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Farming System Research and the quest for a sustainable agriculture

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Abstract. This paper brings together information from four sites in sub-Saharan Africa where FSR&D projects are located (Mali, Benin, Zambia and Tanzania), supported by the Royal Tropical Institute of The Netherlands. Common environmental constraints to agricultural productivity are analyzed, with an emphasis on aspects of soil fertility maintenance. It is shown that when plant nutrients are valued against market prices, annual crop production systems are inefficient due to considerable losses of nutrient resources (e.g., soil erosion) and economically unviable because of unfavourable input and producer price ratios. Technically solutions are available that make agriculture sustainable, but its output is likely to be reduced when accepting the need for environmental protection at various levels of integration (cropping system, field/farm, village territory, etc), since marginal land must be left under natural vegetation, and various forms of buffering elements must be installed on farms. The costs of protective measures (space, labour, energy in community organization) cannot be raised based upon local resources currently available. Making small farmer agriculture in the tropics sustainable and environmentally sound begins by improving economic conditions for farmers, raising producer income and lowering prices for inputs.

1. Introduction

This paper discusses margins for *Farming System Research and Development* (FSR&D), in its search for technological solutions to unsustainable land use in the tropics. It draws upon information and experiences gathered in a number of countries in sub-Saharan Africa, where FSR&D activities receive technical and logistic support from the Royal Tropical Institute (KIT), which is based in the Netherlands. Projects involved include the *Division de Recherche Système de Production Rurale* (DRSPR), the *Projet Lutte Anti-érosive* (PLAE), both located in South Mali, the project *Recherche Appliquée en Milieu Réel* (RAMR) in South Benin, the Lake Zone FSR project in north-west Tanzania and the Adaptive Research and Planning Team (ARPT) in Western Province, Zambia.

All FSR&D projects work within the context of the respective country's national agricultural research infrastructure, promote participation of its clients in all stages of the project, and make explicit use of local knowledge and experience in agricultural technology development.

As a consequence of the very different socio-economic and ecological conditions, a wide variety of research topics has emerged, reflecting locally relevant constraints and opportunities (Table 1).

FSR&D activities fall into two main categories. There is a strong emphasis on research that aims at increasing agricultural productivity, mainly through the introduction of improved crop varieties and inorganic fertilizer use.

Secondly, much attention is given to cultural practices that strengthen the agroecosystem's physical and biological buffer capacity (e.g., stonelines, integration of perennial plant species in various functions). Here, the overall objective is to contribute to the conservation of the resource base, in terms of both soil and vegetation.

Conservational practices are a primary concern in strategy development for sustainability in agriculture. The rationale is that losses of topsoil, through water erosion for example, do not only endanger future possibilities of making a living in agriculture, but also critically lower the current efficiency of resource use.

While in our minds there is little doubt about the merits and technical soundness of most of the measures and policies summarized in Table 1 as such, all projects have difficulties in getting farmers to adopt whatever practices are proposed. This seems an almost univeral experience in FSR&D programmes in the tropical world.

Table 1. FSR&D activities aimed at improving sustainability of agroecosystems.

1. *Methodology development*
on-farm trials (all projects considered)
village counselling on natural resource use (Mali)
defining land use from toposequence analysis (Mali)

2. *Soil fertility management*
promotion of inorganic fertilizers (all projects considered)
animal manure (Tanzania, Mali, Zambia)
grass mulch (Tanzania)
household refuse, crop residues (Mali, Tanzania)

3. *Vegetative buffers separating fields or farms*
grass-strips (Mali)
strips where natural vegetation is maintained, selective clearing (Mali)
live fences (various species, such as *Jatropha, Euphorbia*, Mali)
grass-covered storm drains, stonelines (Mali)

4. *Perennials directly integrated in cropping systems*
separate or single tree systems (e.g. *Vitellaria* and *Parkia* in Mali)
alley-cropping (*Leucaena* and *Gliricidia* in Benin)
selective weeding (potential system with *Bauhinia* and *Baphia*, Zambia)

5. *Sequential vegetative buffers*
oilpalm as planted, productive fallow (Benin)
inter-season *Mucuna* fallow (Benin)

Obviously, in the past, many of the failures of FSR&D could be attributed to its immatureness and lack of proper methodologies. Lately, however, it is felt that FSR&D meets so little success because of other factors as well.

In this paper we argue that a number of agroecosystems in the tropics simply are too marginal and/or too difficult to handle to expect them to be productive under an agricultural regime, and to sustain that productivity over time.

Secondly, evidence is produced to support those who believe that the root cause of unsustainability in small farmer agriculture is related to the fact that prices for agricultural produce in the tropics generally are too low to allow farmers to invest in the maintenance of their livelihood, the lands they occupy.

