential drivers of system behaviour it is necessary to simplify the context within which farmers make operational decisions on a day-to-day basis. However, a simplification that focuses only on one or two components of a farm system is unable to address the opportunity

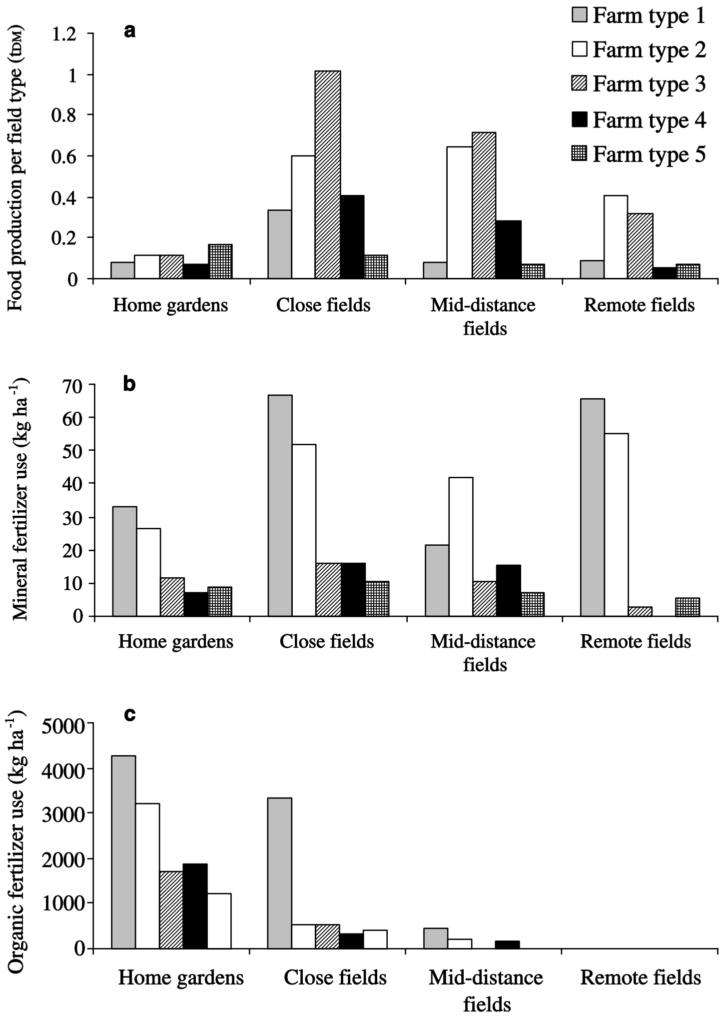

Fig. 2. Food production from and inputs of nutrients to different fields of farms of differing resource endowment at Shinyalu, western Kenya. Total food production per field (a) includes only edible produce, such as grains or vegetable leaves. Mineral (b) and organic (c) fertiliser use includes all types of mineral fertilisers and organic resources used as soil amendments. Farm types 1 and 2 are wealthier, but type 1 farms depend on off-farm income, whereas type 2 farmers derive their income from cash cropping, types 3 and 4 are intermediate and type 5 are poor farmers dependent on agriculture or selling agricultural labour (adapted from Tittonell et al., 2005).

costs of different activities and the trade-offs that are involved in alternative decisions on resource allocation. Thus, an analytical framework consisting of components in a complete farm system is necessary. Within the NUANCES Framework, these components are represented by simple summary models.

2.2. Scaling up – the farm household or 'livelihood' as the unit of analysis

In the preceding section, we have argued the need for raising the focus for analysis from the plot or field scale to the farm or household scale, because at this scale decisions are made regarding resource allocation. However, few farming households in developing countries rely solely for their food or well-being on income derived from agricultural production from their own farm (Reardon, 1997). Livelihoods of smallholder farmers are strongly influenced by opportunities for off-farm earnings through markets for produce and employment, both locally or in urban centres. Remittances from household members working in the city, or earnings from local labour markets, are often (but not always: see de Jager et al., 1998) highly significant components of household income, and of agricultural inputs. This applies not only to smallholder farmers in 'peri-urban' settings, as labour migration occurs over long distances, often beyond national boundaries, and is not a new phenomenon (Andersson, 2002).

