Use of mineral and organic inputs to increase land productivity and sustainability with special reference to the drylands of west Africa

Bationo A., Vanlauwe B., Kihara J., Kimetu J., Tabo R., Koala S. and A. Adamou
Corresponding author: Bationo Andre
TSBF-CIAT, P.O Box 30667, Nairobi, Kenya 00100.

Summary

Poor soil fertility status is the main problem hampering food sufficiency in Africa. Nutrient balances are reported to be largely negative indicating nutrient mining. Low productivity of agriculture is related to the low quality of the soil resource base due to inherent or induced deficiencies of major nutrients N, P, and K or low nutrient holding capacities, high acidity, low organic matter and low use of external inputs. Low soil fertility is also driven by socio-economic factors, which include macro-economic policies, unfavorable exchange rates, poor producer prices, high inflation, poor infrastructure and lack of markets.

Scientists across Africa have evaluated the potential of different technologies in addressing the soil fertility problem. Research results have reported that yields can be increased three to five times with the improvement of soil fertility with organic and inorganic fertilizers. The combinations also improve an array of soil properties such as Organic carbon content, Cation Exchange Capacity (CEC) and pH. The main constraint to combining inorganic-organic is the high costs of inorganic fertilizers and the low availability of organic fertilizers at the farm level.

Crop rotation and intercropping systems are especially important in nutrient and yield improvement as compared to continuous practices. Rotation systems increase nitrogen derived from the soil and fertilizer use efficiency. Similarly, methods of application of organic and inorganic fertilizer sources enhance use efficiency. While hill placement of inorganic

Paper presented at CTA Wageningen, 2003

fertilizers and manure is superior to broadcasting, incorporation of organic amendments such as agroforestry materials is superior to surface placement.

This paper introduces the ISFM approach before presenting highlights of recent research findings and challenges.

1.0 Introduction

Per capita food production in Africa has been declining over the past two decades, contrary to the global trend resulting in widespread malnutrition, a recurrent need for emergency food supply and an increasing dependence on food grown outside the region. The latest figures show that 28% of Africa population is chronically hungry. The average annual increase of cereal yield in Africa is only about 10 kg ha^{-1}, the rate known as the one for extensive agriculture neglecting external inputs. The growth rate for cereal grain yield is about 1% while population growth is about 3%. Although large areas of forests, wetlands, river valley bottoms and grassland savanna have been put under food crops, the food gap (requirements minus production) keeps widening. Agriculture-led development is fundamental to cutting off hunger, reducing poverty, generating economic growth, reducing burden of food imports and opening the way to an expansion of exports.

Land degradation, one of the most serious threats to food production in Africa often indicated by unsustainable production systems, nutrient mining and declined agricultural production is related to population growth and is closely associated with vicious poverty cycle. Poverty in sub-Saharan Africa (SSA) for example, is a rural phenomenon since rural poor comprise 85% of all poor. Rural poverty rate is itself 60% in a region where rural population is 69% of total population. Poverty rates vary across the landscape and this has implications on technology interventions adoption.

Low soil fertility, which is a major bottleneck to increased productivity in Africa, is a factor of biophysical and socio-economic aspects (**Figure** 1) and is itself a large contributor to poverty and food insecurity. Low productivity of agriculture is related to the low quality of the soil resource base which on one hand has been due to inherent or induced deficiencies of major nutrients N, P, and K or low nutrient holding capacities, high acidity, low organic matter and low use of fertilizers. For example, Ferralsol (oxisols) and lixosols which cover 30 and 24% of total area respectively lead to the problems of aluminium and manganese toxicity as well as increased susceptibility to crusting. Other constraints include low capacity for nutrient and water retention (acrisols and arenosols), high P fixation (nitisols) and high erodability and flooding (vertisols). On the other hand low soil fertility is driven by socio-economic factors, which include macro-economic policies, unfavorable exchange rates, poor producer prices, high inflation, poor infrastructure and lack of markets. These multiple causes of low soil fertility are strongly inter-related and the interaction between biophysical and socio economic factors call for an holistic approach in ameliorating the soil fertility constraints in sub-Saharan Africa (Murwira, 2003).

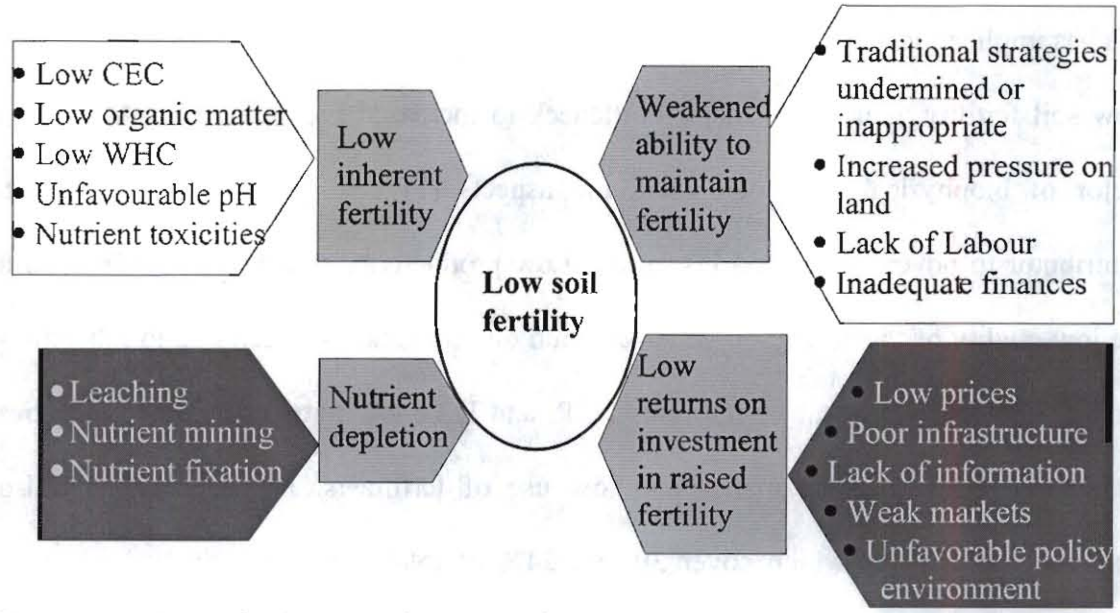

Figure 1: Biophysical and socio-economic factors contributing to low soil fertility in Africa

Approximately 65% (121 million hectares) of Africa's total land (187 million hectares) is degraded. Rates of nutrient depletion are particularly high in areas with favourable climates for crop production and high population densities. There is also high macronutrient loss as compared to application with many cropping systems reporting negative nutrient balances. For example, whereas 4.4 million tonnes of nitrogen per year are removed, only 0,8 million tonnes per year are applied, hence production takes place at the expense of the soil natural capital. **Table** 1 shows percentage decreases in soil fertility after 50 years in farmers' fields in the savanna zone of Nigeria following continuous cultivation. Other problems relate to nutrient losses through high water and wind soil losses from agricultural systems. Soil loss through erosion is estimated to be 10 times greater than the rate of natural formation.

Table 1. Percentage decreases in soil fertility after 50 years in farmers' fields under continuous cultivation in the savanna zone of Nigeria

Zones	Ca	Mg	K	pH
Sudan	21	32	25	4
Northern Guinea	19	27	33	4
Southern Guinea	46	51	50	10

Despite diversity of approaches and solutions and the investment of time and resources by a wide range of institutions, soil fertility degradation continues to prove to be a substantially intransigent problem, and as the single most important constraint to food security in the continent (Sanchez, 1994).

Integrated soil fertility management (ISFM) is now regarded as a strategy that helps low resource endowed farmers mitigate many problems and the characteristics of poverty and food insecurity by improving the quantity and quality of food, income and resilience of soil productive capacity. This paper presents the ISFM approach and discusses recent research highlights on soil fertility restoration.

2.0 The ISFM Paradigm

The period 1960 to the present has seen shifts in beliefs guiding food production. During the 1960s and 1970s, an external input paradigm was driving the research and development agenda and appropriate use of external inputs was believed to be able to alleviate any constraint to crop production. Following the resulting environmental degradation due to massive fertilizer and pesticide use (Theng, 1991) and the abolition of the fertilizer subsidies in SSA (Smaling, 1993), the balance shifted from mineral inputs only to Low Input Sustainable Agriculture (LISA) between mid 1980's and early 1990's where organic resources were believed to enable sustainable agricultural production.

Technical and socio-economic constraints of LISA technologies lead to a focus on biological processes aimed at adapting germplasm to adverse soil conditions, enhancing soil biological activity and optimising nutrient cycling to minimize external inputs and maximize the efficiency of their use (Sanchez, 1994).

The formulation of 'synchrony' and 'SOM' themes (Swift, 1984, 1985, and 1986) between 1984 and 1986, stressed the role of OM in the formation of functional SOM fractions, which gave way to projects related to residue quality and N release patterns. Following this work, recommendations for appropriate use of organic materials, based on their N, polyphenol, and lignin contents resulting in four categories of materials (**Figure 2**) have been generated. Organic resources are seen as complimentary inputs to mineral fertilizers and their potential role has consequently been broadened from a short term source of N to a wide array of benefits both in the short and long term (Vanlauwe et al., 2002).

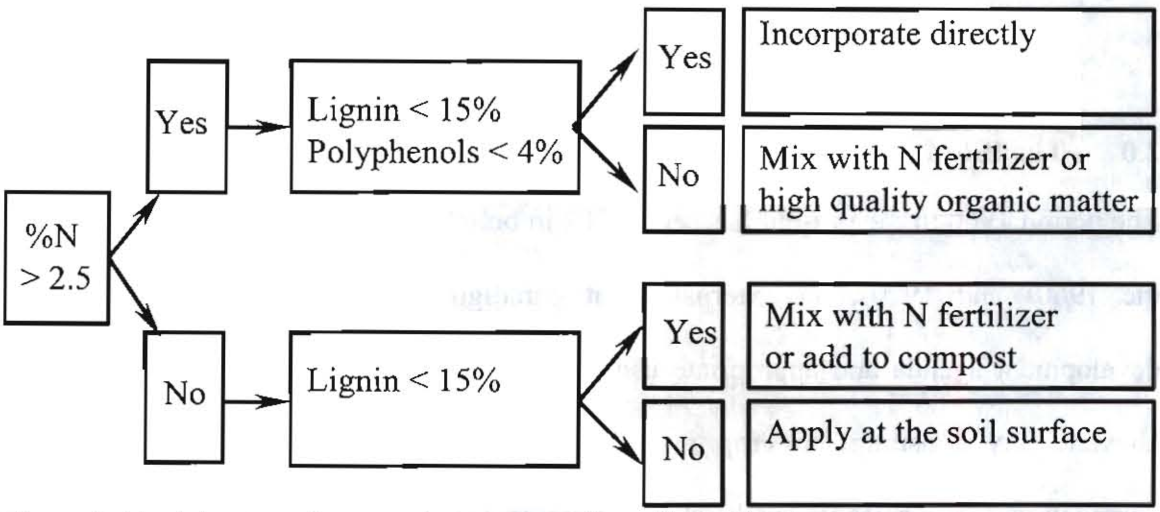

Figure 2: Decision tree for organic resources for soil fertility improvement

Recently, TSBF adopted the Integrated Soil Fertility Management (ISFM) paradigm that forms an integral part of the Integrated Natural Resource Management (INRM) research approach with a focus on appropriate management of the soil resource (**Figure** 3). The

ISFM is an holistic approach to research on soil fertility that embraces the full range of driving factors and consequences- biological, physical, chemical, social, economic and political. Thus, soil fertility can no longer be regarded as a simple mechanism addressed by the issue of organic and inorganic nutrient sources.

