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Research highlights on integrated soil fertility management in the Sahel

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Summary

Soil fertility is the most limiting factor for crop production in the Sahelian zone of West Africa. The region shelters the world's poorest people with the majority gaining their livelihood from subsistence agriculture. Per capita food production has declined significantly over the past three decades. Increasing population pressure has on the other hand decreased the availability of arable land and it is no longer feasible to use extended fallow periods to restore soil fertility. Therefore, there is urgent need to restore/ maintain soil fertility in order to increase agricultural production in this region and improve the farmers' livelihood.

In the recent past, scientists have evaluated the potential of different technologies in addressing the soil fertility problem in the Sahel as approaches to increase food production. 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 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. For example, hill placement of inorganic fertilizers and manure is superior to broadcasting.

Another potential is use of locally available phosphate rock, which could be an alternative to use of high cost imported P fertilizers. Since P is the most limiting factor on most sahelian soils, its correction not only improve yields but also the efficiency of N and water use.

A bottleneck to the use of these profitable soil fertility-enhancing technologies that have been researched is the low capacity of farmers to invest in these technologies. In order to have these technologies to reach millions of farmers, a new integrated soil fertility

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management (ISFM) paradigm has been adopted which integrates biological, physical, chemical, social, economic and political factors.

Future research challenges include combining rainwater and nutrient management strategies to increase crop production and prevent land degradation, increasing the legume component for a better integration of crop-livestock production systems, exploiting the genetic variation for nutrient use efficiency and integration of socio-economic and policy research with the technical solutions. Another very important issue for research is how to increase crop biomass availability at farm level to alleviate the constraint of non-availability of organic amendments. Use of decision support systems, modeling, and GIS is important in order to extrapolate research findings to other areas in which the successful technologies can be expanded/ scaled out to reach several farmers.

1.0 Introduction

The sudano-Sahelian zone of West Africa (SSZWA) shelters the world poorest people and majority of the population live in the villages hence gain their livelihood from subsistence agriculture (Bationo et al., 2003). However, over the last three decades, per capita food production has drastically reduced in this region. Soil fertility depletion has been described as one of the major biophysical root cause of declining per capita food production (Bationo et al., 2003). This has been due to unsustainable production systems and continuous nutrient mining without sufficient external inputs for soil fertility replenishment. 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.

Low soil fertility 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 on the one hand to the low quality of the soil resource base which has been due to inherent or induced deficiencies of major nutrients N, P and K, low nutrient holding capacities, high acidity, low organic matter and low use of fertilizers. 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).