The livelihoods of farm households depend on complex interactions between competing demands for investment of cash and labour, both within and beyond the farm boundaries. Common lands are valuable sources of dry season grazing, of wild herbs or fruits, organic matter for soil amendments and of wood for fuel or for building materials (Campbell et al., 1997; Shackleton et al., 2002). Thus, agricultural production cannot be analysed in isolation from other income sources and possibilities for input use. Farmer decisions on investments of labour and other resources for agricultural production therefore take place within a complex setting, with strong spatial and temporal differentiation.

Although our focus is on efficient use of nutrient resources, these are allocated by farmers through decisions made at farm scale, and their use is constrained by the other principal resources for agricultural production: land, labour and capital. Capital can include cash resources and livestock, as well as access to various forms of 'natural' capital such as forests or common land. In many tropical farming systems, availability of land, labour and capital are interrelated, as is their allocation within the farm. Access to land is often determined by complex sets of local rules and as land may often be leased, it can be a dynamic resource.

Labour is a constraining resource that limits the extent or regulates the timing of operations on a farm. Peak demands for labour occur in seasonal environments. Labour scarcity is exacerbated by health problems of which HIV/AIDS and malaria are of particular concern. Lack of labour at the start of the rainy season for land preparation, planting and weeding can restrict the land area planted, or lead to some fields being planted too late. Effective use of labour may substitute for primary production resources, as the timely targeting of interventions influences the availability and capture of these resources. For example, timely weeding reduces competition and thus increases nutrient and light availability for crops. Soil management such as tied-ridging can improve capture and infiltration of water. Labour and capital are closely related, since labour may be purchased or may have to be sold, and since purchased agrochemicals such as mineral fertilizers and herbicides can substitute for labour-demanding management such as applying organic manure and weeding (Veeneklaas et al., 1991).

3. Resource use efficiency as a key concept

Prior to exploring the consequences of restricted availability of resources on productivity and sustainability of smallholder farming, we briefly consider the concept of resource use efficiency. The spatial and temporal dynamics of resource use efficiency are particularly dependent on the interactions between different resources.

3.1. Defining resource use efficiency

Trenbath (1986) described resource use efficiency using two simple equations:

$$\text{Resource use efficiency} = \text{capture efficiency} \times \text{conversion efficiency}, \tag{1}$$

where

$$\text{Capture efficiency} = \text{interception efficiency} \times \text{absorption efficiency}. \tag{2}$$

These equations discriminate the components of efficiency in essentially the same way as the 'three-quadrant diagram' for nutrient use efficiency developed by C.T. de Wit (see de Wit, 1992). Others have used the terms agronomic efficiency, uptake efficiency and physiological (or internal) efficiency for the three different aspects of resource use efficiency, capture efficiency and conversion efficiency, respectively (Witt et al., 1999). Separation of various components of resource use efficiency allows exploration of the underlying mechanisms that contribute to (in-)efficiencies in resource use, which in turn leads to ready identification of how management practices can best be targeted to achieve efficiency gains. The same approach can be applied to animal production in relation to the resources of feed (and water) where capture efficiency is a function of interception of feed (absolute availability, selection) and absorption efficiency is feed intake (quality-determined). For animals, efficiency of conversion is measured as the energy converted into body weight (growth) and/or other products (such as milk or eggs).

The above equations are broadly applicable to the resources of light, water and nutrients in plant production and to the resources of nutrients in feed and drinking water in livestock production. The various component features of plants that contribute to the overall efficiency of use of the various resources are listed in Table 2, together with their potential interactions.