2. Four case studies

The regions where KIT-supported FSR&D activities take place cannot be considered as marginal in the context of the respective country's agricultural potential, with the exception of Barotse land, Zambia. The importance of including the latter case is to put emphasis on the fact that also here orchestrated action must be developed in order to prevent the area from eventually being destroyed. Instead of narrow-focused programmes aimed at annual crop production development, one could look at the possibilities of combining treecrops with extensive sustainable exploitation of natural forests, wildlife management, and in the future, tourism. Projects then could guide farmers becoming operators in such multi-goal land use schemes. Clearly, there is a need in many situations to look beyond the stricter boundaries of agriculture, when planning for sustainable land use.

The objective of this Chapter is to give brief characteristics of each of the four agroecosystems, particularly referring to the aspect of soil fertility and its maintenance.

Regarding these summaries, we acknowledge the fact that much more relevant information pertaining to the question of sustainability in land use could be given. Little explicit reference, for example, shall be made about the ingenuity of farmers exploiting basically poor soils. Our understanding is that farmers, given means available to them, already extract close to the maximum possible from their environment, although differences in management skills exist. Their experiences therefore are considered as a valuable resource in farming system research and agricultural technology development, and, as Table 1 in the introductory Chapter shows, a major focus of the FSR&D projects considered.

2.1. *The cotton zone of South Mali*

South Mali is the country's main cereal and cotton production area. The latter crop together with live animals (38% of Mali's cattle is raised in the southern region) account for over three-quarters of the country's export earnings [Berthé et al., 1991].

Land in southern Mali is intensively utilized. Particularly over the past 20 years there has been a rapid increase in the area under arable farming, partly due to the introduction of oxen-drawn ploughs, and, consequently, fallow periods are drastically reduced. Farmers do collect and apply farm yard manure, but quantities are far from sufficient. Breman and Traoré [1986] show that, in the savanna zone, for every hectare of cropland farmers would need 15—20 hectare of rangeland in order to feed animals sufficiently for the purposes of breeding, draught power and maintenance of soil fertility. That land is simply not available.

Soils in the region are poor, both chemically and physically. Pieri [1989, p. 224], based on data from Siband [1974], shows that continuous cultivation leads to equilibrium levels of 0.34% of organic carbon in the topsoil. Since the soil's fertility carrier is likely to depend on organic carbon one can assume that CEC values will drop well below 3 meq. per 100 gram of soil.

Janssen [1983, p. 194] assumes that when Cation Exchange Capacity values, determined at pH 7, fall below 3—4 meq. per 100 gram soil, cultivation of annual crops, using purchased fertilizers, becomes economically unviable. There might well be a relationship between Janssen's observation and the fact that for the Soudano-Sahelian Zone as a whole inorganic fertilizer use is low to non-existent (c. 1 kg N and 0.5 kg P annually per ha of cultivated land according to van Keulen and Breman [1990]).

Soil surface crusting, erosion, hardening and compaction, all are problems encountered in these soils [Valentin et al., 1991], making it difficult to use them permanently in a sustainable manner.

Van Keulen and Breman (op. cit.) estimate the maximum population density in South Mali that can be sustained through arable farming, based on natural resources, to be in the order of 5 to 15 persons per km^2, going from the southern Sahel to the savanna. Current population densities vary from 5 to 40 in the southern Sahel, and from 10 to 50 per km^2 in the savanna zone.

The conclusion is that we face an overexploited agroecosystem, in which in principle renewable resources such as groundwater, perennial grasses, trees and shrubs, soil organic matter and nutrient reserves are visibly exhausted.

2.2. *The Adja Plateau, South Benin*

The 'Terre de barre' of the Adja Plateau in South Benin supports high population densities, of over 100 persons per km^2. In Togo even densities of 500 persons per km^2 are found (Schwartz cited by Poss [1987]). These types of soils are found over long distances (from Senegal to Madagascar). The soils are almost perfectly flat, and, because of their excellent permeability, usually hardly eroded at all.

The topsoil shows a sandy texture, since the original clay content has been transported to deeper strata. Under permanent vegetation the open texture is maintained because of intense activity of soil fauna, a quality that rapidly changes when fields are permanently farmed [Raunet, 1971]. Intensively cultivated land may show lower organic carbon contents than are given in Table 2 (0.17—0.46% carbon in the 0—20 cm layer, according to Poss [1987]). An important feature in the agroecosystem is the 'Dura'-type oil-palm. Sown around the 6th year of field cultivation, and regularly cut back during the first couple of years of its existence, the palm gradually takes over as the main component of a planted and productive fallow. The crop produces alcohol, cooking oil, building material and fuelwood. Cattle do not play a significant role in this particular farming system.

While soils in the Benin case are more fertile and easier to manage than those found in South Mali, the hypothesis is that the farmer-invented, palm-based agroforestry system helps create relatively high levels of production system sustainability, allowing higher population densities.

2.3. *The Kalahari sands of Barotse land, Western Province of Zambia*

In the Western Province of Zambia population concentrations traditionally are found near the Zambezi river in the floodplains, and on the edges where the floodplain and uplands meet. The riverplain represents a very diverse agroecosystem: Topography and soil formation, both are strongly influenced by the river. A main characteristic is the low nutrient load of the river water, especially in terms of phosphorus [van Gils, 1988].