The contribution of markets and marketing is also becoming an integral part of the research and development process integrated through participatory market research (PMR). PMR is based on the belief that when market problems are addressed, not only will farmers earn more and improve their livelihoods, but that they will also invest in soil fertility improvement/restoration technologies.

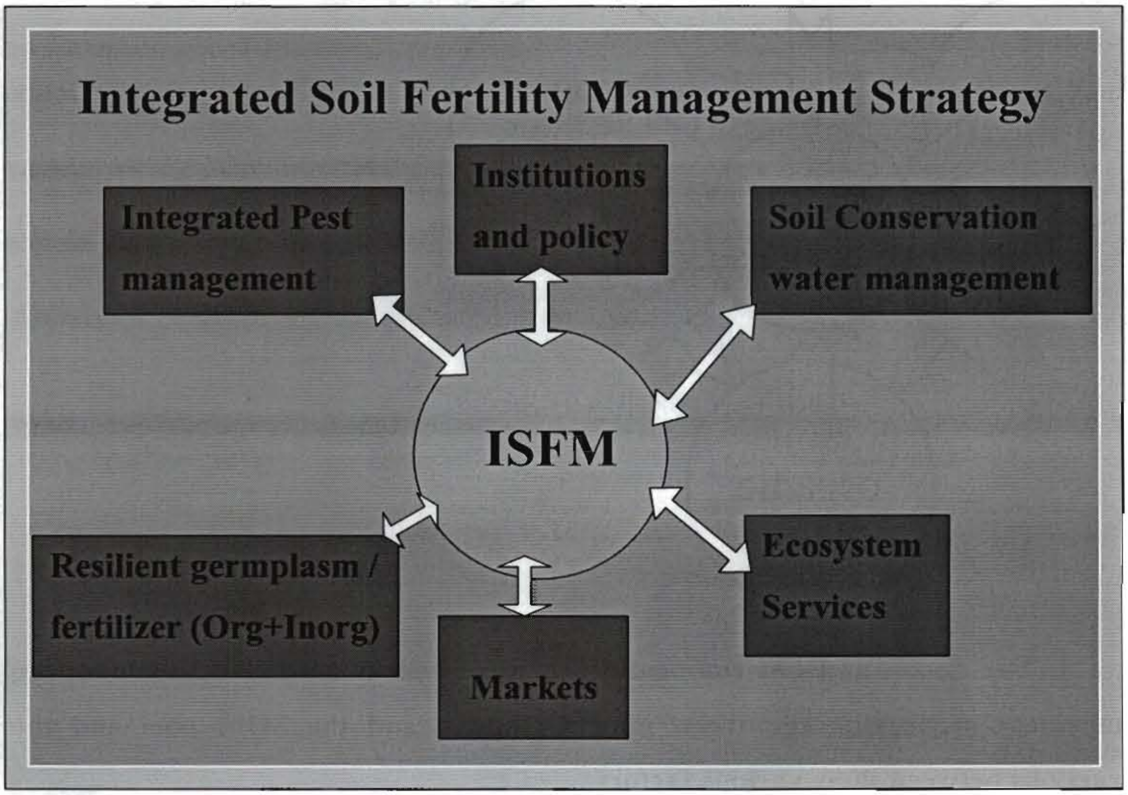

Figure 3: Integrated Soil Fertility Management entry points with wider natural management concerns

ISFMs' technical backbone lies in the optimal management of organic resources, mineral inputs, and the soil organic matter pool **(Figure 4)**. Each of these resources contributes to the provision of goods and services individually, but can also interact with each other to generate added benefits in terms of extra crop yield, an improved soil fertility status, and/or reduced losses of nutrients to the environment (Vanlauwe et al. 2003). ISFM is also broader than Integrated Nutrient Management (INM), recognizing the need of an appropriate physical and chemical environment for plants to grow optimally, besides a sufficient and timely supply of available nutrients.

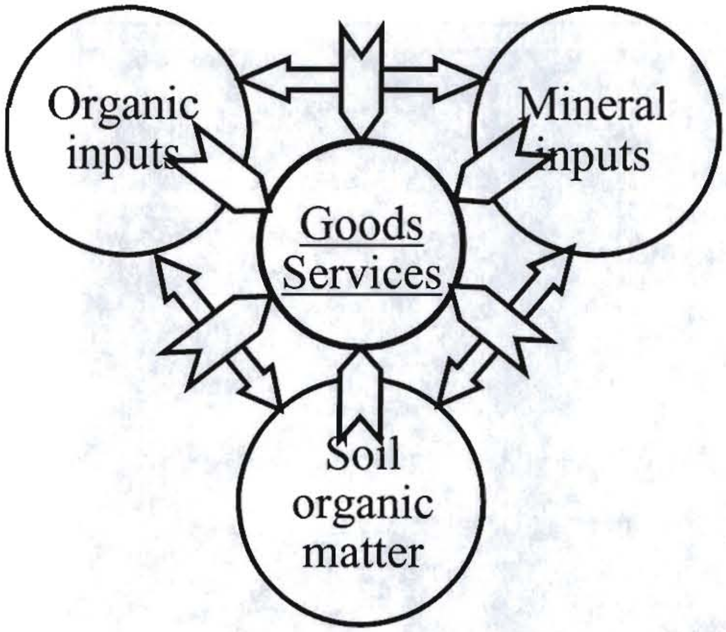

Figure 4. The goods and environmental services generated by the soil following management of organic resources, mineral inputs, and the SOM pool and the interactions between these various factors

In general, long-term soil fertility management strategy requires an evolutionary and innovative, knowledge- intensive process and participatory research and development focus rather than a purely technical focus (Vanlauwe et al. 2003). Recent trend to make

ISFM a knowledge intensive approach is by integrating local and scientific knowledge through the development of Participatory Learning and Action Research (PLAR) for ISFM, as a process to help farmers to improve their soil fertility management strategies (Baltissen et al. 2000, Kimani et al. 2003) through self problem diagnosis, planning, implementation and evaluating alternatives thereby enabling farmers to discover and experiment with new SFM practices on a step-by-step basis, promoting joint learning between farmers and facilitating demand-driven extension (Kimani et al. 2003).

Among success stories in the adoption of multiple purpose options that are embraced by ISFM in parts of SSA include the practices of intercropping and integration of multiple purpose legumes (green manure, cover crops and herbaceous, tree, forage/fodder and grain/food legumes); manure use by low resource endowed farmers; and the emerging spread of improved fallows and biomass transfer, especially of high quality organic inputs; use of regionally and locally available inorganic sources of plant nutrients and amendments (e.g. rock phosphates, limestones, etc.). Another option entails the use of high-efficiency fertilizers on high value crops as opposed to their application to less responsive indigenous crop varieties or cropping systems (Kimani et al. 2003).

The current concern within ISFM is need for integration of socio-economic and policy research to identify factors that may inhibit or favour adoption of more sustainable land management practices, a neglected area of soil fertility research. Other new dimension in the ISFM approach is the focus on farm scale recommendations within farm variability instead of plot scale-base recommendations, up-scaling of strategies beyond village boundaries, and focus on ISFM instead of INM.

3.0 Recent research highlights

Several studies on ISFM components have reported important conclusions indicating potential to improve yield and farmers' income. This section presents results of organic inputs and mineral fertilizer applications both as sole applications and combinations and different application methods as observed from these investigations. It also presents a case-by-case analysis of different cropping systems as well as some economic evaluation in the farmers' fields.

3.1 ISFM for crop production

3.1.1 Effects of manure and crop residues on soil productivity

Manure can substantially enhance crop yields. Powell et Al. (1998) found a very significant effect of manure and urine application on pearl millet in the Sahelian zone. In another experiment in Niger, both dung and urine increased yields by between 80 and 200% above those of cattle dung only at various application rates (**Table** 2).

Table 2. Effect of cattle dung and urine on millet grain and total above ground biomass, Sadore, Niger

Cattle Dung	**+ Urine**		**- Urine**	
Application	Grain	Biomass	Grain	Biomass
0	-	-	80	940
2990	580	4170	320	2170
6080	1150	7030	470	3850
7360	1710	9290	560	3770
S.E.M	175	812	109	496

The contribution of manure in crop productivity from a long-term experiment is shown in **Figure 5**. Continued application of manure lead to annual increase in yield as opposed to lone application of fertilizer and the control both of which recorded annual yield reductions.

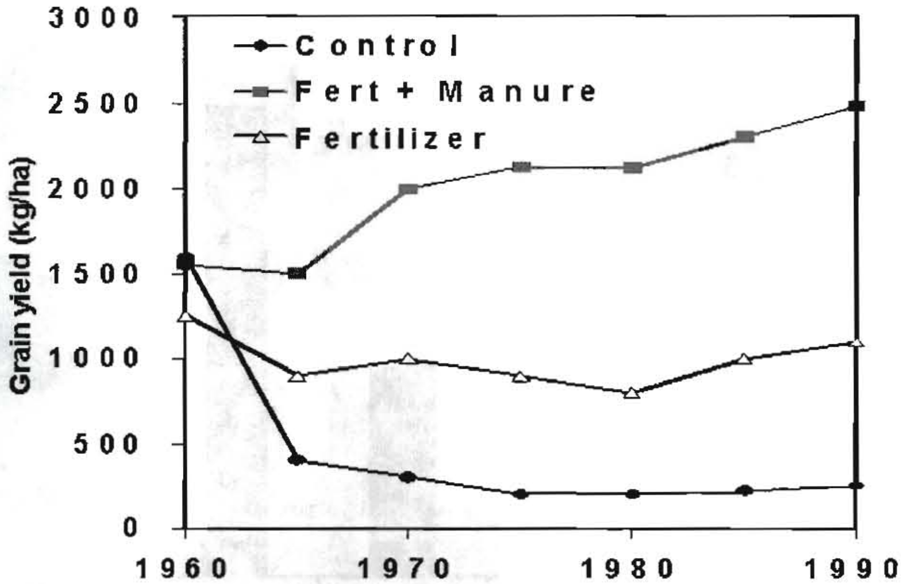

Figure 5. Sorghum grain yield as affected by fertilizer and manure over time

Application of low quality manures in Mali, Burkina and Nigeria reported insignificant but additive increases in yield indicating that these manures contributed little to the N demand for the crops. However, these low quality manures can contribute significantly to overcome P deficiency to maize crop as shown in **Figure** 6. The potential of manure to maintain organic carbon levels and sustain crop production is limited by the number of animals available and the size and quality of the rangeland. In general 10 to 40 ha of dry season grazing land and 3 to 10 of rangeland of wet season grazing to maintain yields on one hectare of cropland. Potential livestock transfer of nutrients in West Africa is 2.5 kg N and 0.6 kg P per hectare of cropland.

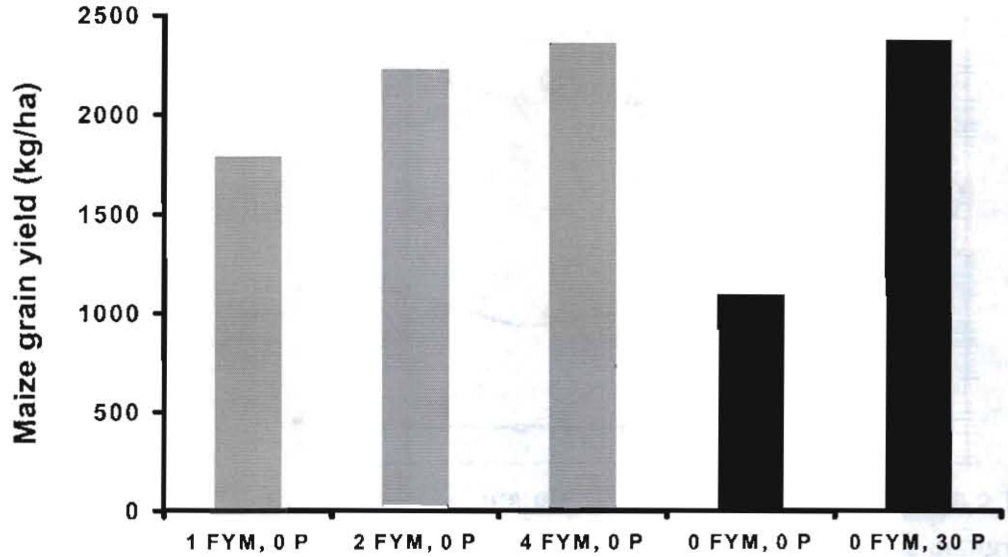

Figure 6. Use of low quality manure (<1%N) to alleviate P deficiency in maize crops in Zaria, Nigeria, 2001

Crop residues also have significant role in increasing productivity. Crop residue alone resulted to the same quantity of total dry matter (TDM) as that with fertilizer alone (**Figure 7**). However, TDM yield was greatly improved when application of fertilizer was combined with crop residue in this long-term crop residue management trial in the Sahel.