3.2. Interactions between resources in relation to land quality

The efficiency with which one resource is used depends on the availability of another resource, but the exact relation between the two has been the subject of a long-standing debate (see for example de Wit, 1992, 1994; Nijland and Schouls,

Table 2
Features of the plant-soil-atmosphere that contribute to the overall efficiency with which resources are used in plant production

Resource	Capture efficiency		Conversion efficiency	Interactions with other resources
	Interception	Absorption		
Light	Leaf area Leaf angle	Chlorophyll concentration	Rubisco concentration	Deficiencies of N and P (and other nutrients) limit leaf expansion
Water	Infiltration capacity, affecting infiltration/run-off partitioning Water holding capacity Root length density	Evapotranspiration Plant demand	Vapour pressure deficit	Nutrient deficiencies and/or lack of fixed carbon caused by light limitations limit root exploration of the sub-soil and leaf area expansion, thus partitioning between transpiration and evaporation
Mobile nutrients (e.g. N)	Mass flow Root length density Early uptake	Active uptake systems Demand Timing (synchrony) Deficiency of other (macro-)nutrients	K effects on partitioning of photosynthate	Water limitation restricts mass flow Nutrient deficiencies and/or lack of fixed carbon caused by light limitations limit root exploration of deeper soil horizons
Immobile nutrients (e.g. P)	Diffusion Root length density and distribution Mycorrhiza	Plant demand Deficiency of other (macro)nutrients		Water limitation restricts diffusion rates Nutrient deficiencies and/or lack of fixed carbon caused by light limitations limit root exploration intensity

1997). This debate is relevant because the nature of the interactions between resources determines the shapes of the response curves. Response curves are difficult to assess in practice, because variability within fields tends to blur and smooth the responses (van Noordwijk and Wadman, 1992). Given the heterogeneity in land qualities among fields of single farms described above, interactions in resource use efficiency co-determine how available resources should be deployed most efficiently within farms.

One of the clearest examples of interactions in the efficiency of use of different resources is that of the effects of nutrient availability on efficiency of water use for plant productivity in semi-arid regions (Fig. 3(a)). The increased response to water in the presence of nutrients arises mainly from increased *capture efficiency*. Interactions also occur where wide variability in the efficiency of nitrogen use is observed with very similar rainfall (Fig. 3(b)). The (agronomic) N use efficiency on a sandy soil on an experimental farm in Zimbabwe was ~50 kg grain kg^{-1} N applied compared with 10 kg grain kg^{-1} N in farmers' fields. This enormous difference in nitrogen use efficiency results from a complex of interacting variables, such as nutrient deficiencies, soil acidity and lower soil water availability under on-farm conditions, due to low soil organic matter contents. Furthermore, weed infestations compete strongly with the crop for N uptake (Mushayi et al., 1999). There is an inverse relationship between N use efficiency of crops and