The lowlands cover approximately 10% of the Province, while uplands account for the remaining 90 per cent. A complex farming system has developed [cf. Trapnell and Clothier, 1957; Peters, 1960; Vierstra, 1990], in which cattle play a dominant role, economically and ecologically. Cattle are instrumental in fertility transport for the purpose of crop production.

Increasingly, because of local over-population, uplands become occupied by farmers. The upland Barotse sands, as Table 2 confirms, have a low available nutrient content, no mineral reserves, a soil organic carbon content that rapidly falls as a function of soil depth, and a low cation exchange capacity. Consequently, these sandy soils are easily robbed of the little nutrients available (note the very low cation saturation levels in Table 2), and water that benefits plant growth is poorly retained.

2.4. *The Bukoba District of North-west Tanzania*

The Bukoba district is located in the extreme north-west of Tanzania, west of Lake Victoria. The principal components of the farming system are bananas, coffee and cattle. According to Friedrich [1968], the soils in the region are lateritic and often badly leached. Nutrients in short supply are in particular phosphorus, potash, magnesium and calcium. In addition trace

Table 2. Soil fertility indicators.

	% Organic carbon	CEC meq.	Saturation of complex	Particulars
South Mali				Ferric Lixisols[a]; data from
0—20 cm	0.58	3.4	67%	Kater et al. [1992]
20—40 cm	0.45	3.6	54%	
South Benin				Nitisols[b], eroded 'Terre
0—20 cm	0.58	3.2	78%	de barre'; Abomey Plateau
20—40 cm	0.29	3.0	50%	data from Raunet [1971]
0—20 cm	0.65	6.0	63%	'Terre de barre'; Adja plateau, uneroded; unpublished data from RAMR Project
Zambia				Barotse sand; data
W. Province				after Brammer & Clayton
0—15 cm	1.45	4.5	7%	[1973]
15—25 cm	0.45	1.2	12%	
25—40 cm	0.37	0.8	12%	
Tanzania				Man-made soils, known as
Lake zone				'rweya' (impoverished type)
'rweya'				and 'kibanja' (enriched);
0—20 cm	1.95	5.0	19%	data after Floor et al.
50—75 cm	1.0	6.1	14%	[1990]
'kibanja'				-idem-
0—20 cm	2.10	10.0	71%	
50—75 cm	0.92	7.1	34%	

[a] According to FAO/UNESCO/ISRIC [1988]; 'Sols ferrugineux tropicaux' according to d'Hoore [1964].

[b] According to FAO/UNESCO/ISRIC [1988]; 'Sols ferralitiques à dominance rouge' according to d'Hoore [1964].

elements such as copper and molybdenum lack. Soils are, however, rich in organic matter (Table 2). Agricultural activities are found at altitudes that range from 1,100 at the lake level to 1,600 m higher up the surrounding ridges. Bananas are grown continuously on the treasured 'kibanja' fields, forming a perennial soil cover. The cropping system is further characterized by the presence of a permanent mulch layer, consisting of all non-edible parts of the banana crop and grass that is cut on open grasslands, known as 'rweya'.

The mulch layer is enriched by farm yard manure from cows that also graze the 'rweya', and all other household refuse, including the content of pit latrines [Floor et al., 1990]. In this system, necessarily, part of the soil resources undergo a gradual impoverishment. While the organic carbon contents of the soils under a 'rweya' and a 'kibanja' regime do not differ, the respective degree of saturation of the cation exchange complex does indeed; Table 2.

As conclusion to this Chapter, Table 2 summarizes a few essential fertility indicators of the soils in the areas discussed. In a number of cases, the average value of the cation exchange complex is around 3—4 meq. per 100 gram soil, the minimum level indicated to permit rational crop production, including economic use of fertilizers. Also, exchangeable cations are low, as the base saturation percentages show.

3. Common issues and constraints

From the cases presented a number of pertinent questions and observations arise, that are very important when considering priorities in Farming Systems Research and Development.

Firstly, in none of the cases it will take long to exhaust existing nutrient supplies unless losses and uptake are compensated for [cf. Pieri, 1990, p. 58; van der Pol, 1992]. These losses can be understood in terms of nutrients that leave the farm in the form of produce sold outside its boundary. In fact, increased crop sales during recent times are thought to be a key reason for diminishing levels of sustainability observed in the Tanzania case [Floor et al., 1990]. Nutrient losses also occur when agricultural products are consumed by the farming family, without returning crop residues (cf. the Tanzania case, where the latter happens scrupulously).

Other sources of nutrient losses are found in soil erosion, particularly a problem in South Mali [Hijkoop and van der Poel, 1989], and leaching. Finally, denitrification and volatilization are held responsible for losses of nitrogen [cf. Ganry, 1980].

If productivity of agroecosystems alike those of the cases given has to be sustained, and certainly when increases in crop output are required, nutrients have to be added. In other words fertilizer application is a must, in order to make cropping systems sustainable. The discussion is about quantities, chemical formulation and composition of plant nutrients and complementary cultural measures to improve efficiency of input use, not about the principle that externally produced fertilizers are needed. Some of the organic farming and agroforestry literature, deliberately or not, fails to acknowledge and sufficiently integrate this fundamental aspect.