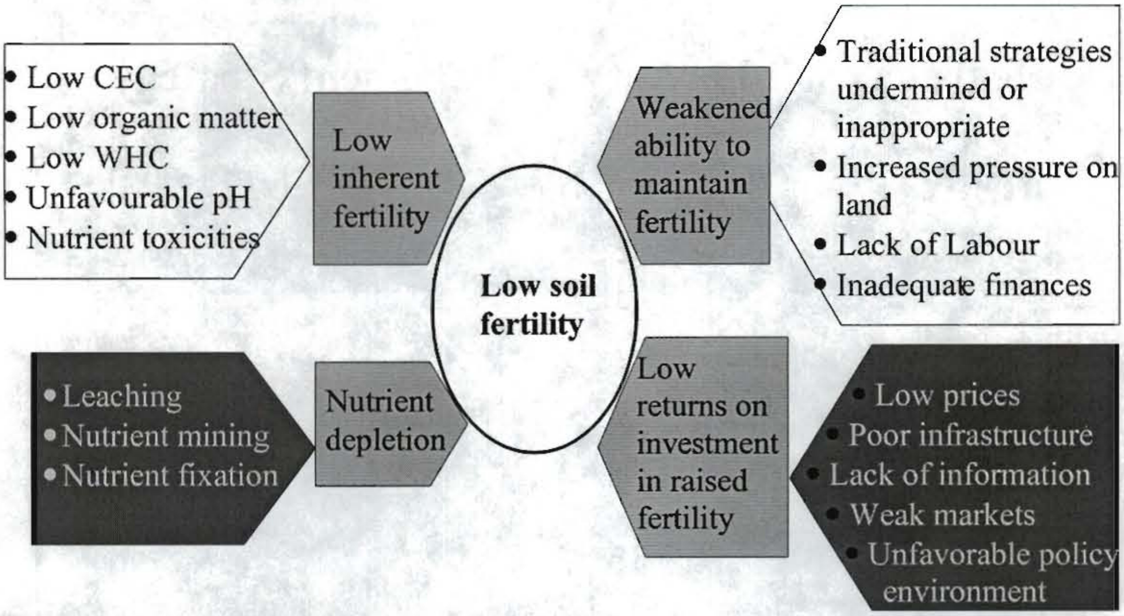

Figure 1: Biophysical and socio-economic factors contributing to low soil fertility in Africa

Soil fertility problems are compounded by the production environment in the sahel. Rainfall is generally low, variable and undependable (Toupet 1965) with a growing period of 60–100 days. The average annual rainfall of the cultivated zones varies from 300 to 900 mm and the ratio of annual rainfall to annual potential evapo-transpiration varies from 0.20 to 0.65. The rains occur in short and intense storms and pose special problems in soil conservation (Kowal and Kassam, 1978). Charreau (1974) reported rainfall intensities between 27 to 62 mm h^{-1}. In Northern Nigeria, Kowal (1970) reported rainfall intensities over 250 mm h^{-1} for a short period. As a result of the high rainfall intensities and low infiltration rates, runoff and soil loss are common in the region. Soil loss through erosion is estimated to be 10 times greater than the rate of natural formation. Wind soil loss from agricultural systems is also a contributing factor.

Integrated soil fertility management (ISFM)

Integrated soil fertility management (ISFM) is now regarded as a strategy that helps low resource-endowed farmers escape poverty and food insecurity by improving the quantity and quality of food, income and resilience of soil productive capacity. The holistic approach to ISFM is shown in **Figure 2** and embraces the full range of driving factors and consequences- biological, physical, chemical, social, economic and political.

The contribution of markets and marketing is 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.