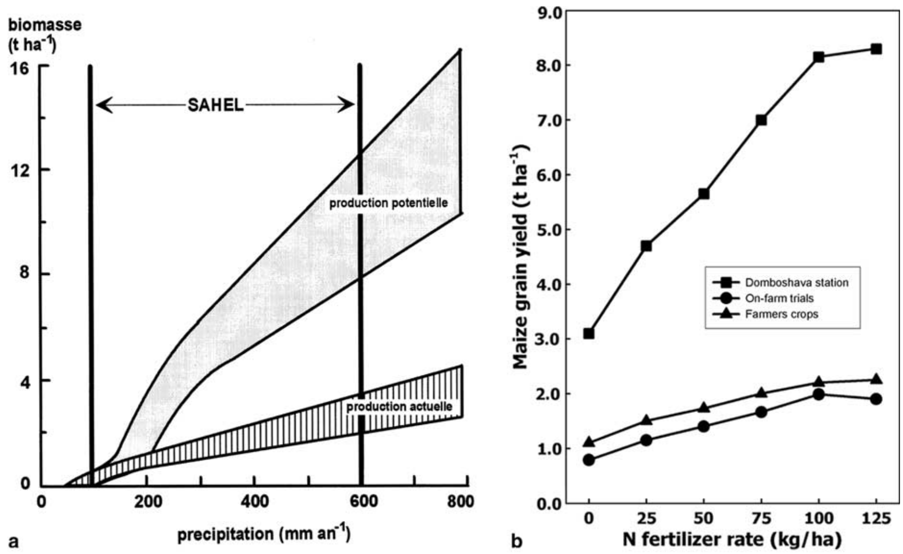

Fig. 3. (a) Primary production of grass savanna in Mali across a rainfall gradient in the presence (potential production) or absence (actual production) of added nutrients (from Penning de Vries and Ditèye, 1991). (b) Poor efficiency of N use by maize on smallholder farms in sub-humid Zimbabwe, compared with N use efficiency on Domboshava Training Centre Farm close to Harare (after Mushayi et al., 1999). Preliminary evidence from on farm experiments indicates that nutrient efficiency in the infields of smallholder farms is close to that on the Domboshava Farm.

the potential 'leakiness' of the cropping system (de Wit, 1994; Giller et al., 2002), which is high when crop growth is limited by growth factors other than N. In weathered soils in tropical Africa, P deficiency is often a critical limiting factor, but other soil acidity-related factors, such as aluminium toxicity can constrain root growth. Giller et al. (2002) recognized three ways in which soil amendments can improve the capture and use efficiency of other resources: (1) short-term effects of nutrients stimulating plant growth; (2) amelioration of adverse chemical conditions in the soil, such as reduction of aluminium toxicity by adding cations in lime or manure; and (3) altering soil moisture relations through short-term effects of mulching on water capture (infiltration versus runoff) and long-term effects on soil physical properties through increasing soil organic matter contents. Most of the interactions described influence overall resource use efficiency through effects on resource capture, but some interactions result in a higher *conversion* efficiency. For instance, better K nutrition can stimulate loading of photosynthate into the grain (Marschner, 1995).

4. Resource use at farm scale

4.1. The development of heterogeneous patterns of soil fertility and crop yield

Rowe et al. (2006) used a simple farm model with crop/soil modules for three fields within a farm to evaluate conditions that could create soil fertility gradients. They demonstrated that repeated application of manure to infields could create gradients in soil fertility of similar magnitude to those found on smallholder farms in Zimbabwe within 5–10 years of opening of the land from forest. The development of gradients of soil fertility depended on the availability of organic manures. If the supply of organic manure was not limited in relation to the land area, the fertility of all land was sustained, representing the case of wealthier farmers.

Yields of crops have been observed to vary strongly among fields owned by the same farm household. This is not only due to concentration of nutrients, as investments of labour and management intensity also vary with distance from the homestead (Tittonell, 2003; Tittonell et al., 2005). Fields close to the homestead tend to be ploughed and planted early in the growing season, planting density tends to be higher and the weeding effort invested is greater. Thus, the effects of soil fertility and crop management are inextricably confounded, as management results in the development of soil fertility gradients, which in effect are also crop management gradients.

The preferential allocation of organic resources and labour investment on fields closer to the homestead can be due to various factors. If the supply of labour is limited, fields closer to the homestead can be most conveniently accessed, although on small farms of 1 ha or less, the time taken to walk to an 'outfield' is negligible. Maintaining an area of the farm with optimal soil fertility may be seen as a means of guaranteeing food security for a farmer, and close fields are less susceptible to theft of harvestable produce.

4.2. Short-term dynamics of organic and mineral nutrient resources

The dynamics of nutrient supply to crops are dominated by two factors: water and the type, frequency and timing of organic matter and/or mineral fertilizer additions.

A sound understanding of the roles of organic resources for N management over the short-term has been developed (see Palm et al., 1997; Giller, 2000; Palm et al., 2001b). Organic residues, and particularly those from legumes, are important sources of N, but generally poor in P so that effects on P availability are largely indirect through influencing chemical processes of P-fixation in soil (Palm, 1995). Rates of decomposition of plant residues and their ability to supply N for plant growth are determined by a hierarchy of factors, within which the N content (C:N ratio) is dominant (Cadisch and Giller, 1997), and that further contains concentrations of lignin and reactive polyphenols (tannin). A decision tree based on this knowledge has been developed to assist discussions on the various uses of organic resources in agriculture (Palm et al., 1997; Giller, 2000). Despite advances in our understanding of the dynamics of N availability from organic residues, synchrony with plant demand has proven difficult to manage (Handayanto et al., 1997). In contrast, availability of nutrients from mineral fertilizers can be effectively managed by timing top-dressings of N with periods of maximum crop demand. Piha and co-workers (1993,1998) developed an approach to managing mineral fertilizer in relation to unpredictable rainfall. Significant gains in the economic efficiency of fertilizer use were achieved by applying basal fertilizer, followed, as the season progressed, with small amounts of N in split doses in relation to target yields.