Three out of four cases show that cattle traditionally play a role in concentrating scarce nutrients in the agroecosystem, and transporting the resource acquired to places where farmers want it. The systems developed, each adapted to local circumstances and opportunities, are in fact fairly sophisticated. E.g., in the Zambian kraaling system manure use does not suffer from obvious losses, apart from ammonia, since no transport is involved from a fixed stable to the field. Cattle is kept in moveable enclosures, directly on the fields that will be cultivated later on [Penninkhoff, 1990]. Looking at the inherent poverty of the soils in this case, one wonders whether crop production would be possible at all, without cattle as concentrators of scarce nutrients.

Probably because of such examples, cattle is usually considered as an unconditionally positive factor in fertility maintenance of farming systems. In the context of this discussion, this point of view should really be challenged. Cattle essentially cause nutrients to move faster through the agroecosystem. Consequently, there is a higher risk to lose precious nutrients. Further, if vegetation is fed to animals it can no longer play a role in physically protecting the soil, be it in the form of living leaves, as litter or as a mulch. Vegetation converted into manure no longer has that type of protective value.

In a sustainability analysis, we propose to consider domestic animals as consumers, just like human beings that live of the land, and to critically follow what really happens with the nutrients consumed.

A crucial understanding is that the soil's cation exchange capacity determines the efficiency of the use of inorganic fertilizers and manure. If the capacity of a soil to hold nutrients is too low (say CEC < 4 meq. per 100 g soil, at pH 7), and leaching is a dominant force, particularly annual crops cannot be expected to rationally use fertilizers.

This observation is particularly relevant in the context of the Zambia case. Here, we find an almost impossibly infertile soil. While it is likely that in the nearby future farmers will be forced to find a living using the Barotse sands for agricultural purposes, the question is whether it is reasonable to expect investment in agricultural research aimed at sustainable use of such poor soils. One can predict with a high degree of probability that margins for economic use of costly inputs will be small, and that the level of management required to maintain the quality of the soil will definitely be a problem for certain categories of farmers. As suggested earlier, much broader sets of solutions, including forestry and wildlife exploitation, must be considered.

Admittedly, the CEC values in the horizon below 15 cm in the Zambia case are exceptional; Table 2. However, the low values as they are found in South Mali and in degraded 'Terre de barre' in South Benin certainly are not unusual. It is a fact that CEC values in that order already are a serious constraint to agricultural productivity, and cannot be remedied like, for example, a shortage of a particular plant nutrient.

In many weathered tropical soils, with low activity clays, the maintenance of the soil organic matter is crucial, for both the nutrient exchange capacity [Sanchez, 1976; Kater et al., 1992] and soil structure [Lal, 1988]. Little factual information, however, is available about the quantity of organic matter needed seasonally to compensate for losses [cf. Young, 1986]. Also, the requirements of an important consumer group (apart from human beings and domestic animals) that depends on the vegetative biomass produced, soil life, are largely unknown and rarely consciously respected. Still, soil life is responsible for the soil's functioning as substrate to produce crops.

Developing sustainable land use would mean to answer the question what percentage of the vegetative biomass should go into feeding the soil, and afterwards to determine how the rest is distributed among man and his beasts.

However, we fear that in the lowland tropics, 'building' soils through gradual accumulation of organic matter, may be an illusion. Jenkinson and Ayanaba [1977] demonstrated that the turnover of organic matter in tropical soils may be about four times faster than under temperate conditions.

That we find high levels of organic matter in the Tanzania case may simply be caused by the fact that the farming system there operates at relatively high altitudes.

4. Conditions for sustainable land use in agriculture

4.1. *The nutrient factor*

In 1978 D. W. Norman published his well-known results on farming systems research in Nigeria [see Kowal and Kassam, 1978]. Profits for farmers regarding innovations in their farming systems were calculated. Although the approach was innovative at the time, the results told a half-truth only. While cropping system budgets (inputs, yields) for farmers were presented, the soil's contribution hidden in those profits was completely ignored, and so was in fact the question about sustainability of the crop production systems discussed.

In what is usually referred to as 'traditional' agricultural systems, nature provides a limited quantity of nutrients, an input free of charge. The origin of these nutrients is in processes like weathering of minerals, atmospheric deposition and nitrogen fixation. As long as the quantity of nutrients exported and lost is not exceeding those added by nature, agricultural production, albeit at a low level of productivity, can be sustained. This principle underlies the sustainability of long fallow systems.

At present, in many African countries, agriculture is in a transitional state, from systems essentially based on using naturally available nutrient resources, to production systems based on nutrients that are to be paid for on a market. The root cause of this transition is that with growing populations the end of free land resources (and free nutrients) has come in sight.