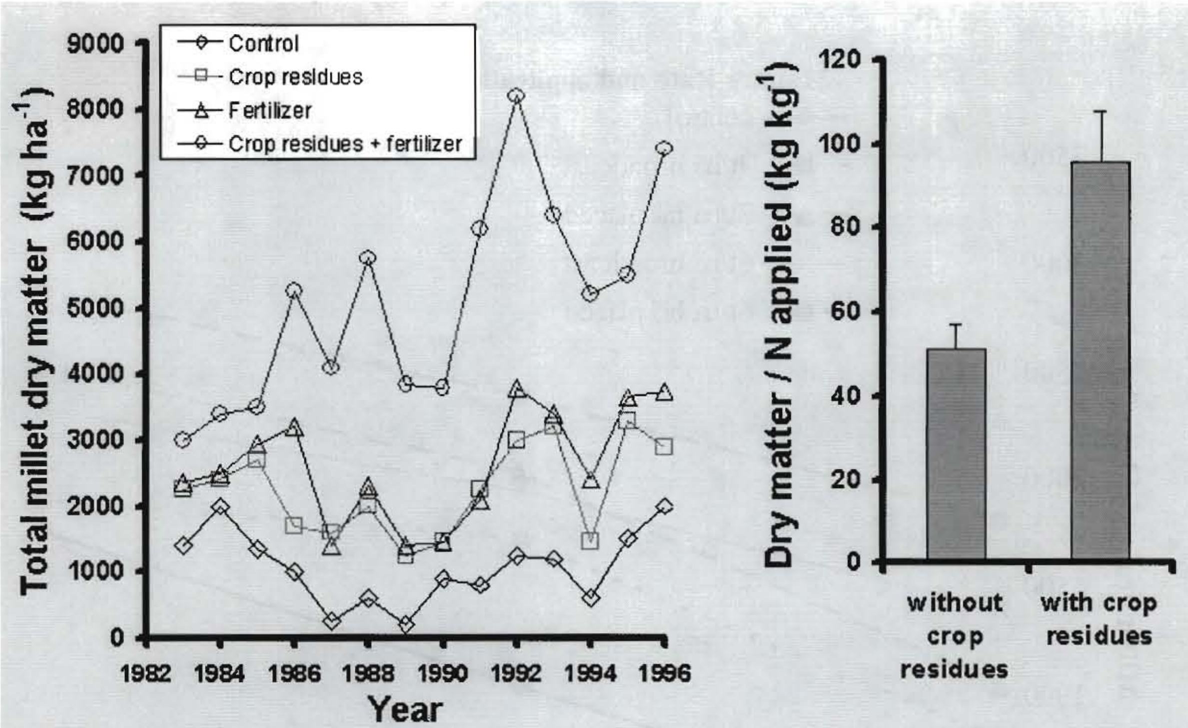

Figure 7. Total millet dry matter yield as affected by long-term application of crop residues and fertilizer, Sadore, Niger.

3.1.2 Placement of organic and inorganic fertilizer sources

Methods of application of organic and inorganic fertilizer sources affect fertilizer use efficiency. In a complete factorial experiment carried out in Niger, West Africa, with three levels of manure (0, 3, 6t ha^{-1}) and three levels of P (0, 6.5 and 13 kg P ha^{-1}) using pearl millet, hill placement of manure performed better than broadcasting and with no application of P fertilizer. Broadcasting 3 t ha^{-1} of manure resulted on pearl millet grain yield of 700 kg ha^{-1} whereas the point placement of the same quantity of manure gave about 1000 kg ha^{-1} (**Figure** 8). A similar effect was observed using cowpea.

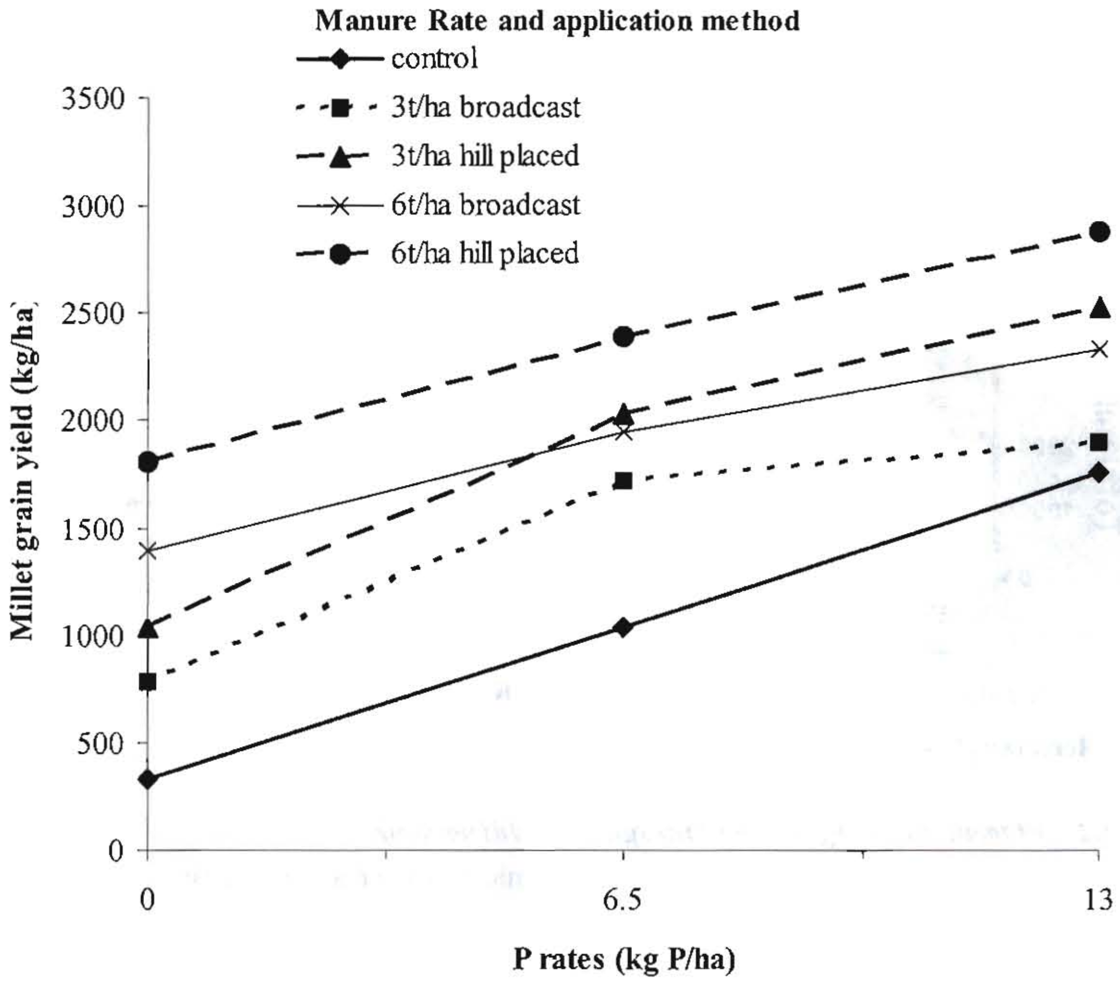

Figure 8: Millet grain yield response to P and manure applied at different rates and methods, Karabedji, Niger, 2002 rainy season

Hill placement of small quantities (3-5kg ha^{-1}) of P has shown the highest use efficiency with the efficiency decreasing with increasing quantity of P (**Table** 3). Whereas P use efficiency in 1995 was 111kg grain kg^{-1} P with the hill placement of 3kgP ha^{-1}, the P use efficiency was only 47kg grain kg^{-1} P when 13kgP ha^{-1} was broadcast.

Table 3. Effects of P sources and application method on millet grain yield (kg ha^{-1}) and PUE (kg grain kg^{-1} P applied)

	1995		1996	
P applied (kg P ha^{-1})	**Yield**	**PUE**	**Yield**	**PUE**
0	532	-	641	-
13 (BC)	1138	47	1240	46
3 (HP)	864	111	846	68
5 (HP)	937	81	996	71
7 (HP)	1018	69	1074	62
13 (BC)+ 3 (HP)	1382	53	1279	40
13 (BC)+5 (HP)	1425	50	1295	36
SE	92		89	

BC- broadcasting, HP= Hill placement

In a follow-up experiment, addition of Tahoua Phosphate rock (TPR) and crop residue (CR) further increased yield. Yield can be substantially increased when both TPR and CR are added in combination with small amounts of inorganic P in hill placement (**Table 4**). In field trials at Karabedji from 1998 to 2002, research was conducted to assess the nutrient use efficiency on degraded and non-degraded land. Nitrogen use efficiency increased from 8.6 kg grain kg^{-1} N in the degraded land to 15.3 kg grain kg^{-1} N in the non-degraded land indicating that farmers are better to apply the fertilizer to homestead non-degraded fields than to the degraded bush field.

Table 4. Effect of hill placement of Phosphorus, Tahoua Phosphate rock and crop residue on yield

Phosphate rock is available from several deposits within Africa (**Figure 9**) and their use can greatly improve production.

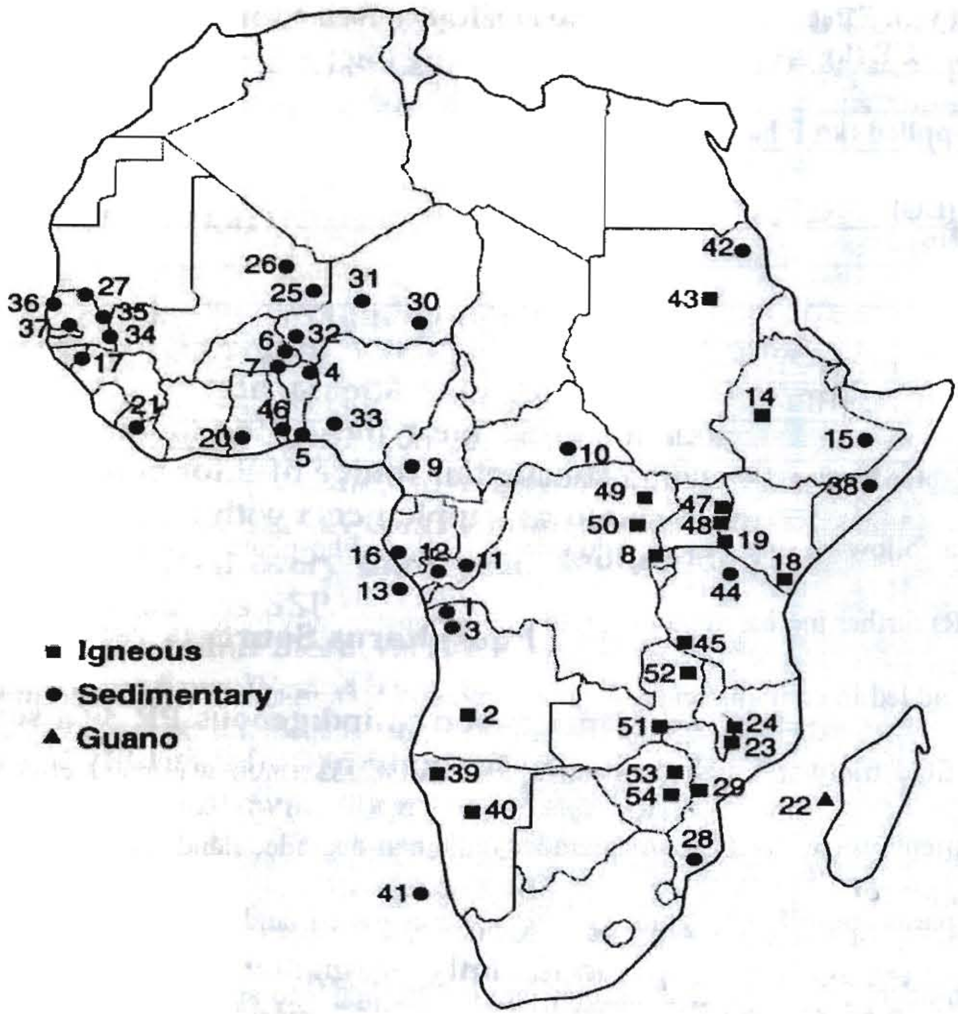

Figure 9. Phosphate rock deposits in SSA

Source: McClellan & Notholt 1986; P. van Straeten 1997

Rock phosphate can be applied either directly or in its acidulated form. The data in **Table** 5 clearly indicated that the agronomic effectiveness of Parc-W phosphate rock is about 40% as compared to water-soluble phosphorus whereas the high reactive Tahoua Phosphate rock can be upto 80%.

