Increasing land sustainability and productivity through soil fertility management in the West African Sudano-Sahelian zone

Bationo A.[1], Vanlauwe B[1]., Abdoulaye M.S[2], Adamou A[2]., Kimetu J[1]., Kihara J[1]., Tabo R[2]. and S. Koala[2].
1 T.S.B.F., P.O. Box 30677, Nairobi, Kenya
2 ICRISAT, B.P. 12404, Niamey, Niger

1. Introduction

The Sudano-Sahelian zone of West Africa (SSZWA) is the home of the world poorest people, 90% of whom live in villages and gain their livelihood from subsistence agriculture. Per capita food production has declined significantly over the past three decades. According to FAO, total food production in Sahelian countries grew by an impressive 70% from 1961 to 1996, but it lagged behind the population which doubled, causing food production per capita to decline approximately by 30% over the same period [1].

The present farming systems in the Sahel are unsustainable, low in productivity and destructive to the environment. Plant nutrient balances are negative [2]. The increasing need for cropland has prompted farmers to cultivate more and more marginal lands that are prone to erosion.

In this paper, after a brief presentation of the crop production environment, we will present the state of the art of nitrogen, phosphorus and organic matter management for sustainable land use in the Sudano-Sahelian zone. Before presenting the new opportunities for future research for soil fertility restoration in this zone, we will discuss the effect of different cropping systems on soil fertility and also the main research achievements of the on-farm evaluation of soil fertility restoration technologies.

Land degradation is one of the most serious threats to food production and soil lost through erosion is about 10 times greater than the rate of natural soil formation while deforestation is 30 times greater than of planned reforestation. Buerkert et. Al. (1996a) [3] measured absolute soil lost of 190 t ha^{-1} in one year on bare plots, as opposed to soil deposition of 270 t ha^{-1} on plot with 2 t ha^{-1} millet stover mulch. Sterk et. Al. (1996) [4] reported a total loss of 45.9 t ha^{-1} of soil during four consecutive storms. Buerkert et. Al. (1996b) [5] reported that in unprotected plot up to 7 kg of available P and 180 kg ha^{-1} of organic carbon are lost from the soil profile within one year. Wind erosion will decrease also the exchangeable base and increase soil acidification. Wind erosion constitutes one of the major causes of land degradation. The loss of the top soil which can contain 10 times more nutrients than the sub-soil is particularly worrying, since it potentially affects crop productivity on the long-term by removing the soil that is inherently rich in organic matter.

The data in Table I shows physical and chemical properties of soils in the SSZWA. Most of the soils are sandy. One striking feature of these soils is their inherent low fertility which is expressed in low levels of organic carbon (generally less than 0.3%), low total and available phosphorus and nitrogen and low effective cation exchange capacity (ECEC). The ECEC is attributed to low clay content and the kaolinitic mineralogy of the soils. Bationo and Mokwunye (1991) [6] found that the ECEC is more related to the organic matter than to the clay content, indicating that a decrease in organic matter will decrease the ECEC and then the nutrient holding capacities of those soils. Ridder and Van Keulen (1990) [7] reported that a difference of 0.1% in organic carbon content results in a difference of 4.3 Cmol kg^{-1} in ECEC.

Workshop Bamako,

Table I: Mean and standard deviation of physical and chemical properties of selected West African soils, 0-15 cm

Parameters	Mean	Standard deviation
pH H_2O (2:1 water:soil)	6.17	0.66
pH KCl (2:1 KCl:soil)	5.05	0.77
Clay (%)	3.9	2.67
Sand (%)	88	8
Organic matter (%)	1.4	1.09
Total nitrogen (mg kg^{-1})	446	455
Exchangeable bases (cmol kg^{-1})		
Ca	2.16	3.01
Mg	0.59	0.55
K	0.20	0.22
Na	0.04	0.01
Exchangeable acidity (cmol kg^{-1})	0.24	0.80
Effective cation exchange capacity (ECEC; cmol kg^{-1})	3.43	3.801
Base saturation (%)	88	17
	3	8

Source: [3]

Soil nutrient depletion is a major bottleneck to increased land productivity in the region and has largely contributed to poverty and food insecurity. Soil nutrient depletion occurs when nutrient inflows are less than outflows. Nutrient balances are negative for many cropping systems indicating that farmers are mining their soils. Table II shows the aggregated nutrient budgets for some West African countries.