Where inputs for the maintenance of soil fertility (industrially produced fertilizers, but also organic sources of plant nutrients) have prices, it is erroneous to maintain the notion of agriculture as a primary production process. Similar to industrial conversion of primary inputs, a sustainably productive agriculture must deal with basic economics, such as quantification of the added value, while converting primary inputs into products. Secondly, which fraction of the added value must subsequently be reinvested into primary materials in order to maintain the production system itself. The complement can then be regarded as real net income.

This reasoning makes clear that sustainability has its price.

There is historical evidence that, during the transition from mining existing soil nutrient resources to agricultural systems based on investments in soil fertility maintenance, real net incomes necessarily are low. If one studies for example the transition of fallow-based agricultural systems to permanent systems in Flanders, North-west Europe, which took place around 1700, data reveal that farmers intensely searched for materials that could prolong the use of their fields.

Besides manure, shells, seaweed, marl, mud from city canals, bones and blood were applied as sources of nutrients in agriculture. The huge quantities required, forced farmers to invest heavily in labour and transport. At that time, over 50% of the gross margin for agricultural activities was reinvested in nutrients, and if the required labour is included in the calculations the total spending on fertilizing the land could easily surpass 60% of the farmer's income [Slicher van Bath, 1987].

The summaries of the farming systems presented earlier show that farmers in the project areas under consideration have developed their strategies to cope with declining nutrient resources, exploiting locally available opportunities: Cattle as concentrators of nutrients, returning household refuse to fields, mining the contents of pit latrines, etc. However, degradation of the physical quality of soils and nutrient depletion is a reality in all four cases.

Since sustainability of crop production systems requires a balanced nutrient budget, it is worthwhile to map nutrient flows for a particular situation.

Part of the activities of the *Agricultural Development* Department of the Royal Tropical Institute in support of FSR&D projects is to conduct nutrient balance studies with a regional perspective. For South Mali such study has recently been completed [van der Pol, 1992]. For Mono Province in South Benin a similar study is in preparation.

South Mali revisited

Nutrient balances for South Mali have been analyzed according to the model described by van der Pol [1992], based on earlier work by Frissel [1978] and Pieri [1989]. In the analysis nutrients directly available to plants and those incorporated in soil organic matter are considered. The model searches quantification of a variety of causes that lead to losses (erosion, export in produce, etc), as well as additions (dry deposit of nutrients, mineralization).

The model has been used to quantify the nutrient (N, P, K) balance for all major crops in South Mali; cotton, sorghum, pearl millet, rainfed rice, groundnut, cowpea, as well as for a fallow, that is used for extensive grazing. The research is based on crop statistics available for South Mali and extensive study of literature sources regarding nutrient behaviour in soils.

Since balances are based on estimates from literature (e.g., fertilizer use, losses through erosion, etc.) and crop statistics, data which naturally vary, three situations are actually presented: a probable value, an optimistic- and a pessimistic value for the nutrient balance (Fig. 1). Regarding nitrogen and potassium, crop production in South Mali in all cases runs a deficit. Crops like pearl millet, groundnut and rice, show deficits between 40 and 50 kg/ha/ year. The nutrient balance for cotton is less unfavourable (net losses between 10 and 20 kg/ha/year), because of fertilizer application.

The nitrogen balance for the region as a whole is negative (between 14 and 40 kg N/ha), with a probable value of about 25 kg N/ha removed from the soil's nitrogen reserve each year.

The situation is less dramatic for phosphorus. On the average, exportation is compensated: Where cotton is grown in rotation with cereals, phosphorus

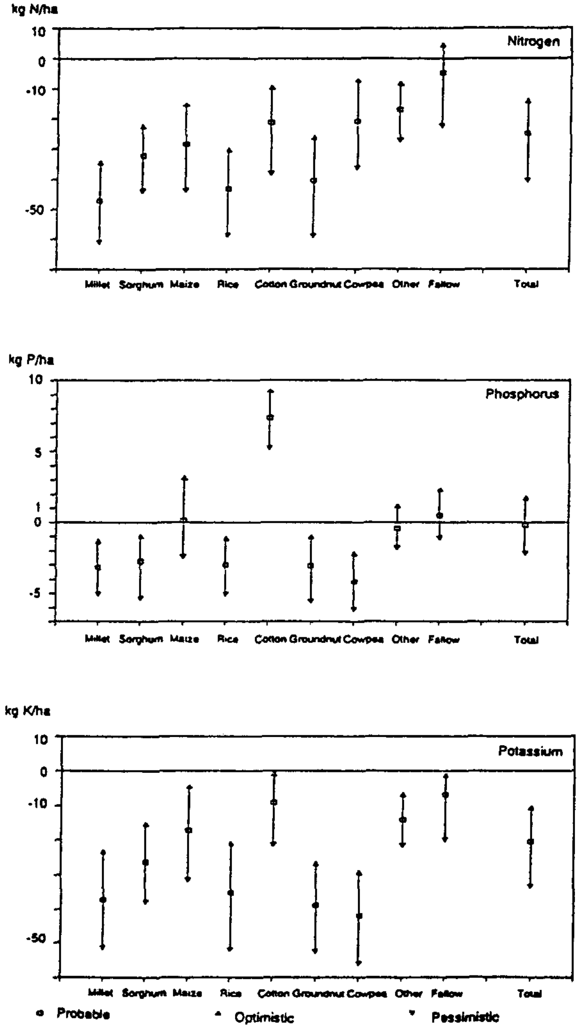


Fig. 1. Balances for individual crops for the 3 major nutrients (Source: van der Pol, 1992).

export by the latter crop is counter-balanced by the use of fertilizers in the first crop.