Table 5. Relative agronomic effectiveness (%) of P sources at Gobery (Niger)

P sources	1985	1986	1987
Tahoua Phospahte Rock (TPR)	82	67	76
TPR partially acidulated at 50%	46	36	46
Parc W Phophate Rock (PPR)	43	41	46
PPR partially acidulated at 50%	69	65	68
TSP	87	91	93
SSP	100	100	100

Regardless of the method of application, N and P use efficiency is further depended on the site. Higher use efficiency is observed on non-degraded as compared to degraded sites (**Table** 6).

Table 6. Use efficiency of N and P in degraded and non-degraded sites at Karabedji, Niger 1998-2002.

Fertilizer	Site condition	Nutrient Use Efficiency (%)
Nitrogen N at 60	Degraded	8.6
	Non-degraded	15.3
Phosphorus P at 30	Degraded	50
	Non-degraded	58

Use of leguminous crops in the previous season improves the availability of P from phosphate rock. Vanlauwe et al. (2000a) found both *Lablab purpureus* and *Mucuna pruriens* to increase the status of Olsen P and N concentration in particulate organic matter pool after addition of phosphate rock. Their effects were site and species-specific increases in grain, total N and total P uptake of a subsequent maize crop due to improvement in soil P status (Vanlauwe et al., 2000b). These increases were highest for mucuna than lablab although the effect depended on the initial Olsen-P content

3.1.3 Combining organic and inorganic plant nutrients in production

As already shown in **Figure 5 and Figure** 7, manure and crop residue combined with inorganic fertilizers have a significant contribution to yield increase and sustainability even in the long run. Combined application of organic resources and mineral inputs forms the technical backbone of the Integrated Soil Fertility Management approach. The data in **Table** 7 clearly indicate the comparative advantage to combine organic and inorganic plant nutrients for the low suffering soils in the Sahel. Combination of both organic and inorganic P and N sources achieved more yield as compared to inorganic sources alone. In 2002, application of 6 t ha^{-1} of manure plus 3 kg P ha^{-1} of inorganic fertilizer resulted in cowpea fodder yield of 4625 kg ha^{-1} as compared to 3156 kg ha^{-1} with the application of mineral fertilizer alone.

Table 7: Optimum combination of plant nutrients for cowpea fodder yield (kg ha^{-1}), Gaya, Niger

Treatments	Yield, 2001	Yield, 2002
Absolute Control	1875	2406
30 kg N ha^{-1}	2531	2625
12 kg P ha^{-1}	3781	3281
8 tons manure + 30 kg N ha^{-1}	5718	3531
6T manure + 3kg P + 30 kg N	4843	4625
4T manure + 6 kg P + 30 kg N	4656	3625
2T manure + 8 kg P + 30 kg N	4281	3375
12 kg P + 30 kg N	5000	3156
SE	204	200
CV	14%	12%

The advantage of combining organic and inorganic nutrients is explained by base saturation and pH (water) for soil experiments in Saria, Burkina Faso where Pichot et al (1981) found chemical fertilizer to acidify the soil and reduce base saturation from 0.63 to 0.37 whereas crop residues application at 5t ha^{-1} actually increased the base saturation to 7.0 and maintained the same pH level.

Vanlauwe et al (2001) observed that interactions between organic inputs and urea resulted in added benefits from their mixed rather than sole applications. Maise in the mixed treatments, receiving 45kg ha-1 urea N and 45kg ha-1 N as organic inputs, produced 1.6 and 3.7 Mg ha-1 grain in Sekou and Glidji, respectively. Based on the yields from sole application of either organic inputs or urea, added benefits from the mixture were 0.49 Mg ha-1 grain ($p<0.001$) in Sekou and 0.58 Mg ha-1 ($P<0.15$) in Glidji. These benefits were generated during drought prevalent grain filling stage due to likely improved soil water conditions due to mixed applications as compared to sole applications.

Superior results following combination of crop residues and inorganic fertilizer have also been reported from a long-term soil fertility management experiment established by ICRISAT Sahelian Center in 1986 to study the sustainability of pearl millet based cropping systems in relation to management of N, P, and crop residue, rotation of cereal with cowpea and soil tillage (**Table** 8). Whereas in this long-term trail millet grain yield was 118 kg ha^{-1} in the traditional practices over the 5 years, average yields of 1301 kg ha^{-1} was obtained in the improved system where P was applied with crop residue and nitrogen in cowpea/pearl millet rotation system.

Table 8: Effect of fertilizer, crop residue, tillage and rotation on pearl millet grain yield, Sadore (kg ha^{-1}), Niger 1998-2002

Main treatments in the operational scale	-CR-N	*-CR+N*	+CR-N	+CR+N
	MG	*MT*	CG	CF
1= Traditional practices	118	177	197	295
2= Animal traction (AT) +no rotation +Intercropping + P	463	567	596	736
3= Animal traction (AT) + rotation +Intercropping + P	777	923	939	1107
4= Hand Cultivation (HC) +no rotation +Intercropping + P	389	596	627	768
5= Hand Cultivation (HC) + rotation +Intercropping + P	769	868	981	1104
6= Animal traction (AT) +no rotation +Pure millet + P	484	646	626	846
7= Animal traction (AT) + rotation + Pure millet + P	802	957	1033	1141
8= Hand Cultivation (HC) +no rotation + Pure millet + P	526	785	708	1065
9= Hand Cultivation (HC) + rotation + Pure millet + P	818	1030	1135	1301
SE	43	43	43	43
CV	27%	27%	27%	27%

Numbers in italic are sole cowpea yield in rotation.

3.1.4 Fertilizer equivalencies

Studies have attempted to find out the optimal combinations of organic and inorganic nutrient sources. Evaluation of organic incorporation of Tithonia and sesbania in Zambia, Tanzania and Kenya (**Figure** 10). At Kabete yield increases over the control with combination of 50% organic and 50% inorganic was 190% whereas with the application of 100% inorganic fertilizer, yield increase over the control was only 40%. With sesbania in Zambia, there was no difference between the treatments (**Figure** 10).

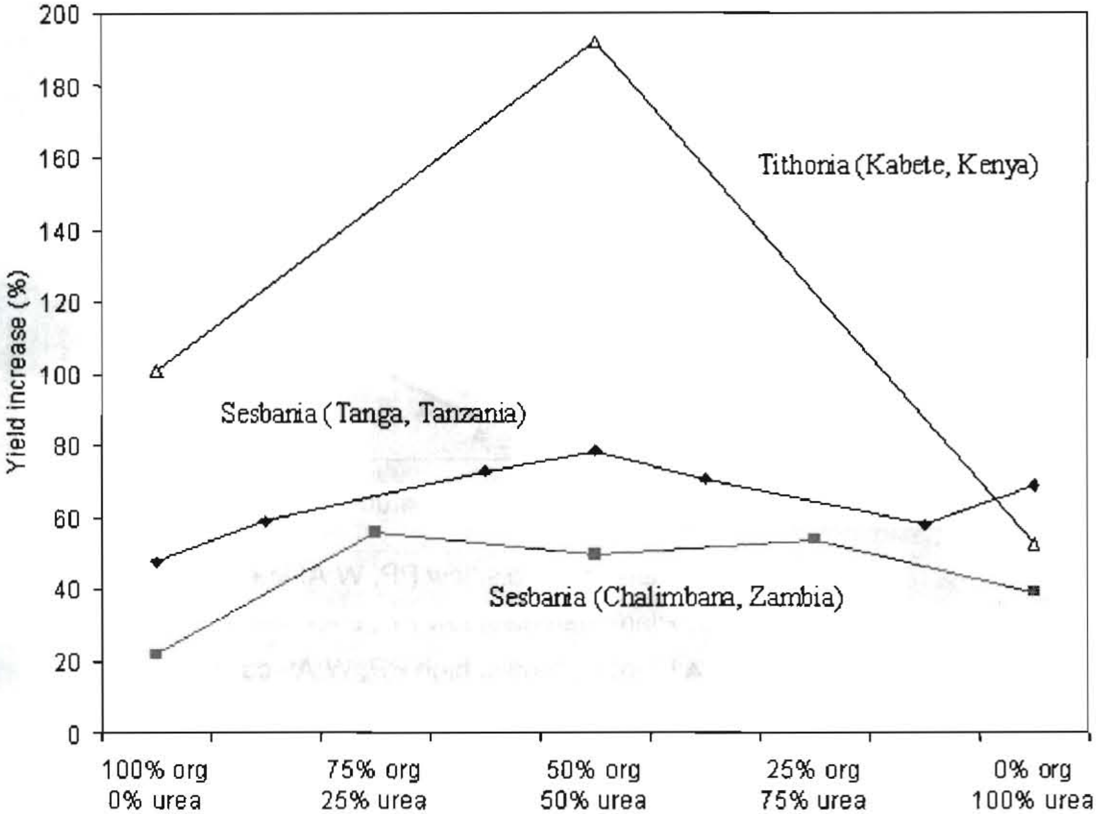

Figure 10: Effect of Tithonia and Sesbania combined with urea on maize yield The effect on yield increase is determined by the quality of the organic materials used. For example, fertilizer equivalencies of different plant materials and calliandra in East, South and West Africa show that materials with low N content have low fertilizer equivalencies. The level of polyphenol will also affect the fertilizer equivalency of the different organic materials (**Figure** 11)