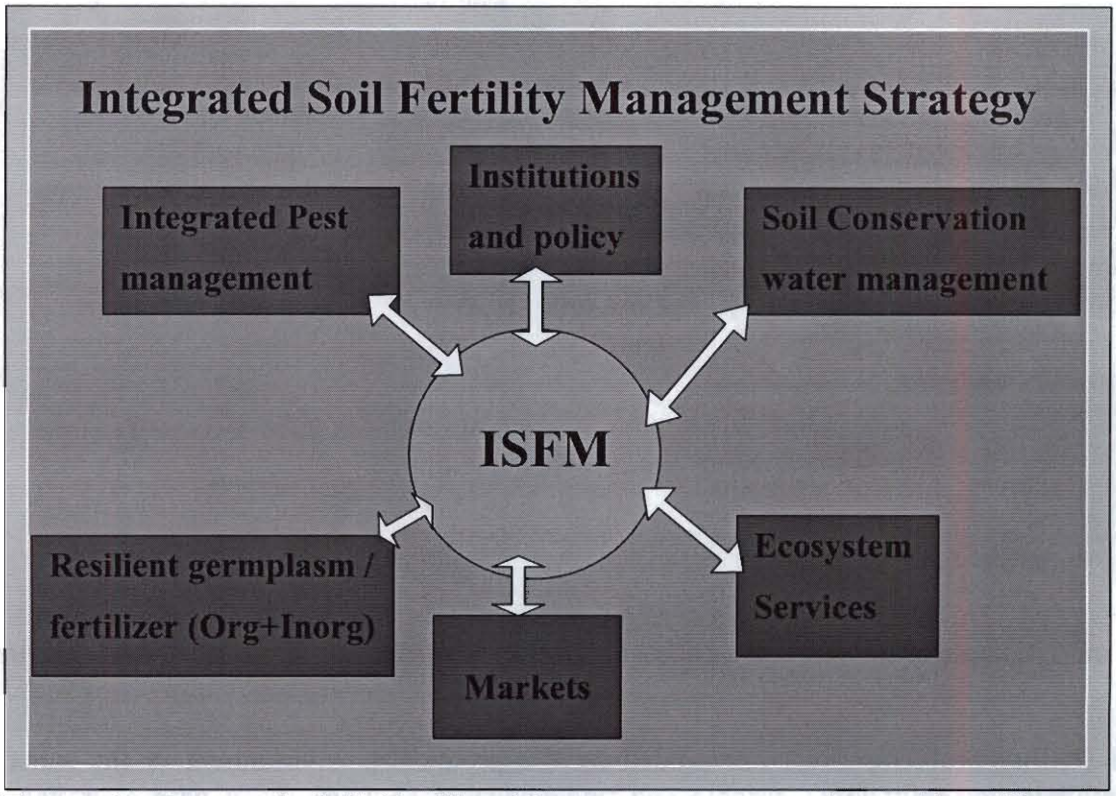

Figure 2: Integrated Soil Fertility Management entry points with wider natural management concerns

ISFMs' technical backbone lies in the optimal management of organic resources, mineral inputs and the soil organic matter pool for provision of goods and services. 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).

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-based 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.

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** 1).

Table 1. 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

A long-term experiment showed continued application of manure led to annual increase in yield as opposed to lone application of fertilizer that recorded annual yield reductions. Low quality manures can contribute significantly to overcome P deficiency to maize crop, although having additive but insignificant increases in yield (Bationo et al., Unpublished). Potential livestock transfer of nutrients in West Africa is 2.5 kg N and 0.6 kg P per hectare of cropland.

3.1.2 Placement of organic and inorganic fertilizer sources

Methods of application of organic and inorganic fertilizer sources affect fertilizer use efficiency. Hill placement of three levels of manure (0, 3, 6t ha^{-1}) performed better than broadcasting and with no application of P fertilizer in Niger. Broadcasting 3 t ha^{-1} of manure, for example, 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** 3). A similar effect was observed using cowpea.

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** 2). 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. Yield can also be substantially increased when both Tahoua Phosphate rock (TPR) and CR are added in combination with small amounts of inorganic P in hill placement **(Table 3)**. Phosphate rock is available from several deposits within Africa.

Regardless of the method of application, N and P use efficiency is further depended on the site. Higher use efficiency was observed on non-degraded as compared to degraded sites in Karabedji, Niger. In this site, with a Nitrogen N at 60kg ha^{-1}, N use efficiency was 15.3 and 8.6% in non-degraded and degraded site respectively. A similar trend was observed with P use efficiency recording 58% for non-degraded and 50% for degraded site, at a Phosphorus P rate of 30 kg ha^{-1}.