Much of the research and thinking on nutrient resources has been framed in the context of 'organic-inorganic interactions'. It has often been assumed that organic and inorganic sources of nutrients can substitute for each other, with insufficient recognition of the different management potentials of organic and mineral nutrient sources. Organic resources are bulky and generally have a more restricted but more sustained capacity to supply nutrients. They can rarely be applied after planting. Mineral fertilizers are concentrated nutrient sources and the immediate availability of nutrients allows flexible management in relation to crop demand. Rather than focusing on nutrient requirements of individual crops, greater attention to the most efficient use of organic and mineral nutrient resources for complete rotations is warranted (Giller, 2002). Use of animal manure or mineral fertilizers to ensure better growth of legumes may supply a greater input of N to subsequent cereal crops (McDonagh et al., 1995; Chikowo et al., 1999). Indeed, one of the strongest nutrient interactions that can be managed to enhance crop productivity is the alleviation of P deficiency to increase growth and N_2-fixation by legumes (Giller, 2002).

4.3. Long-term effects on soil organic matter contents

There are important trade-offs between managing nutrient provision for crop production and managing soil organic matter contents in the long term. Organic resources that are good for supplying nutrients are those that decompose relatively quickly and are therefore not good for increasing soil organic matter (Giller et al., 1997; Palm et al., 2001a). Soil organic matter contents depend on the dynamic balance between the inputs of organic resources, and their rates of decomposition (Feller and Beare, 1997). The rate of decomposition is a function of the residue quality and environmental conditions (Heal et al., 1997). The clay content of the soil is of great importance in stabilizing its organic matter, i.e. the potential for building up soil organic matter stocks, and of course soil N contents, increases proportionally with clay content (Fig. 4). Soil organic matter management in sandy soils is therefore particularly difficult as organic matter decomposes rapidly, and as a result it is difficult to build up soil N stocks in such soils (Giller et al., 1997). Enhancement of soil organic matter contents can have important feedbacks on water use efficiency: higher organic matter contents affect soil physical properties, improving soil structure and soil moisture capture (infiltration) and retention which directly increase the amount of water available to crops. The role of soil organic matter in influencing long-term efficiency of nutrient capture by crops is poorly understood. In acid soils, greater organic matter contents increase pH, cation exchange capacity and availability of P and cations.

5. Resource use efficiency at farm scale

5.1. Effects of soil fertility gradients on resource use efficiency

Given that gradients of soil fertility are so ubiquitous in smallholder farming systems, the question arises as to whether they have positive effects on the efficiency of resource use, or whether the gradients are simply the unfortunate result of a lack of resources. Rowe et al. (2006) concluded that spreading nutrient resources is more efficient than concentrating them, if labour is not taken into account. If the amount of

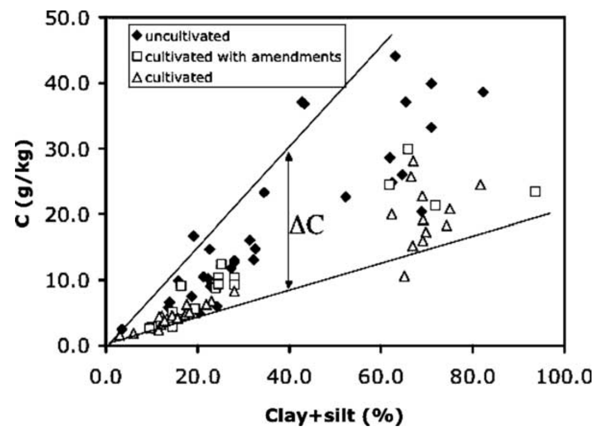

Fig. 4. The C storage capacity of soils as a function of clay plus silt contents. ΔC represents the difference in C between fully exploited soils under continuous cropping with little inputs and the saturation potential that is possible (after Feller and Beare, 1997).

organic amendments available to the farmer is restricted, preferential allocation to infields will cause soil organic matter contents of the outfields to decline. Once the soil organic matter falls below a critical threshold that influences the efficiency of resource use, it becomes more efficient to concentrate the resources on land of better quality.