Table II: Nutrient losses for some West African countries

Country	Area (1000 ha)	Nutrient losses (1000 tons)		
		N	P_2O_5	K_2O
Benin	2972	41.4	10.4	32.5
Burkina Faso	6691	95.4	27.8	78.8
Ghana	4505	137.1	32.3	90.5
Mali	8015	61.7	17.9	66.7
Niger	10985	176.1	55.3	146.6
Nigeria	32813	110.7	316.7	946.2

Source: [2]

Short and intense rainfall storms frequent in the region pose special problems in terms of soil conservation [8]. Charreau (1974) [9] reported on rainfall intensities between 27 to 62 mm h^{-1}. Runoff and soil loss will depend on soil types and erodibility, land form and management system [10].

2. Management of Nitrogen, Phosphorus and Organic Matter

2.1 Nitrogen

2.1.1 Introduction

For many years, several scientists in the Sudano-Sahelian zones initiated research to 1) assess the performance of the different sources of N fertilizers 2) to assess the efficiency of different methods of N placement 3) to calculate ^{15}N balances in order to determine N uptake and losses and 4) to determine efficiency of N under different management systems and the effect of the different soil and agro climatic factors on the performance of N fertilizers [11, 12, 13, 14 and 15].

2.1.2 Efficiency of N fertilizers as affected by N sources, methods of placement and time of application

Chriastainson and Vlek (1991) [13] used data from long-term experiment from the Sudano-Sahelian Zone to develop response function to N by pearl millet and sorghum and found that the optimum rate is 50 kg N/ha for sorghum and 30 kg N/ha for pearl millet. At these N rates the returns were 20 kg grain per kg N for sorghum and 9 kg grain per kg N for pearl millet.

The use of ^{15}N in order to calculate N balances and to determine fertilizers N uptake and losses provide an important tool for nitrogen management. Results with ^{15}N research in early years are reported [11] from which the following conclusion can be made.

1) Apparent uptake of fertilizer N exceeds measured uptake using ^{15}N.
2) Uptake of ^{15}N labelled fertilizer and apparent recovery of unlabelled N decreases with increasing rates of application.
3) Loss of ^{15}N labelled fertilizer to the atmosphere and recovery of ^{15}N in the soil increases with increasing rates of fertilizer application.
4) Estimated losses of N are high regardless of N sources.

The urea and calcium ammonium nitrate (CAN) are the most common sources of nitrogen in the region. Trials were undertaken to evaluate these two sources of nitrogen with basal or split application, banded, broadcast or applied point placed as urea supergranule (USG) or CAN point placed. ^{15}N was applied in microplot in order to construct N balances and to determine N uptake and losses from the different sources of N, methods of application and timing of application.

From the data in table V, VI and VII the following conclusion can be made: 1) Fertilizer N recovery by plant was very low, averaging 25 – 30% over all years. 2) There is a higher loss of N with the point placement of urea (USG) (> 50%) and the mechanism of N loss is believed to have been ammonia volatilization. 3) For all years losses of N from CAN were less than from urea because one-half of the N in CAN is in the non-volatile nitrate form. 4) Although CAN has a lower N content than urea, it is attractive as an N source because of its low potential for N loss via volatilization, and its point placement will improve its spatial availability. The data in Figure 1 clearly indicates that CAN point placed outperformed urea point placed or broadcast and ^{15}N similar trials indicate that ^{15}N uptake by plants was almost three times higher from CAN than that of urea applied in the same manner (Table VII).