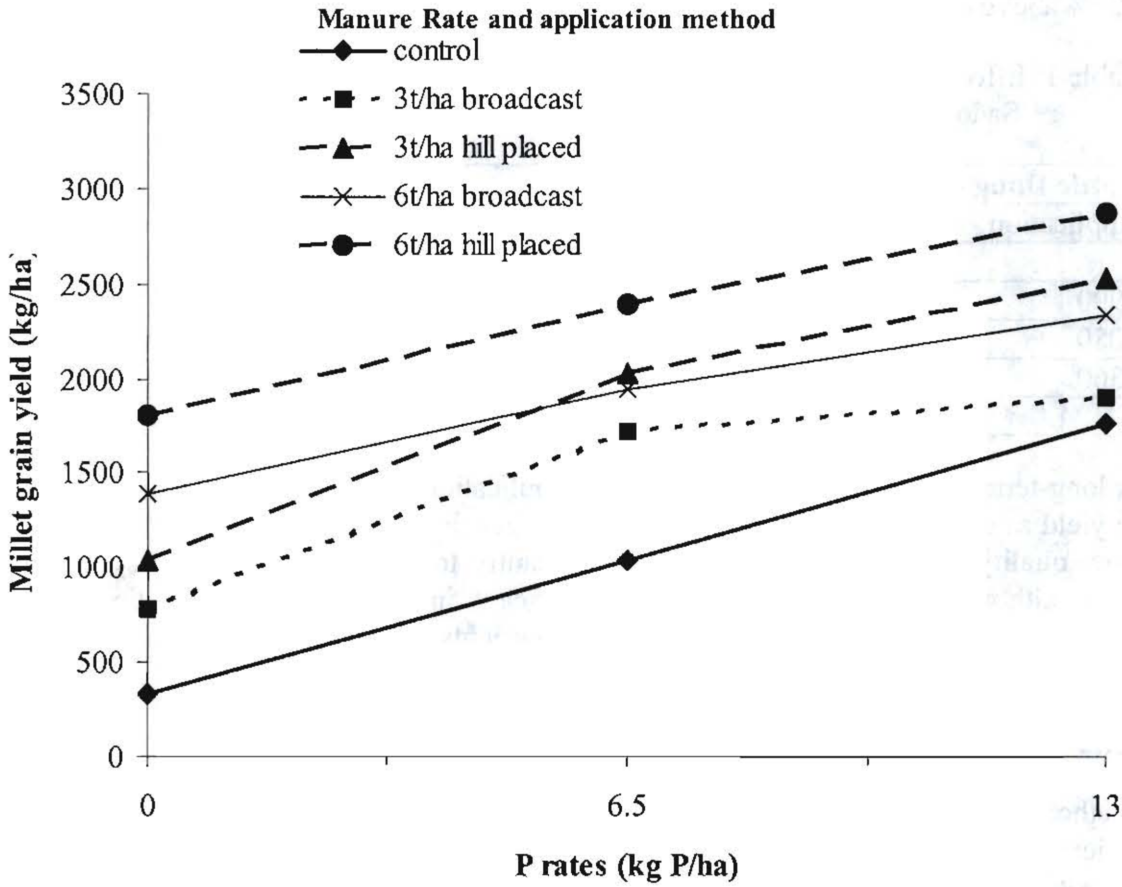

Figure 3: Millet grain yield response to P and manure applied at different rates and methods, Karabedji, Niger, 2002 rainy season

Table 2. 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

Table 3. Effect of hill placement of Phosphorus, Tahoua Phosphate rock and crop residue on yield

Treatment	1998	1999
Control	429	455
P Hill Placed	926	928
P Hill Placed + TPR	1099	1150
P Hill Placed + TPR + CR	1210	1333
SE	88	131
CV	14%	12%

3.1.3 Use of leguminous crops

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

3.1.4 Combining organic and inorganic plant nutrients in production

The data in **Table** 4 clearly indicate the comparative advantage to combine organic and inorganic plant nutrients for the suffering soils in the Sahel. 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. In another study, based on the maize yields from sole application of either organic inputs or urea, Vanlauwe et al (2001) observed added benefits from the organic-inorganic mixture of upto 0.49 Mg ha-1 grain ($p<0.001$) in Sekou and 0.58 Mg ha-1 ($P<0.15$) in Glidji.

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. Another explanation is the likely improved soil water conditions due to mixed applications as compared to sole applications (Vanlauwe et al 2001).

Table 4: Optimum combination of plant nutrients for cowpea fodder yield (kg ha^{-1}), Gaya, Niger in 2001 and 2002

Treatments	2001	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%

3.1.5 Water-harvesting technologies

Planting crops directly in pits (Zai technology) increased yields by 300 kg ha^{-1} that of planting on flat land. When small quantities of manure or compost (3t ha^{-1}) added in small pits dug in the degraded soil, yields rose to 960 kg ha^{-1}, more than double that of Zai without manure (**Table** 5).