The potassium balance resembles that of nitrogen. About 20 kg K/ha/year (range 10 to 33 kg) is extracted. Just as for nitrogen, the depletion of nutrients largely stems from unfertilized production of cereals.

If nutrients extracted, used and lost in crop production in the major crop systems are valued against current fertilizer prices, some interesting insights result (Table 3). The Table demonstrates an important feature of South Mali agriculture. Figures show only low added values of agriculture relative to the market value of nutrients. As argued earlier, as long as nutrients can be acquired free of charge there is no problem, but if production must be based on bought inputs there certainly is one. Part of the problem is that food prices are often deliberately kept low, and since fertilizers are usually expensive, it does not really pay to use these.

But there is a second, in fact related problem as well, and that is the low efficiency of the agricultural systems in general. Roughly a third of the nutrients used during the crop production cycle is lost through soil erosion, volatilization and leaching [van der Pol, 1992, p. 18]. Losses are especially important in rainfed cereal production.

While fertilizers are inevitably part of a strategy to arrive at sustainable crop production in the tropics, its application can never be rational economically speaking, unless nutrients are used more efficiently. This means that loss prevention is the second basic condition for sustainability in agriculture.

Table 3. Sustainability of crop rotations in S. Mali.

	Rotation			
	Average S. Mali	Cotton-maize-Sorghum	groundnut 2× millet	millet-fallow
Value nutrients used FCFA/ha				
Nitrogen	14,958	20,568	20,454	11,964
Phosphorus	1,123	1,649	1,358	834
Potassium	10,344	12,445	14,665	9,391
Value nutrients in FCFA/ha	26,425	34,662	36,477	22,189
Gross income from crop(s) FCFA/ha	40,144	75,313	38,333	18,750
Added value in FCFA/ha	13,719	40,651	1,856	none
Added value as part of gross income	34%	54%	5%	negative
Reinvestment required as % of gross income	66%	46%	95%	all
Actually invested	11%	16%	15%	0

N.B. the low replacement value of phosphorus is a result of the fact that phosphorus is locally found in Mali as rock phosphate.

4.2. *Loss prevention: enhancing the agroecosystem's buffer capacity*

With respect to nutrient use efficiency cropping systems in the tropics differ. An analysis of some of the systems with an acknowledged efficiency shows us why. In irrigated rice, the water layer provides a buffer against the deteriorating influence of the climate on the soil, cultural techniques (e.g., soil puddling) limit leaching of nutrients, and, as a bonus the water layer provides living conditions of organisms that fix nitrogen. Erosion is not a significant factor in properly irrigated rice.

A second example, an oilpalm plantation, mimicks the original forest vegetation, including many of its nutrient conserving mechanisms that reduce losses [cf. Jordan, 1985; Ewel, 1986]. Here, the perennial biomass acts as buffer between soil and atmosphere. On a yearly basis, a relatively small proportion of the standing vegetation is harvested (less than 5 per cent of the total). If residues, after oil extraction, are returned to the field, nutrient export is truly limited, since pure palm oil contains mostly carbon, hydrogen and oxygen.

Rainfed annual cropping systems do not possess similar inherent protective buffers. In the tropics, removal of a perennial vegetative cover, followed by permanent cultivation, consistently results in a gradual, but clearly noticeable breakdown of the soil's potential to support life: Nutrient leaching increases, organic matter decomposition is accelerated, erosion of the topsoil by means of wind and/or water is often very visible, and soil organisms decrease in numbers, while some species even completely disappear.

All these phenomena are consequences, directly or indirectly, of the exposure of the soil to the aggressive climate found in the tropics. New equilibria do establish, but at such low levels [Pieri, 1989, p. 224] that using degraded soils for crop production is hardly rational from an economic point of view.

Is degradation of tropical upland soils, as a result of their use for annual crop production inevitable, or can we as technicians develop elements that, when put together, allow at least the maintenance of the original soil properties?

We do support the emphasis on external inputs as a key factor in sustaining increases of agricultural productivity per unit area [cf. van Keulen and Breman, 1990]. However important, nutrients are but one factor. We assume that the organic carbon cycle is equally important in maintaining and enhancing the efficiency of agricultural production systems. The rationale is simple: If a soil's cation exchange complex depends significantly on the presence of organic carbon [cf. Brams, 1971; Budelman and Zander, 1990; Kater et al., 1992], sooner or later its depletion will render economic use of fertilizers impossible. In other words, a minimum percentage of organic matter is a prerequisite for sensible use of externally acquired inputs.