Table V: Recovery of ^{15}N in the millet plant and soil at harvest, Sadore, Niger 1982

Treatment	Grain yield[a] (kg ha)	N recovery (%) Grain	Plant[b]	Soil	Loss
Check	590	-	-	-	-
CAN split band	970	20.8	36.8	38.2	25.0
Urea split band	1.070	19.0	31.0	37.3	31.7
Urea split broadcast	1.070	17.0	31.3	41.0	27.7
Urea basal broadcast	1.010	16.9	26.7	41.6	31.7
USG basal	960	16.2	27.5	39.3	33.2
USG split	1.070	14.3	26.5	33.2	40.3
LSD (0.01)	167	4.6	6.0	6.0	9.8

a. Average yield for all N rates for each source
b. Sum of grain and stover ^{15}N
CAN: Calcium ammonium nitrate
USG: Urea super granule
Sources: [16]

Table VI: Yield and recovery of 15N in the millet plant and soil at harvest (1983-85), Sadore, Niger

Year	Treatment	Grain yield[a] (kg ha^{-1})	Stover yield (kg ha^{-1})	^{15}N recovery (%)			
				Grain	Plant[b]	Soil	Loss
1983	Check	660	-	-	-	-	-
	CAN split band	940	-	13.0	28.8	34.2	37.0
	Urea split band	1.040	-	9.8	22.8	39.2	38.0
	USG split	990	-	8.0	22.0	25.3	52.7
	LSD (0.01)	110	-	1.6	3.2	3.4	2.2
1984	Check	460	1.570	-	-	-	-
	CAN split band	480	1.850	9.9	36.8	37.1	26.1
	Urea split band	470	1.930	5.5	20.0	40.1	39.9
	USG split	490	1.780	8.1	21.6	24.8	53.6
	LSD (0.01)	30	220	1.6	3.8	4.2	4.4
1985	Check	900	2.315	-	-	-	-
	CAN split band	1.320	2.910	-	-	-	-
	Urea split band	1.225	3.020	-	-	-	-
	USG split	1.350	3.000	-	-	-	-
	LSD (0.05)	175	386	-	-	-	-

^{15}N was not used in 1985

[a]. Average yield for all N rates for each source

[b]. Sum of grain and stover ^{15}N

CAN: Calcium ammonium nitrate

USG: Urea super granule

Sources: [16]

Table VII. Recovery ^{15}N fertilizer by millet applied at Sadore, Niger, 1985

N source	Application method	^{15}N Recovery			
		Grain	Stover	Soil	Total
		(%)			
CAN	Point incorporated	21.3	16.8	30.0	68.1
CAN	Broadcast incorporated	10.9	10.9	42.9	64.7
Urea	Point incorporated	5.0	6.5	22.0	33.5
Urea	Broadcast incorporated	8.9	6.8	33.2	48.9
Urea	Point surface	5.3	8.6	18.0	31.9
SE		1.2	2.0	1.9	2.4

Sources: [13]

CAN: Calcium ammonium nitrate

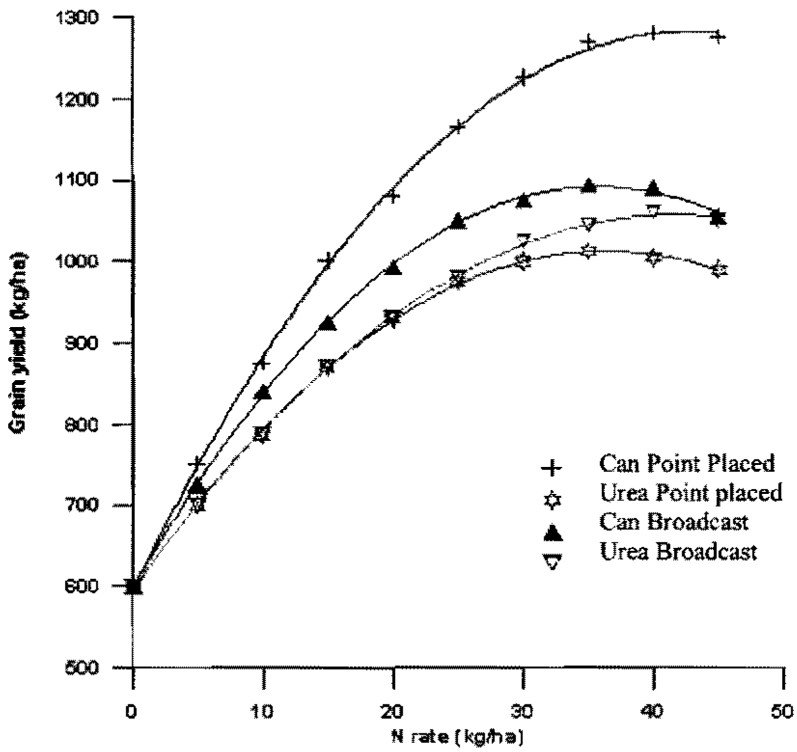

Figure 1: effects of urea and calcium ammonium nitrate application on grain yield, Goberl, Niger, 1985
Source: [13]