Table 5. Effect of the zai and manure application on pearl millet grain yield in Western Niger

Treatment	Grain yield (kg ha^{-1})
Planting in flat	150
Planting in "zai" without manure	450
Planting in "zai" with 3 tons/ha of manure	960

Source: Fatondji (personal communication)

Other important water-harvesting technologies include use of micro- catchments (v, half-moon, etc), stones bounds and ridging.

3.1.6 Relationships between cropping systems and fertility management

3.1.6.1 Intercropping

Research has clearly underlined the importance of intercropping in farming systems. These include profit maximization and risk minimization (Norman, 1974), income and yield stabilization (Abalu, 1976; Baker, 1980; Finlay and Wilkinson, 1963; Willey, 1979; Willey et al., 1985; Steiner, 1984), exploiting the temporal differences between crops (Fussel, 1985; Serafini, 1985; Fussel et al., 1986; Baker, 1979), increased yields (Fussell and Serafini, 1985; ICRISAT, 1985). Ntare (1989) and Fussell and Serafini (1985) reported yield advantages of 20-70% and 10 –100% respectively depending on the different combinations of pearl millet and cowpea cultivars.

The most common intercropping associations are cereal/cowpea, cereal/groundnut, and cereal/cereal such as millet/sorghum/maize and millet/sorghum/cowpea. In the cowpea/cereal intercropping, the cowpea and cereal are usually planted in alternating rows, but recent research at IITA has shown that planting four rows of cowpea to two rows of cereal is more productive (Reference).

3.1.6.2 Relay and sequential cropping

In zones with longer growing season and higher rainfall there is greater opportunity to manipulate the systems with appropriate genotypes and management systems. Field agronomic 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).

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. Sivakumar et al. (1990) reported that years with early onset of rains in the sahelian zone can be exploited by establishing a second crop of cowpea after the millet.

3.1.6.3 Crop rotation

Cereal/ legume rotation effects on cereal yields have been reported for the sahelian zone of West Africa (Bagayoko et al., 1996; Klaij and Ntare, 1995; Stoop and Van Staven, 1981; Bationo and Ntare, 1999). **Table 6** shows the effect of cowpea-millet rotation on millet grain and total biomass production. In a period of three years, there was an increase of about 3 t ha^{-1} of total dry matter production when millet was grown in rotation with cowpea.

Table 6: Millet grain and total dry matter yield at harvest as influenced by millet/cowpea cropping system at Sadore (Niger).

	Grain yield			Total dry matter yield		
	1996	1997	1998	1996	1997	1998
Continuous millet	937	321	1557	4227	2219	6992
Millet after cowpea	1255	340	1904	5785	2832	8613
P > F	<0.001	0.344	<0.001	<0.001	<0.001	<0.001

Source: Bationo and Ntare, 1999

Other reported advantages include total yield increases (Bationo and Ntare, 1999), improvement of soil biological and physical properties, solubilization of occluded P and highly insoluble calcium-bounded phosphorus by legume root exudates (Gardner et al., 1981; Arhara and Ohwaki, 1989), increased soil microbial activity and N availability (Bationo et al., 1999), soil conservation (Stoop and Staveren, 1981), soil organic carbon and organic matter restoration (Bationo et al., Unpublished; Spurgeon and Grisson, 1965) and pest and disease control (Sunnadurai, 1973), although the effect varied with sites and years (Bagayoko et al., 2000).

3.2 ISFM and ecosystem services

There is much evidence for rapid decline of Corg levels with continuous cultivation (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** 7). For the sandy soils, average annual losses in Corg often expressed by the K value, 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 7** 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 4** 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. Corg contents are highly correlated with total N (R = 0.97) indicating that without the application of mineral N fertilizers, N nutrition of crops largely depend on the maintenance of soil Corg levels (Manu et al., 1991).