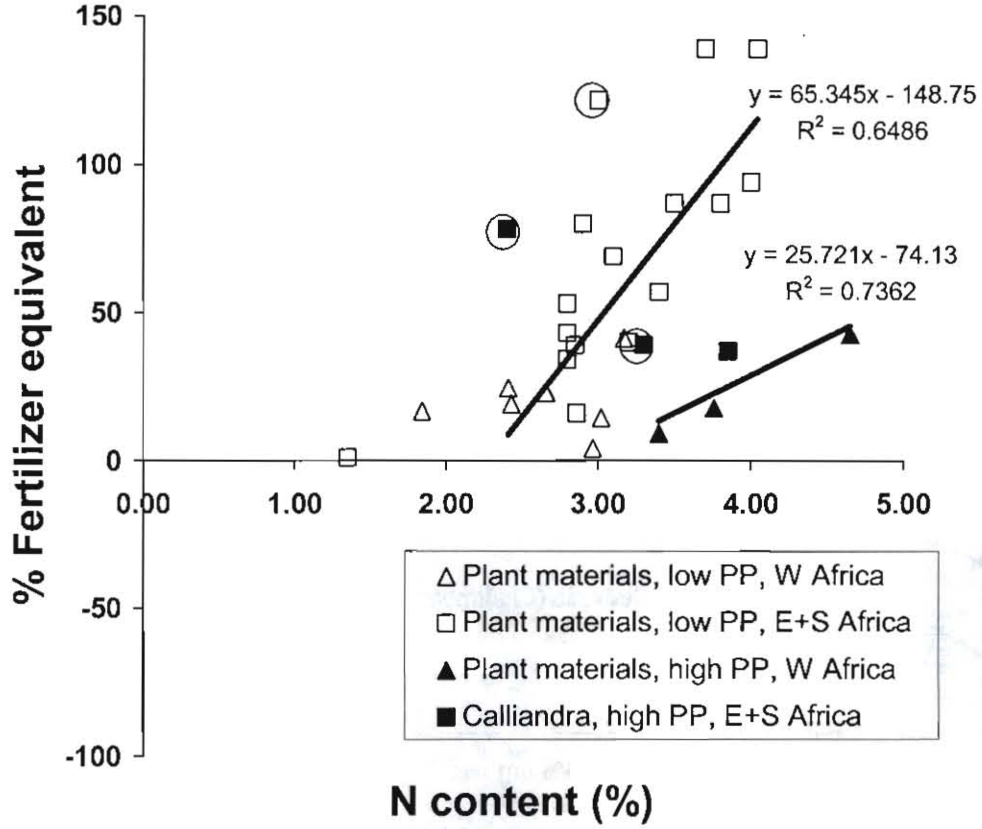

Figure 11: Fertilizer equivalencies as affected by N content

A recent study in Kenya revealed that for maize the sole application of tithonia, senna and calliandra could maintain the yield at the same level with the application of urea alone. The response of combining organic and inorganic plant nutrients is site specific and there is need to use modeling tools for a better understanding of this differential response (**Figure** 12).

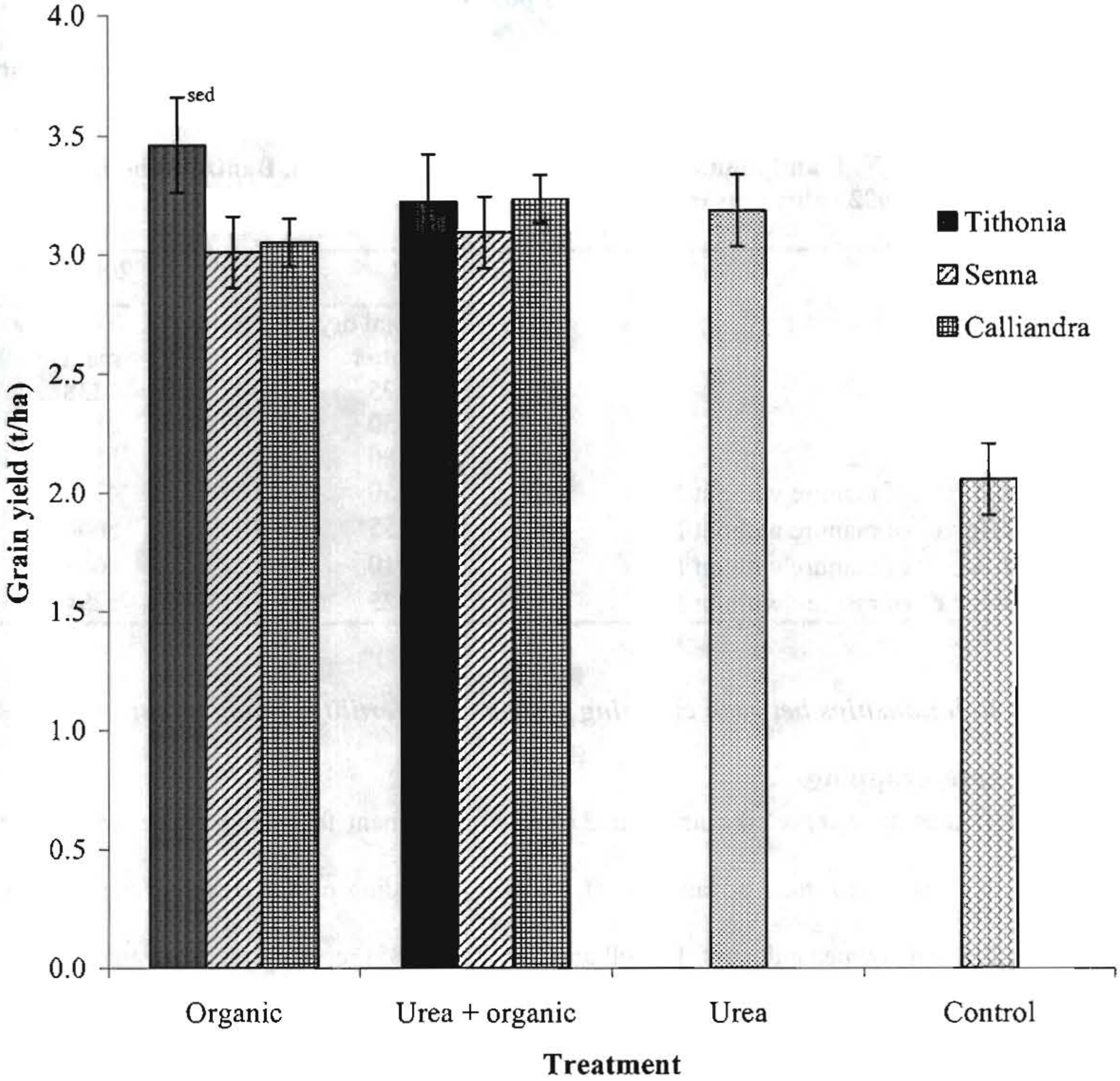

Figure 12: Effect of combined nitrogen sources on maize grain yield at Kabete Kenya (Source: Kimetu, 2002)

A factorial experiment of manure (0, 2 and 4 t/ha), nitrogen (0, 30 and 60 kg N/ha) and phosphorus (0, 6.5 and 13 kg P/ha) was established in Banizoumbou, Niger, to assess the fertilizer equivalency of manure for N and P. A very significant effect of N, P and manure on pearl millet yield was obtained **(Table 9)**. Whereas P alone accounted for 60% of the total variation, nitrogen accounted for less than 5% in the total variation indicating that P is the most limiting factor at this site. Manure accounted for 8% in the total variation. The fertilizer equivalency for N of low quality manure was 80% indicating that manure in addition to adding nutrients to the soil is having also other benefits such as the increase of water holding capacity.

Table 9: Effect of N, P and manure on pearl millet yield (kg ha^{-1}), Banizoumbou, Niger, 2001 and 2002 rainy seasons

Treatments	2001		2002	
	Grain	Total dry matter	Grain	Total dry matter
Absolute control	290	1275	338	1238
Control for N	1210	4550	1008	3895
Control for P	635	2280	916	3545
Yield at 2t ha^{-1} of manure without N	1530	5450	1167	4746
Yield at 4t ha^{-1} of manure without N	1695	4855	1609	5640
Yield at 2t ha^{-1} of manure without P	810	2910	1229	4659
Yield at 4t ha^{-1} of manure without P	1070	3625	1411	5294

3.1.5 Relationships between cropping systems and fertility management

3.1.5.1 Intercropping

Several studies have reported nutrient and yield improvement following intercropping systems. Ntare (1989) reported yield advantages of 20-70% depending on the different combinations of pearl millet and cowpea cultivars. Fussell and Serafini (1985) reported yield advantages from 10-100% in millet-cowpea systems. Yield stability is a major advantage of intercropping since farmers want to rely on management practices that increase yields, while improving stability of the production in both good and poor rainfall years (Baker 1980 and Finlay and Wilkinson 1963).

3.1.5.2 Relay and sequential cropping

In agro-ecological zones with longer growing season and higher rainfall there is greater opportunity to manipulate the systems with appropriate genotypes and management systems. Field trials have been conducted in the sahelian zone to examine the performance of the cultivars under relay and sequential systems and revealed the potential of these alternative systems over traditional sole or mixed cropping (ICRISAT, 1985 and 1984-1988).

In Mali, by introducing short season sorghum cultivars in relay cropping with other short duration cowpea and groundnut cultivars, substantial yields of legumes and sorghum were obtained as compared to traditional systems (Sedogo 1993).

In the Sahelian zone data of the onset and ending of the rains and the length of the growing period analysed found that an early onset of the rains offers the probability of a longer growing period while delayed onset results in a considerable short term growing season. The above analysis suggests that even for the Sahelian zone, cropping management factors using relay cropping can increase soil productivity with an early onset of the rains.

3.1.5.3 Crop rotation

The effect of crop rotation on yield and organic carbon is shown in **Figure** 13. Continuous millet TDM is lower by at least 2500kg ha-1 as compared to rotation with cowpea at all levels of P application. The rotation system was also found to have higher levels of soil organic carbon as compared to the continuous millet system due to the dropping of the cowpea leaves.

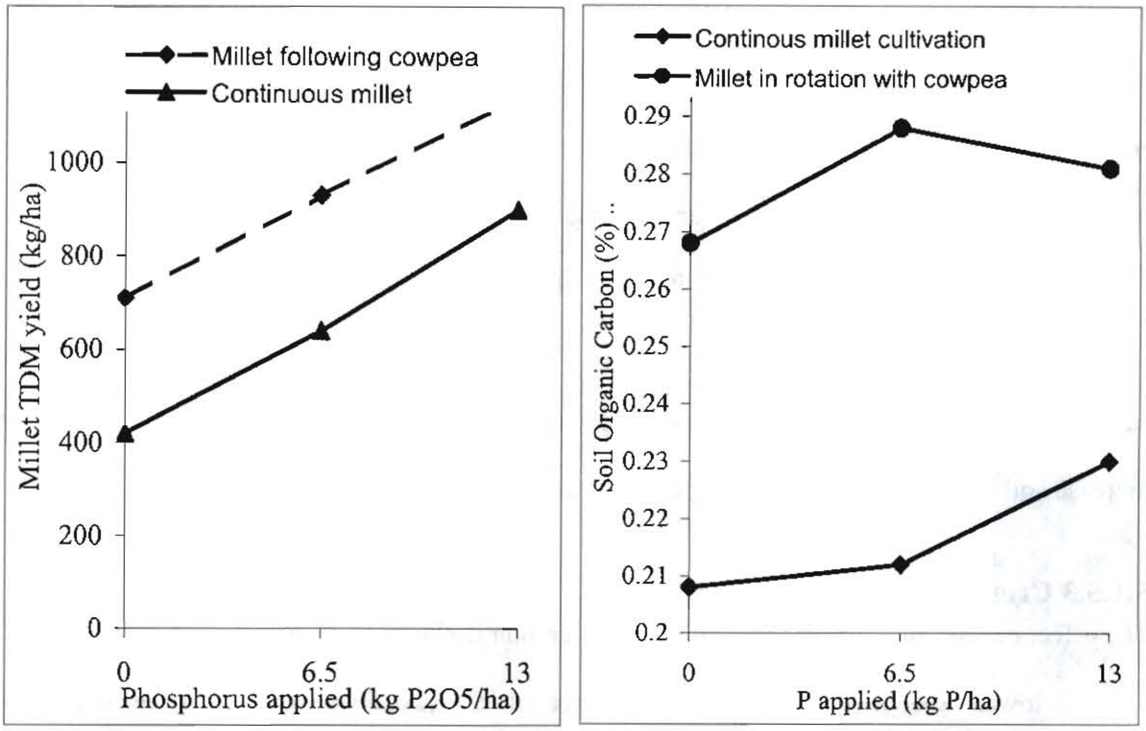

Figure 13. Effect of rotation on millet yield (right) and on soil organic carbon (left)

Using ^{15}N to quantify the amounts of nitrogen fixed by cowpea and groundnut under different soil fertility levels in the Sahel, it was found that nitrogen derived from the air (NDFA) varied from 65 to 88% for cowpea and 20 to 75% for groundnut. In the complete treatment where all nutrients were applied cowpea stover fixed up to 89 kg N ha^{-1} while for same treatment groundnut fixed 40 kg N ha^{-1}.