2.1.3 Efficiency of N fertilizers as affected by soil and crop management and rainfall

Mughogho et. Al. (1986) [11] found significant relationships between crop yields and N recovery. N losses averaged 20% in the humid and sub-humid zones with maize and were significantly less than the average loss of 40% found over all treatments in the Sudano-Sahelian zone.

In the Sahelian zone, nitrogen use efficiencies of 14% in plots without lime and phosphorus was reported [17] whereas this amount increased to 28% when P and lime were applied.

Rotation of cereals with legumes could be a way to increase N use efficiency. [Bationo and Vlek (1998) [17] reported a nitrogen use efficiency of 20% in the continuous cultivation of pearl millet but its value increased to 28% when pearl millet was rotated with cowpea.

Bationo et. Al. (1989) [12] found a strong effect between planting density and response to N fertilizer. Chriatianson et. Al. (1990) [34] developed a model on the effect of rainfall on N for pearl millet production in the Sahel and found that the response to N was affected by rainfall over a 45 days yield-sensitive period which coincides with the culms elongation and anthesis growth stages for millet (Figure 2).

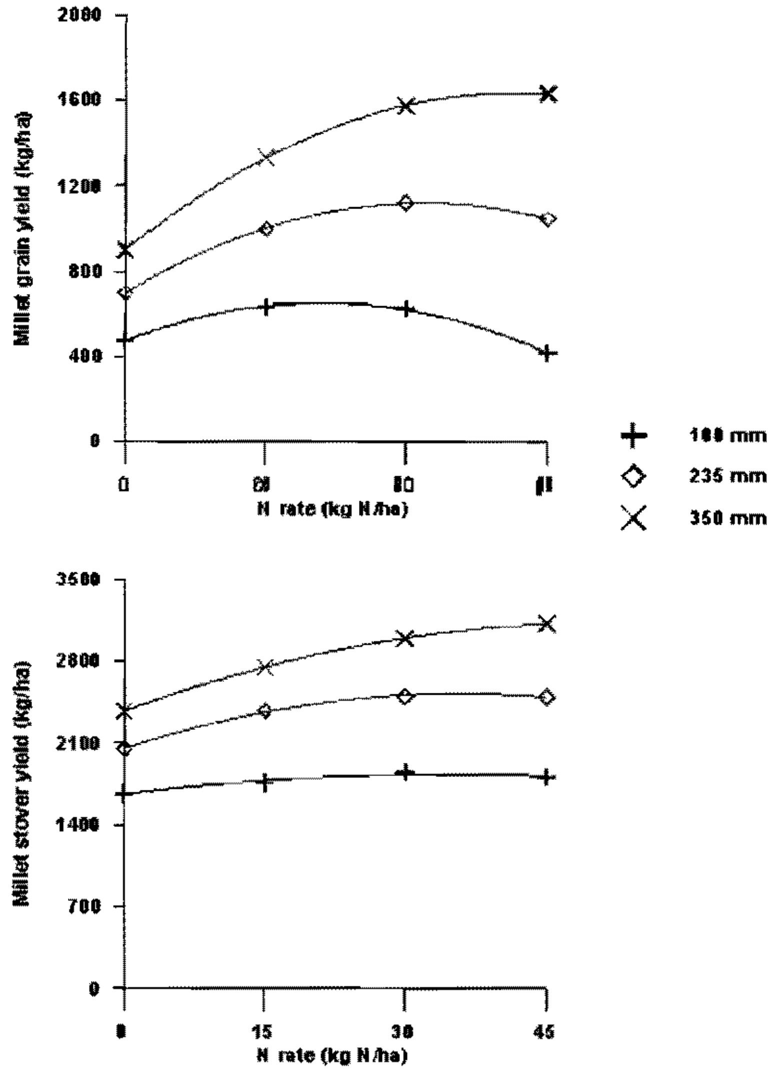

Figure 2: Grain and stover yields affected by N rate and midseason rainfall, Sadore, Niger, 1982-1985. Source: [16]