Quantifying this minimum value [cf. Young, 1986], and its upward margin that can be considered realistic given ecological conditions, is an important goal of research for sustainable land use. So are practical proposals to adapt cropping systems that cater for the fresh biomass that allows sustenance of this minimum value for soil organic matter present [cf. Budelman, 1991].

A second reason to look at biomass, when addressing the issue of cropping system sustainability, is related to its role as buffer, physically protecting a fragile substrate. A number of authors stress the need for diversity and discontinuity in tropical land use for the purpose of rainfed agriculture [Margalef, 1970; Hart, 1980; Ewel, 1986]. In their view land development must be based on 'balanced mosaics' [Ewel, 1986], or rather 'honeycombs' of productive and protected areas [Margalef, 1970].

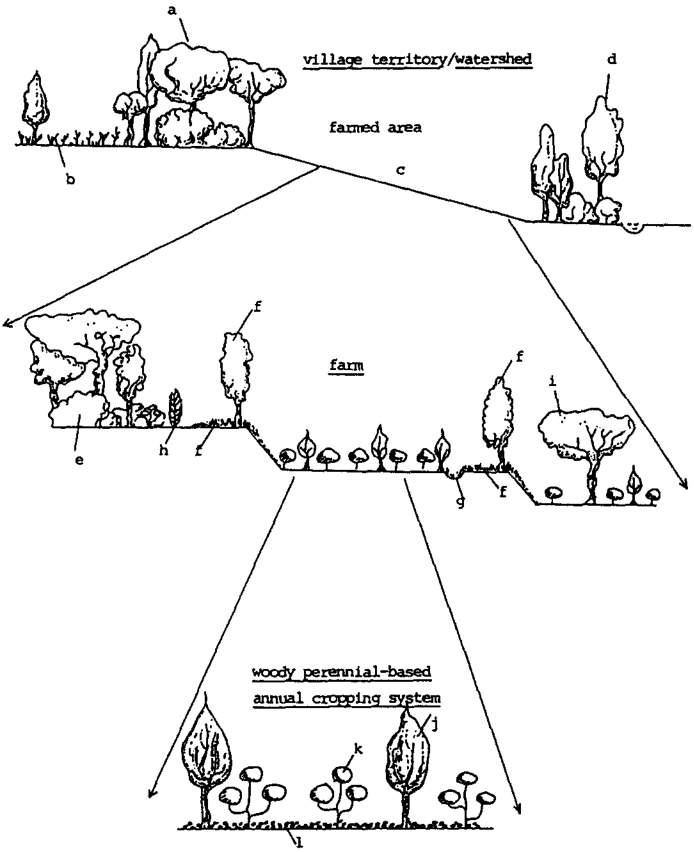
Looking at the scale of a watershed or a village territory, hilltops are particularly sensitive landscape elements that need protection. Soils at the top of the toposequence are often shallow and chemically poor, and should be left under natural vegetation as buffer to regulate an area's hydrology, rather than being cultivated with meagre results because of poverty of the soil. Similar considerations play a role in conserving forest strips along water courses (Fig. 2). At lower levels of integration (farm, field, cropping system) a similar mix of productive and protective elements and cultural practices can be conceived as well (Fig. 2 and Table 1). For experiences with a wide-ranging collection of protective techniques, see Rochette [1989].

A fair number of these cultural practices can be grouped under the heading 'agroforestry', these days a popular domain to search for solutions [cf. Steppler and Nair, 1987]. A word of warning, however, is useful. There is growing awareness that the potential of agroforestry to contribute to sustainable land use has been overemphasized in the past, particularly where it concerns drier areas [Kessler and Breman, 1991].

Sanchez [1987] already has pointed at the fact that descriptions of the well-known success stories (cf. Felker [1978] on *Faidherbia albida* (syn. *Acacia albida*)) contain few or no studies at all in which soil fertility was measured before and after planting of the trees. One should raise the question whether higher levels of soil fertility found under trees are not the result of the tree's biased distribution towards more fertile areas. Also, higher levels of soil fertility under trees may be the result of a redistribution over time of the limited nutrient resources available, at the expense of treeless sites, as suggested by Kessler and Breman [1991].

It is quite clear that the role of trees in soil improvement, expressed for example in higher organic matter content, is limited [Kater et al., 1992]. It takes years of accumulation, and only a few seasons to lose it, when soils are improperly managed. The same holds in principle for the nutrients accumulated under trees. Lastly, while well-managed agroforestry systems in the humid tropics, such as alley-cropping, may be advantageous to raise and sustain productivity of main crops [Kang et al., 1984; Budelman, 1991], competition from the trees may be too severe under drier circumstances [Kater et al., 1992; Kessler, 1992] (Table 4).