The potential of rotation systems has also been shown by an experiment to determine ^{15}N recovery from different cropping systems of pearl millet grown continuously, in rotation with cowpea, in rotation with groundnut, intercropped with cowpea, and intercropped with groundnut which indicated that nitrogen use efficiency increased from 20% in continuous pearl millet cultivation to 28% when pearl millet was rotated with cowpea (Bationo and Vlek 1998). The same authors reported that in the Sudanian zone nitrogen derived from the soil increased from 39 kg N ha^{-1} in continuous pearl millet cultivation to 62 kg N ha^{-1} when pearl millet is rotated with groundnut. Those data clearly indicate that although all the above ground biomass of the legume will be used to feed livestock and not returned to the soil, rotation will increase not only the yields of succeeding cereal crop but also its nitrogen use efficiency.

3.2 ISFM and ecosystem services

There is much evidence for rapid decline of Corg levels with continuous cultivation of crops in Africa (Bationo et al, 1995). Annual losses of between 1.5-7.0% of soil organic carbon can be observed depending on management systems as compared to 1.2% and 0.5% following 2 and 4 years of fallow respectively (**Table** 10). For the sandy soils, average annual losses in Corg often expressed by the K value (calculated as the percentage of organic carbon loss per year), may be as higher as 4.7%, whereas for the sandy loam soils, reported losses seem much lower, with an average of 2%. The data in **Table 10** also clearly indicated that soil erosion can increase Corg losses from 2% to 6.3% and management practices such as crop rotation, following soil tillage, application of mineral fertilizers and mulching will have a significant effect on annual losses of Corg. **Figure** 14 shows that application of 4 t of crop residue per hectare maintained top soil organic carbon at the same level as that in an adjacent fallow field but continuous cultivation without mulching resulted in drastic reduction of Corg.

A survey of millet producing soils by Manu et al. (1991) found an average soil Corg content of 7.6 g kg^{-1} with a range from 0.8 to 29.4 g kg^{-1}. The data also showed that these Corg contents were highly correlated with total N ($R = 0.97$) which indicates that in the predominant agro-pastoral systems without the application of mineral N fertilizers, N nutrition of crops largely depend on the maintenance of soil Corg levels.

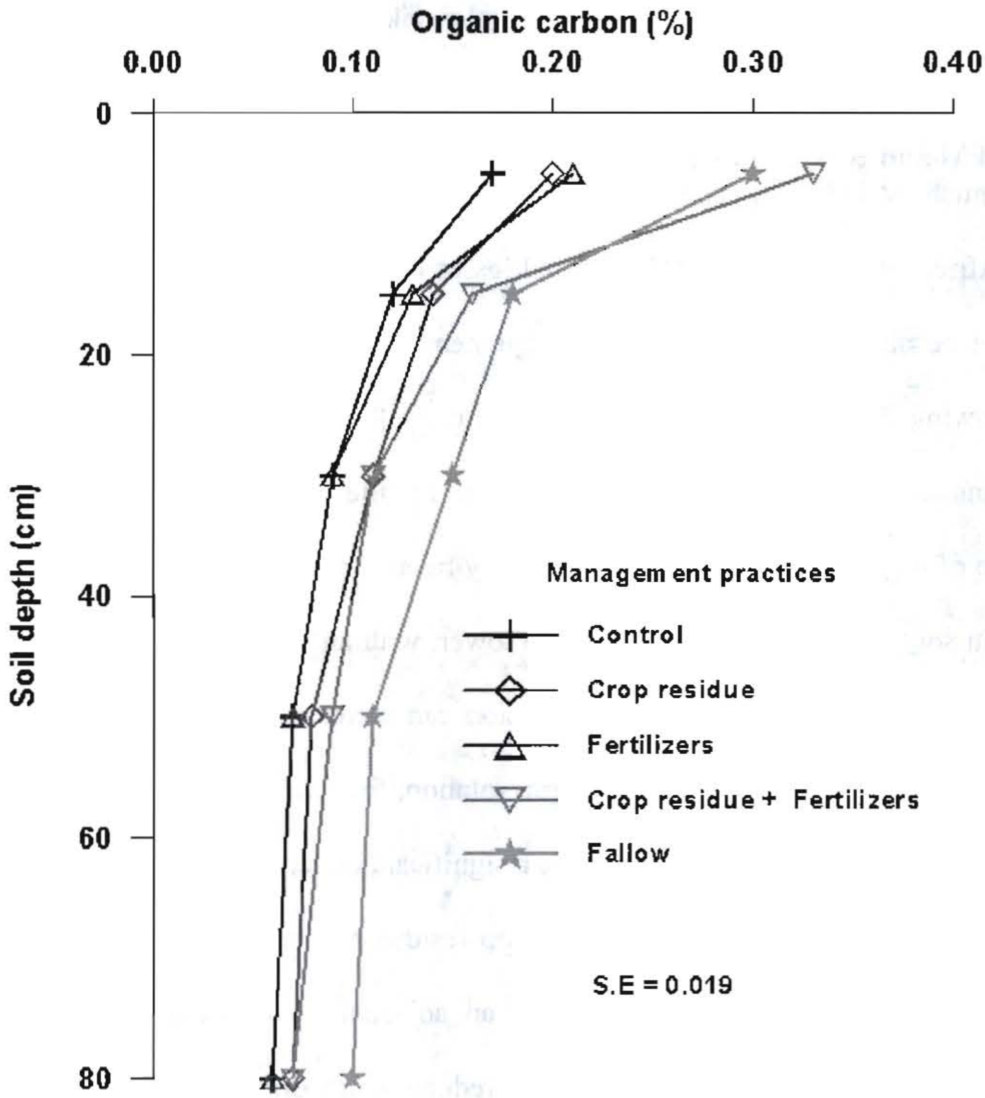

Figure 14: Effect of different management practises on soil organic carbon content after 14 years of cultivation, Sadore, Rainy season 1997

Table 10: Annual loss rates of soil organic carbon measured at selected research stations in the SSWA

Place and Source	Dominant cultural succession	Observations	Clay + Silt (%) (0-0.2 m)	Annual loss rates of soil organic carbon (k)	
				Number of years of measurement	k (%)
Burkina Faso		With tillage			
Saria, INERA-IRAT	Sorghum monoculture	Without fertiliser	12	10	1.5
	Sorghum monoculture	Low fertilizser	12	10	1.9
	Sorghum monoculture	High fertiliser	12	10	2.6
	Sorghum monoculture	Crop residues	12	10	2.2
CFJA, INERA-IRCT	Cotton-cereals	Eroded watershed	19	15	6.3
Senegal		With tillage			
Bambey, ISRA-IRAT	Millet-groundnut	Without fertiliser	3	5	7.0
	Millet-groundnut	With fertiliser	3	5	4.3
	Millet-groundnut	Fertiliser + straw	3	5	6.0
Bambey, ISRA-IRAT	Millet monoculture	with PK fertiliser + tillage	4	3	4.6
Nioro-du-Rip, IRAT-ISRA	Cereal-leguminous	F0T0	11	17	3.8
	Cereal-leguminous	F0T2	11	17	5.2
	Cereal-leguminous	F2T0	11	17	3.2
	Cereal-leguminous	F2T2	11	17	3.9
	Cereal-leguminous	F1T1	11	17	4.7
Chad		With tillage, high fertility soil			
Bebedjia, IRCT-IRA	Cotton monoculture		11	20	2.8
	Cotton - cereals			20	2.4
	+ 2 years fallow			20	1.2
	+ 4 years fallow			20	0.5

F0 = no fertiliser, F1 = 200 kg ha^{-1} of NPK fertiliser, F2 = 400 kg ha^{-1} of NPK fertiliser + Taiba phosphate rock, T0 = manual tillage, T1 = light tillage, T2 = heavy tillage.

Reduction in organic carbon is associated with reduction in soil pH and cation exchange capacity. Bationo et al. (1995) reported that continuous cultivation in the Sahelian zone has led to drastic reduction in organic matter and a subsequent soil acidification. Bationo and Mokwunye (1991) reported that in the Sudano-Sahelian zone of West Africa, the effective cation exchange capacity (ECEC) is more related to organic matter than to clay, indicating that a decrease in organic matter will decrease the ECEC and subsequently the nutrient holding capacity of these soils. A study to quantify the effects of changes in organic carbon on cation exchange capacity (CEC) found that a difference of 1 g kg^{-1} in organic carbon results in a difference of 4.3 mol kg^{-1} (De Ridder and van Keulen, 1990). In many cropping systems few if any agricultural residues are returned to the soil. This leads to declined soil organic matter, which frequently results in lower crop yields or soil productivity.

3.3 ISFM and farmer evaluation

Past research results indicated a very attractive technology consisting of hill placement of small quantities of P fertilizers. With DAP containing 46% P2O5 and a compound NPK fertilizer (15-15-15) containing only 15% P2O5, fields trials were carried out by farmers to compare the economic advantage of the two sources of P for millet production. As hill placement can result in soil P mining another treatment was added consisting of application of phosphate rock at 13 kg P ha^{-1} plus hill placement of 4 kg P ha^{-1} as NPK compound fertilizers.

There was no difference between hill placement of DAP and 15-15-15 indicating that due to its low cost per unit of P associated with DAP, this source of fertilizer should be recommended to farmers. The basal application of Tahoua Phosphate rock (TPR) gave additional 300 kg ha-1 of pearl millet grain (**Figure 15**). The combination of hill placement of water-soluble P fertilizer with phosphate rock seems a very attractive option for the resource poor farmers in this region.