Organic matter management has important effects on moisture availability. In the short-term, infiltration rates are affected by mulching (Hulugalle, 1994). On sandy soils, prone to surface sealing, runoff occurred within minutes and 86% of the rainfall was lost in continuous maize plots, whereas no runoff was observed after cutting of legume tree fallows where a thick litter mulch was present (Nyamadzawo et al., 2003). Long-term effects include increased water holding capacity at higher organic matter contents, although such effects are often minimal in the field. There is increasing evidence that nutrient use efficiencies are greater on well-managed infields than in depleted outfields (e.g. Fig. 3(b), IFDC, 2002).

5.2. Restoration of degraded outfields

While more degraded soils need to be restored to agricultural productivity, targeting soil-improving technologies to such soils is often unsuccessful. Soil-improving legumes often grow extremely poorly on degraded lands and give little benefit in enhancing soil fertility (Giller, 2001). Considerable investment of animal manure and other soil amendments may be necessary before the potential N-contribution of grain legumes or legume green manures and trees through N_2-fixation to poorer land can be realised. As a consequence, land where legumes could grow strongly enough to make a significant contribution to soil fertility improvement is often the land that farmers prefer to commit directly to production of staple or cash crops.

Variability in resource use efficiency has clear implications for the economic returns to investment in external inputs (Breman, 2003). Amendments that solve multiple nutrient deficiencies and improve the soil as a rooting medium, such as combinations of fertilizers with cattle manure and other organic amendments are required in degraded soils before mineral N fertilizers can be used effectively.

Yield-reducing processes, such as pest, disease and weed infestation (Rabbinge and van Ittersum, 1994) can also result in strong reductions in efficiency of resource use. The intensity of pernicious weeds, such as stoloniferous grasses and *Striga* spp., can be exacerbated in soils that have been poorly managed. Additional labour input is often (though not always) a means for control of such problems. Efficiency of labour use, in terms of returns to labour invested, varies strongly in relation to yield potentials, which in turn are determined by availability and use of other resources such as nutrients and water.

6. The wider context – political and socio-economic environments as determinants of system responses

Given that profitability of crop and livestock systems influences choices and possibilities for investment, we cannot ignore the broader political and socio-economic environments within which farming takes place. Sumberg (2002) argues that such factors should be accepted as inherent system characteristics when developing technologies and interventions. While agreeing with this principle, political and socio-economic conditions should not be accepted as permanent features that determine the agenda for research and development. Analysis of opportunities for investment in agriculture at farm and livelihood scale can help to expose the weaknesses in current trade policy, and assist in the identification of new opportunities.

Policies operate at a wide range of scales, from the choice of crops or varieties that are promoted by governmental or private research and extension services, to liberalization of fertilizer use. For example, recent de-regulation of the fertilizer market in southern Africa has resulted in widespread adulteration of fertilizers. In Zimbabwe, the requirement for inclusion of at least 4% sulphur in all fertilizer blends no longer holds and problems of S deficiency have emerged, given the dominance of sandy soils that are inherently poor in S. At the national, regional and international scales, the effects of world trade agreements on pricing policies for major commodities have an overriding influence on local profitability of agriculture (Bigman, 2002; Koning, 2002). This means that approaches to agricultural development that disregard these effects and emphasise local markets for commodities that are traded internationally, are unlikely to succeed. Insights from 'New Institutional Economics' highlight the need for strong technologies, supply chains, markets, information flows and all other components of production systems to be in place to induce successful changes in agriculture (Dorward et al., 1998). A thorough understanding of the context in which the farmers are operating, and how this influences their management decisions and production opportunities, is required for informed debates surrounding national and international policies for enhancement of food security and livelihoods in rural communities (Breman, 2003).