Our understanding is that agroforestry has a potential to enhance nutrient



a. **communally managed forest on hilltop** (land use in function of toposequence properties; cf. Vierich and Stoop, 1990; Figure 2)
b. **communally managed grazing area**
c. **arable land**
d. **gallery forest protecting water course**
e. **strip of original vegetation separating farms**
f. **grass-strip with planted/conserved woody species to stimulate natural terrace-formation** (cf. Roose, 1986)
g. **grass-covered stormdrain** (cf. Hijkoop et al., 1991: p.46, 50)
h. **live fence inhibiting animals from uncontrolled trespassing**
i. **single tree** (cf. Kessler, 1992; Kater et al., 1992)
j. **auxilairy perennial species that produces mulch and soil-cover during off-season period** (cf. Budelman, 1991)
k. **annual crop**
l. **mulch/litter layer made of plant material with a high C:N ratio** (as a rule mulches from N-fixing woody species disappear faster than that they are produced, cf. Budelman, 1991: p.28. Litter is more important in preventing sheet erosion than the vegetation itself, cf. Wiersum, 1985)

Fig. 2. Elements in landscape buffer capacity at three levels in a farming system (source: adapted after Budelman and Huijsman, 1991).

use efficiency of agricultural production systems. On its own terms, however, integrating perennial species does not guarantee sustainable land use. Instead of looking at agroforestry as a 'no-input' strategy (unfortunately sometimes sold as an option that could be sustained), we propose to consider agroforestry principles as a basis to develop systems that use nutrients efficiently, including the option to rationally apply high fertilizer dosages [cf. van der Pol, 1985].

Table 4. Estimated yield reduction in three crops as function of two tree species present on farmers' fields, South Mali.

Crop	Vitellaria paradoxa	Parkia biglobosa
Cotton	2%	65%
Sorghum	44%	66%
Millet	60%	60%

Source: Kater et al., 1992.

Figure 2 gives a number of practices and policies at different levels of integration, that are all meant to increase the buffer capacity of an agroecosystem, thereby improving the system's capacity to retain nutrients and to protect its basic resources (soil and vegetation). The essential idea behind the measures is to move away from open plant production systems, exemplified strongest in seasonal sole-cropping strategies, to systems that are less discontinuous in time, and more so in space, hence better adapted to the peculiar ecosystems and climates found in the tropics.

In this respect, every measure that improves soil cover and its continuity is an option worth considering. The problem is, however, that resource protection at every level (community, farm, crop system) demands a price in the form of labour, space, sometimes capital, and of energy spent in community organization. Such resources are scarce, and as a consequence, implementing improved land management based on local resources demands a long and arduous process [cf. van Campen, 1991]. Moreover, results of protective action do seldom directly translate into increases of agricultural productivity.

After all, proposals aimed at maintaining the resource base to guarantee future generations a living are difficult to sell to those farmers who are hard pressed to make ends meet on a season to season basis.

5. Conclusion

In the context of the discussion concerning the transition of sub-Saharan African small farmer agriculture, we basically tried to address the small margins in any current set of solutions. Aspects touched upon are the notoriously low CEC of certain important categories of upland soils, their chemical poverty and fragile structure, the ruinous effects of the climate on soils once vegetation is removed, but also the observation that current price policies in fact prohibit farmers to cultivate sustainably, even if they want to. The nature of the cropping systems applied, so we conclude, is part of the problem of non-sustainability: When they are seasonal, when sole-cropping is practised, and when a product is acquired that pays too little to afford a fertilizer, whatever its origin. Especially annual foodcrop cultivation is difficult to make sustainable, in case the traditional long rest period can no longer be respected.

If these observations are correct, in the long run, the policy of self-sufficiency in food production, so often pursued as a national priority, spells in fact ecological disaster. There lies an important role for agronomists and soil scientists, to further substantiate this message and to pass it on to policy-makers in agriculture. It must become clear that, while technologies are available that may enhance sustainability of land use, the first and most important step towards a solution will be the structural widening of economic margins in tropical agriculture.

It surely is counter-productive to wait and believe that new technologies will eventually emerge, that will effectively address the problem discussed. In that context the gradual demystification of agroforestry as the cure for all problems concerning resource use in agriculture is most welcome.

Improved efficiency of production systems, technically, must come from differentiated use of natural resources. We suggest to pay attention to locally appropriate mixtures of productive and protective elements in land use planning and implementation; see Fig. 2. However, after Young's challenging statement of the problem in 1986, judging from literature, little concrete progress seems to have been made in this particular domain.

The idea that differences in soil type must be translated into differences in use, nicely fits the approach currently developed in South Mali to take the analysis of the toposequence as point of departure in land use planning and advice at farm level. Merging farmers' knowledge and interpretation of the productive value of the various soil types along the toposequence on the one hand, and soil analytical data on the other, opens the possibility to improve the relevance to users of soil mapping in land use planning. This is a very concrete opportunity where soil scientists can be of great help to FSR&D, and in fact, can provide the much wanted base to properly root strategy development for sustainable natural resource use.

A third principle, that will be fundamental in strategy development, is to create recommendations for fertilizer application that differentiate according to soil, climate and production system. The practice of blanket fertilizer recommendations is one of the reasons of inefficiency in nutrient use.

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