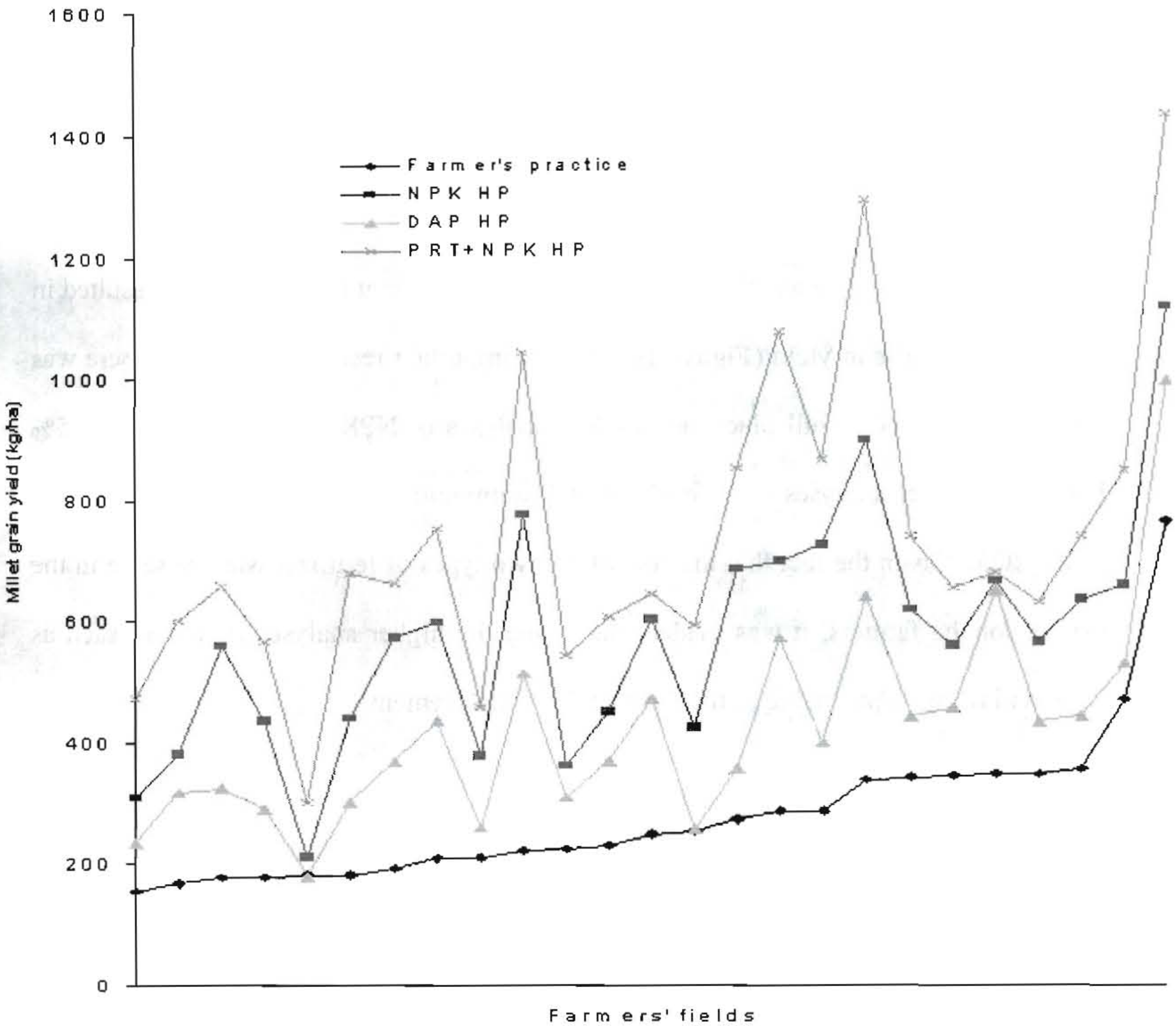

Figure 15: Millet grain response to different management practices, Gaya, Niger, 2002 rainy season

Different technologies were tested for many years in areas with annual rainfall between 400-800mm and various soil types. The recommended practise was to apply 13kgP ha^{-1} as Single Super Phosphate (SSP) and 30kgN ha^{-1} as Urea. Both were to be broadcast and incorporated. With the recent evaluation of the currency in Niger, West Africa (Fcfa), the cost of fertilizer almost tripled. This was not always followed by the grain yield. Therefore, new strategies were developed to reduce application by hill placing small quantities of P fertilizer at planting time to increase P use efficiency and achieve profitable production for small-scale farmers. The hill placement consisted of placing 4kgP ha^{-1} and the sources of P tested were compound 15-15-15 fertilizer, SSP and DAP.

In all agro-ecological zones, the hill placement of small quantities of fertilizer resulted in significant increase in yield (**Figure 16**). A very important result also was that there was no yield difference in hill placement of low analyses of NPK fertilizer with only 15% P2O5 and higher analyses of P fertilizer of Diammonium Phosphate (DAP) containing 46% P2O5. Given the fact that the cost of the two types of fertilizer was the same in the market for the farmers, it was evident that using the higher analyses P content such as DAP will be more profitable to the farmers for hill placement.

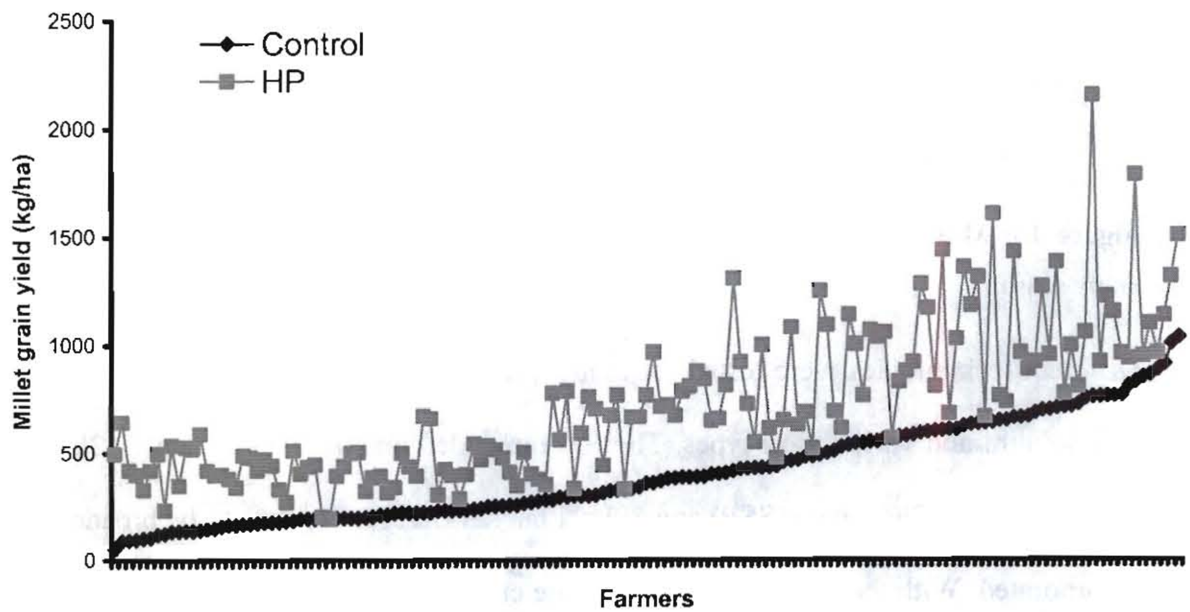

Figure 16: Millet grain yield response to HP application in 150 farmers fields in Sadore, Karabedji and Gaya in Niger

Average grain yield of the farmers practise was 400kg ha^{-1} as compared to 720kg ha^{-1} with HP application. These average yields from the sites were used for the economic analyses to determine which technologies are viable and more likely to be of interest to the farmers. The study has shown that use of DAP as the P source is superior to 15 15-15 and is a viable option with all the practices at all fertilizer and crop prices. The inferior results of 15-15-15 as P fertilizer source were investigated through a further analyses involving plotting the benefit/cost ratio against the fertilizer/crop price ratio (**Figure** 17). Viability of most HP 15-15-15 technologies is limited to fertilizer/crop price ratio of <2.0. Their practise when the fertilizer/crop price ratio is >2.0 return a benefit cost ratio of less than 2. On the other hand, their benefit/cost ratios are limited to <7.0 (**Figure 17**). However, both rotation and intercropping show superior performance and viability even at higher fertilizer/crop price ratio with rotation as the best practise. Though the technology involving only an application of 4kgP ha^{-1} as 15-15-15 resulted to the highest benefit/cost ratio, its viability is limited to a fertilizer/crop price ratio of no more than 2.

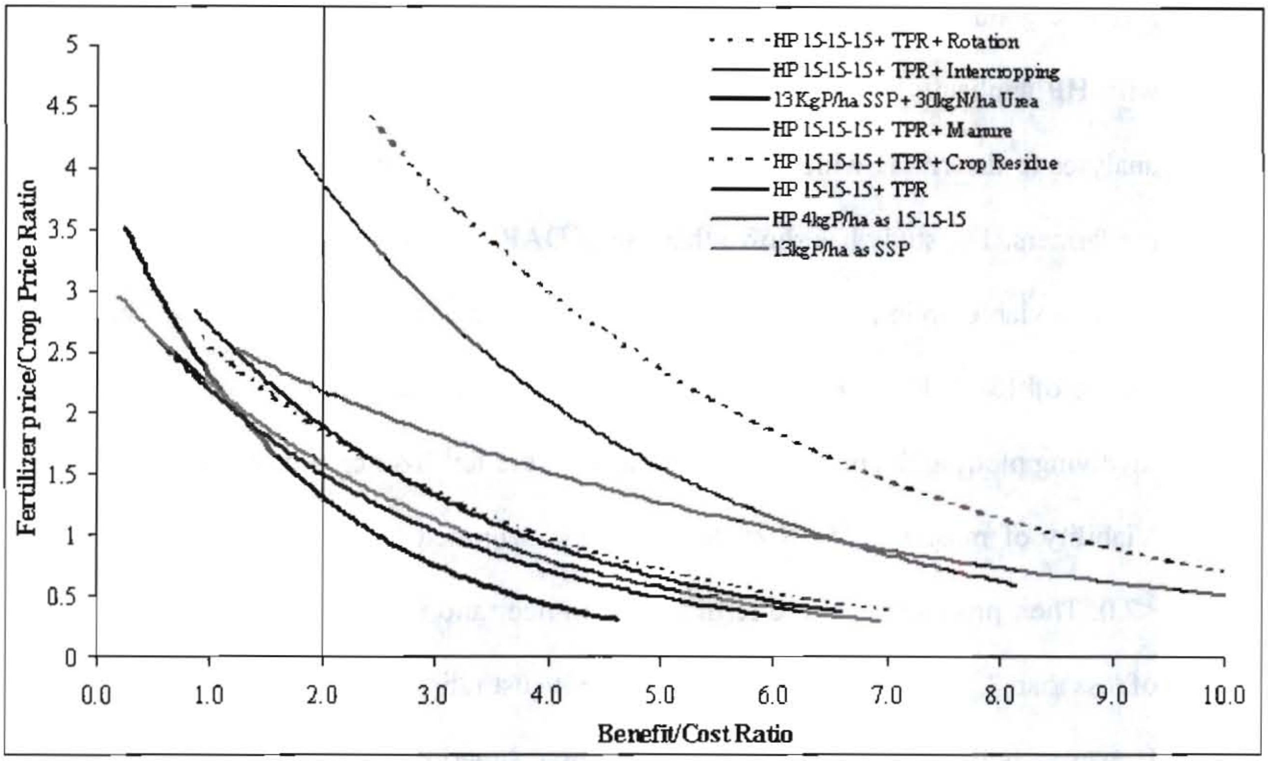

Figure 17: Benefit/ cost ratio of technologies with HP 15-15-15 at various price ratios

Notes: HP 15-15-15 is hill placement of 4kgP ha^{-1} of 15-15-15 fertilizers; TPR is broadcast of 13kg ha^{-1} of Tahoua Phosphate rock; Manure is applied at 2 tons/ha; crop residue is applied at 2 t ha^{-1}; Control grain yield and stover yield were 400kg ha^{-1} and 1700kg ha^{-1} respectively

4.0 New research opportunities in the SSZWA

4.1 New strategies for integrated nutrient management

The holistic approach of ISFM recognizes need to integrate socio-economic and policy research with technical or biophysical research. Soil fertility is a function of both biophysical and socio-economic aspects. Tools are also available to integrate farmer concerns through participatory approaches thus enriching ISFM by integrating local and scientific knowledge. ISFM therefore has the potential to enhance optimal management of organic resources, mineral inputs, and the soil organic matter pool through development of soil nutrient management technologies. Future research needs to adopt this new holistic approach to integrated nutrient management.

4.2 Combining rain water and nutrient management strategies to increase crop production and prevent land degradation

In the SSZWA high inter-annual variability and erratic rainfall distribution in space and time result in water-limiting conditions during the cropping season. In areas with inadequate rainfall or in runoff-susceptible land, water conservation techniques and water harvesting techniques offer the potential to secure agricultural production and reduce the financial risks associated with the use of purchased fertilizers. Under the conditions of adequate water supply, the addition of organic and inorganic amendments is the single most effective means of increasing water use efficiency. Future research needs to focus on enhancing rainwater and nutrient use efficiencies and on capitalizing on their synergies for increasing crop production and preventing soil degradation.