7. Analysing trade-offs between short-term productivity and long-term sustainability

Our overall aim is to increase our understanding of the tactical and strategic decisions farmers make in allocating resources and the underlying trade-offs, where immediate needs of the family may often override the possibilities of investing in the longer-term sustainability of the farm. By synthesizing knowledge, we can analyse trade-offs between implementation of various soil fertility technologies for smallholder farmers in mixed crop/livestock systems in Africa. The emphasis is on efficiency of targeting and use of nutrients and legume-based soil improving technologies, with outputs evaluated in terms of costs, benefits and compromises in productivity, economics and environmental services. The potential for using integrated crop-livestock simulation models in scenario analysis was recently reviewed by Thornton and Herrero (2001) who warned of the risk for being drowned by complexity. Our approach is to use simple component subsystems to avoid being overwhelmed by detail, but to include enough components to allow scenarios of sufficient reality to be analysed.

The vast diversity of farming households and farming livelihoods must be recognised when targeting technologies and interventions. This is obvious when considering interventions that require use of external inputs, such as mineral fertilizers, but it is equally true for technologies that are directly designed as being low-external-input or ‘free’, like N_2-fixing legumes. Many low-external-input technologies, such as use of legume green manures, are highly demanding for labour and do not yield immediate returns. In Africa, the poorest households are often single female-headed households (often widows) with limited land and limited opportunity for off-farm earnings, who are unable to invest in labour-intensive technologies. Analysis of success stories where low-input approaches have been widely adopted, certainly those using N_2-fixing legumes, suggests that the most successful approaches produce multiple products such as food and fodder, or that actually reduce demands for labour (Giller, 2001). Farmers readily chose grain legumes over green manures when these were compared in rotation with maize in depleted soils (Chikowo et al., 2004). The rapid spread of *Mucuna pruriens* var. *utilis* as a green manure in both Central America and in Benin was due to suppression of weeds and reduced labour requirements, rather than to soil fertility improvements per se (Versteeg et al., 1998; Buckles and Triomphe, 1999).

Consideration of both socio-economic and agro-ecological conditions allows identification of the windows of opportunity in both time and space that will favour particular forms of management. Thus, the attractiveness of technologies will grow, and wane, as intensity of land use and links to urban markets for both produce and employment develop (de Ridder et al., 2004). The concept of ‘multiple stable states’ (Holling and Gunderson, 2002) is useful in conceptualising potential scenarios for future development of farming livelihoods. For a given combination of agro-ecological and socio-economic conditions, a multitude of different combinations and trajectories of response by farmers may be equally productive. Innovation by farmers and researchers has provided numerous components in terms of crop species and varieties and management techniques that can be adopted with or without adaptation and employed for enhancing agricultural production. Increased attention to the multiple goals and constraints of farmers when developing new varieties and/or designing new technologies is required, recognising the potential benefits of reliable production and contributions to fodder supply and soil fertility improvement, in addition to direct yields. 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. This suggests that relatively labour-intensive technologies, such as green manuring, are more likely to be attractive to middle-income farmers. Technology development specifically for poor farmers needs to target labour-saving approaches: in Zimbabwe management to increase the abundance of leguminous weeds in farmers’ fallows 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., 2003).

Fundamental questions in analysis of resource dynamics and potential for modification of complex farming systems relate to the degree of simplification of processes that is allowed and the site-specific knowledge that is necessary to integrate and move from one scale to the next. Understanding which factors are the most important in determining site-specific response to changes in management is a central issue.

Comparative studies of farming systems will allow exploration of the linkages to policies that will favour investment in smallholder agriculture. Improving resource use efficiency in tropical agriculture demands a reformulation of research approaches, going beyond traditional concepts of farming systems research and encompassing contributions from all disciplines. Above all, this requires the embedding of research in the broad context of the diverse and extended livelihoods of farmers in the tropics.

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