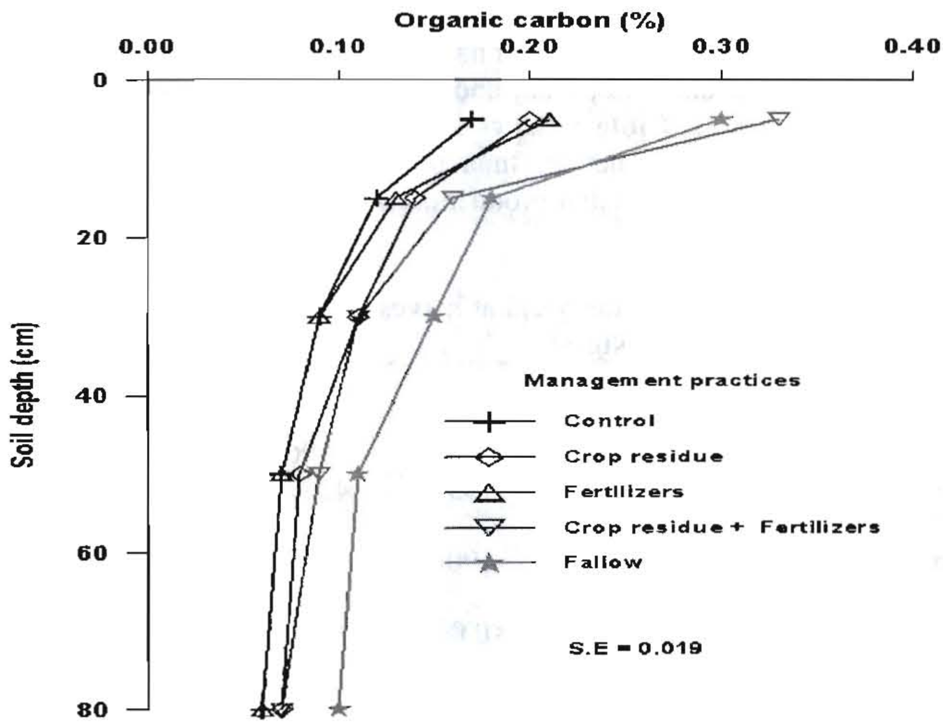

Figure 4: Effect of different management practises on soil organic carbon content after 14 years of cultivation, Sadore, Rainy season 1997

Table 7: 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					
Bebedjia, IRCT-IRA	Cotton monoculture	With tillage, high fertility soil	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 due to continuous cultivation that leads to drastic reduction in organic matter (Bationo et al., 1995; Bationo and Mokwunye, 1991). A difference of 1 g kg^{-1} in organic carbon results in a difference of 4.3 mol kg^{-1} CEC (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

Farmer field trials carried out in Niger in an economic evaluation showed no yield difference in hill placement of low analyses of NPK fertilizer with only 15% P_2O_5 and higher analyses of P fertilizer of Diammonium Phosphate (DAP) containing 46% P_2O_5 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. 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.

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. Farmer socio-economic and cultural setting should be an integral part of technology development and testing. Farmer trials a good pillar in strengthening the ISFM approach.

African researchers and farmers need to take advantage of the available resources such as phosphate rock deposits, manure and crop residue to increase yields. Efficiency optimization strategies will increase benefits from these resources and increase their appeal to the farmers. Also 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.

Future research challenges include combining rainwater and nutrient management strategies to increase crop production and prevent land degradation, increasing the legume component for a better integration of crop-livestock production systems, exploiting the genetic variation for nutrient use efficiency and integration of socio-economic and policy research with the technical solutions. Another very important issue for research is how to increase crop biomass availability at farm level to alleviate the constraint of non-availability of organic amendments. Use of decision support systems, modeling, and GIS is important in order to extrapolate research findings to other areas in which the successful technologies can be expanded/ scaled out to reach several farmers.

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