4.3 Increasing the legume component for a better integration of crop-livestock production systems

The rotations of cereals with legumes have led to increased cereals yield at many locations in the SSZWA. Factors such as mineral nitrogen increase, enhancement of Vesicular-Azbuscular Mycorrhizal (VAM) for better P nutrition and a decrease in parasitic nematodes have been identified as mechanisms accelerating the enhanced yield of cereals in rotation with legumes. Most of the research quantify has focused on the quantification of the above-ground N fixed by different legumes cultivars, but very little is known on the below-ground N fixed.

There is need to increase the legume component in the mixed cropping systems for a better integration of crop-livestock. The increase of legume component in the present cropping system will not only improve the soil conditions for the succeeding cereal crop, but will provide good quality livestock feed, and the manure produced will be of better quality for soil amendment.

4.4 Exploiting genetic variation for nutrient use efficiency

Phosphorus is the most limiting plant nutrient for crop production in the SSZWA and there is ample evidence that indicates marked differences between crop genotypes for P uptake. A better understanding of the factors affecting P uptake such as the ability of plants to i) solubilize soil P through acidification of the rhizosphere and the release of chelating agents and phosphate enzymes ii) explore a large volume of soil and iii) absorb P from low P solution would help screening for the genotypes the best appropriate for nutrient use efficiency.

Another important future research opportunity is the selection of genotypes that can efficiently associate with Vesicular-Arbuscular Mycorrhizal (VAM) for better utilization of P applied as indigenous phosphate rock.

4.5 Use of decision support systems, modelling, and GIS for the extrapolation of research findings

Farmers' production systems vary with respect to rainfall, soil types and socio-economic circumstances and therefore they are complex. Dealing with such complexity only by empirical research will be expensive and inefficient. Use of models and GIS will facilitate the transfer of workable technologies to similar agro-ecological zones. The use of DSSAT, APSIM and GIS will facilitate extrapolation of findings to other agro-ecozones similar of the benchmark sites chosen for testing technologies and will be cost effective.

4.6 Fertility gradients

Quantification of the range of within-farm soil fertility gradients and identification of the major biophysical and socio-economic factors driving their generation is important for better management and optimizing the efficiency of resource use. Fertilizer recommendations usually cover large areas and ignore within-farm soil fertility gradients, which are a common feature of African smallholder farms. Hence a framework for their assessment and management needs to be developed if more realistic and farmer friendly recommendations are to be made. The premise is that within-farm soil fertility gradients vary, according to site, inherent soil properties, farmer management style and farmer resource endowment and that responses to specific nutrients vary for soils with a different soil fertility status. Additionally, the impact of within-farm soil fertility gradients on the most relevant soil processes (e.g., nutrient supply, C decomposition and stabilization) governing integrated soil fertility management practices should be assessed.

4.7 Long-term effects

Management practices engaged influence the nature of fauna population composition and structure and could lead to elimination/ reduction of key groups and/or species of soil fauna and in some cases to low abundances or biomass. Although research has for a long time recognized the need to consider biodiversity studies in agroecosystems, these have been conducted in short-term experiments with little work on long-term effects. It is also evident from most of the work that the main focus of long-term investigations has been on the effect of soil fertility restoration on crop yield and to a lesser extent on the changes of soil chemical properties with little or no focus on soil biodiversity. There is need therefore to aim to enhance better management of soil belowground biodiversity for sustainable food production, through focusing on the changes in soil chemical and physical properties, soil biodiversity dynamics and relationships between soil biodiversity parameters and land productivity and sustainability in several cropping and management systems following various treatments.

5.0 Conclusions

There is great potential for yield improvement in the African agro-ecosystems through soil fertility restoration technologies cleverly invented together with the users. Adoption is one of the main obstacle. Farmer socio-economic and cultural setting should be an integral part of technology developed and testing. Both intercropping and rotation systems that have proved superior in many research works for example, need to be tested together with farmers on farm if they are to be adopted. Farmer trials are indispensable in this era of research and are a good pillar in strengthening the ISFM approach.

There is need to take advantage of the available resources such as phosphate rock deposits, manure and crop residue to amend the soil inorder to improve the efficiency of mineral fertilizers and make external inputs mote profitable to the farmers.

Consideration of the economic benefits of the technologies may be an important preliquisite for the success of adoption of the technologies. Besides, markets are increasingly becoming part of the research process since farmers have to trade off cash crops and the excess of their food crop produce. Participatory farmer research monitoring product prices, post harvest processing and storage, farmer cooperatives should be conducted and may become an important incentive for technology adoption.

Use of decision support systems such as modeling and GIS applications will also help to extend the already concluded research findings to other areas. Such systems should find more use in future research activities as pointers to new research and dissemination areas based on socio-economic and biophysical constraints of farmers.

References

Baker E F I 1980 Mixed cropping in northern Nigeria. IV. Extended trials with cereals and groundnuts. Experimental Agriculture 16:361-369

Baltissen, G.; Wabwile, E. and T. Defoer (2000) Up-scaling and institutionalizing Participatory Learning and Action Research (PLAR) for Integrated Soil Fertility Management (ISFM) in Western Kenya. Managing Africa's Soils No. 20, IIED, UK.

Bationo A Buerkert A Sedogo MP Christianson BC and Mokwunye AU (1995) A critical review of crop residue use as soil amendment in the West African Semi-Arid Tropics. In: Powell JM Fernandez-Rivera S Williams TO and Renard C (ed) Livestock and Sustainable Nutrient Cycling in Mixed Farming Systems of Sub-Saharan Africa, pp 305--322. Volume 2: Technical Papers. Proceedings of an International Conference, 22-26 November 1993. International Livestock Centre for Africa (ILCA), Addis Ababa, Ethiopia.

Bationo A, and Vlek P L G 1998 The role of nitrogen fertilizers applied to food crops in the Sudano-Sahelian zone of West Africa. In: G: Renard, A Neef, K Becker and M von Oppen (Eds.). Soil Fertility Management in West African Land Use Systems. Margraf Verlag, Weikersheim, Germany. Pp 41-51.

Bationo, A., Mokwunye, A.U., 1991. Role of manures and crop residues in alleviating soil fertility constraints to crop production with special reference to the Sahelian zones of West Africa. Fert. Res. 29, 125-177.

De Ridder, N and H. van Keulen. 1990. Some aspects of soil organic matter in sustainable intensified arable farming systems of West African semiarid tropics. Fert. Res. 26:299-310

Finlay K W and Wilkinson G N 1963. The analysis of adaptation in a plant-breeding programme. Australian Journal of Agricultural Research 14:742-54

Fussell L K and Serafini P G 1985 Associations de cultures dans les zones tropicales semi-arides d'Afrique de l'Ouest: strategies de recherché anterieures et futures. (In Fr) Pages 254-278 in Technologies appropriees pour les paysans des zones semi-arides de l'Afrique de l'Ouest)Ohm, H.W. and Nagy J.G., eds.). West Lafayette, Indiano, USA: Purdue University

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1985. Annual report 1984. Patancheru, A.P. 502 324, India: ICRISAT.

ICRISAT, 1984-1988, Annual Report, 1984 to 1988. Patancheru, A.P. 5023, India, IITA (International Institute of Tropical Agricultue) 1992 Sustainable food production in sub-Saharan Africa: 1. IITA's contributions. IITA, Ibadan, Nigeria.

Kimani S. K., S. M. Nandwa, S. N. Obanyi, J. Ojiem, H. K. Murwira & A. Bationo. 2003. Principles of integrated soil fertility management. In: Gichuru M.P., Bationo A., Bekunda M.A., Goma P.C., Mafongoya P.L., Mugendi D.N., Murwira H.M., Nandwa S.M., Nyathi P. and M.J. Swift. Soil fertility management in Africa: a regional perspective. TSBF-CIAT. 2003

Kimetu, J. M. (2002) Determination of nitrogen fertilizer equivalent for organic materials based on quality and maize performance at Kabete, Kenya. A thesis submitted to Kenyatta University in partial fulfilment of the requirements for the degree of Master of Environmental Studies in Agroforestry and Rural Development. 64 pages.

Manu A, Bationo A and Geiger S C 1991 Fertility status of selected millet producing soils of West Africa with emphasis on phosphorus. Soil Sci. 152:315-320.

Manu A, Bationo A and Geiger S C 1991 Fertility status of selected millet producing soils of West Africa with emphasis on phosphorus. Soil Sci. 152:315-320.

Murwira H. K. 2003. Managing Africa's soils: approaches and challenges. In: Gichuru M.P., Bationo A., Bekunda M.A., Goma P.C., Mafongoya P.L., Mugendi D.N., Murwira H.M., Nandwa S.M., Nyathi P. and M.J. Swift. Soil fertility management in Africa: a regional perspective. TSBF-CIAT. 2003

Ntare B R 1989 Intercropping morphologically different cowpea with pearl millet in a short season environment in the Sahel. Experimental Agriculture 26. 41-47

Powell JM, Ikpé FN, Somda ZC Fernandez-Rivera S (1998) Urine effects on soil chemical properties and the impact of urine and dung on pearl millet yield. Expl. Agric. 34:259-276.

Sanchez PA 1994 Tropical soil fertility research: Towards the second paradigm. P. 65-88. In Inaugural and state of the art conferences. Transactions 15th World Congress of Soil Science. Acapulco, Mexico.

Sedogo MP (1993) Evolution des sols ferrugineux lessivés sous culture: influences des modes de gestion sur la fertilité. Thèse de Doctorat Es-Sciences, Abidjan, Université Nationale de Côte d'Ivoire.

Smaling EMA 1993 An Agro-ecological Framework of Integrated Nutrient Management with Special Reference to Kenya. Wageningen Agricultural University, Wageningen, The Netherlands.

Swift MJ 1984 Soil biological processes and tropical soil fertility: a proposal for a collaborative programme of research, Biology International Special Issue 5, International Union of Biological Sciences, Paris, France.

Swift MJ 1985 Tropical soil biology and fertility: planning for research. International Union of Biological Sciences, Paris, France.

Swift MJ 1986 Tropical soil biology and fertility : inter-regional research planning workshop, Biology International Special Issue 13, International Union of Biological Sciences, Paris, France.

Theng BKG 1991 Soil science in the tropics - the next 75 years. Soil Science 151, 76-90.

Vanlauwe B, O. C. Nwoke, J Diels, N Sanginga, R. J. Carsky, J. Deckers and R Merckx. 2000a. Utilization of rock phosphate by crops on a representative toposequence in the Northern Guinea savanna zone of Nigeria: response by *Mucuan pruriens*, *Lablab purpureus* and maize. Soil Biology and Biochemistry, 32: 2063-2077.

Vanlauwe B, J Diels, N Sanginga, R. J. Carsky, J. Deckers and R Merckx. 2000b Utilization of rock phosphate by crops on a representative toposequence in the Northern Guinea savanna zone of Nigeria: response by maize to previous herbaceous legume cropping and rock phosphate treatments. Soil Biology and Biochemistry, 32: 2079-2090.

Vanlauwe B, K. Aihou, S. Aman, E. N. O. Iwuafor, B. K. Tossah, J Diels, N Sanginga, O. Lyasse, R Merckx and J. Deckers. 2001 Maize yield as affected by organic inputs and urea in West African moist savannah. Agronomy journal, 93: 1191-1199.

Vanlauwe B, J Diels, N Sanginga and R Merckx 2002 Integrated Plant Nutrient Management in sub-Saharan Africa: From Concept to Practice. CABI, Wallingford, UK, 352 pp.

Vanlauwe B. 2003. Integrated Soil Fertility Management research at TSBF: the framework, the principles, and their application. In: Bationo A (ed). Managing nutrient cycles to sustain soil fertility in Sub-Saharan Africa.