2.2 Phosphorus sources and management

2.2.1 Introduction

Among soil fertility factors, phosphorus deficiency is a major constraint to crop production in the Sudano-Sahelian zone. For many years, research has been undertaken to assess the extent of soil phosphorus deficiency, to estimate phosphorus requirement of major crops, and to evaluate the agronomic potential of various phosphate rock (PR) from local deposits [18; 19; 20; 21; 22; 23; 24; 25; 26; 27;28; 29; 30; 31]

About 80% of the soils in sub-Saharan Africa are short of this critical nutrient element and without the use of phosphorus, other inputs and technologies are not effective. However, sub-Sahara Africa use 1.6 kg P/ha^{-1} of cultivated land as compared to 7.9 and 14.9 respectively for Latin America and Asia. It is now accepted that the replenishment of soil capital phosphorus is not only a crop production issue, but an environmental issue and P application is essential for the conservation of the natural resource base.

Availability and total P levels of soil are very low in the SSZWA as compared to the other soils in West Africa [25; 32; 33; 34]. For the sandy Sahelian soils total P values can be as low as 40 mg P kg^{-1} and the value of available P less than 2 mg P kg^{-1}. A study of the fertility status of selected pearl millet producing soils of West Africa, [35] found that the amount of total P in these soils ranged from 25 to 340% mg kg^{-1} with a mean of 109% mg kg^{-1}. The low content of both total and available P parameters may be related to several factors including 1) Parent materials, which are mainly composed of eolian sands, contain low mineral reserves and lack primary minerals necessary for nutrient recharge. 2) A high proportion of total P in these soils is often in occluded form and is not available to crop [9]. 3) Low level of organic matter and the removal of crop residue from fields. Organic matter has a favourable effect on P dynamics of the soil; in addition to P release by mineralization, the competition of organic ligands for Fe and Al oxides surface can result in a decrease of P fixation of applied and native P.

The P sorption characteristics of different soil types have been investigated and as compared to the soils of the more humid regions, the soils of the SSZWA have very low capacity to fix P [25; 36; 37; 38]. For pearl millet producing soils, [35] fitted the sorption data to Langmuir equation (Langmuir 1918) and P sorption maximum was determined using the method of [39]. From these representative sites in the Sudano-Sahelian zone the values of maximum P sorbed ranged from 27 mg kg^{-1} to 253 mg kg-1 with a mean of 94 mg kg^{-1}.

Phosphorus deficiency is a major constraint to crop production and response to nitrogen is substantial only when both moisture and phosphorus are not limiting. Field trials were established to determine the relative importance of N, P and K fertilizers. The data in Table VIII indicates that from 1982 to 1986 the average control plot was 190 kg grain ha^{-1}. The sole addition of 30 kg P2O5/ha without N fertilizers increased the average yield to 714 kg ha^{-1}. The addition of only 60 kg N/ha did not increase the yield significantly over the control and the average grain yield obtained was 283 kg ha^{-1}. Those data clearly indicate that P is the most limiting factor in those sandy Sahelian soils and there is no significant response to N without correcting first for P deficiency. When P is applied the response to N can be substantial and with the application of 120 kg N ha-1 a pearly millet grain yield of 1173 kg ha-1 was obtained as compared to 714 kg ha-1 when only P fertilizers were applied. For all the years the addition of potassium did not increase significantly the yield of both grain and total dry matter of pearl millet.

Table VIII: Effect of N, P, and K on pearl millet grain and total dry matter (kg/ha) at Sadoré and Gobery (Niger)

	1982		1983		1984		1985	1986	
Treatments	Sadoré		Sadoré	Gobery	Sadoré		Sadoré	Sadoré	
	Grain	TDM	Grain	Grain	Grain	TDM	Grain	Grain	TDM
N0P0K0	217	1595	146	264	173	1280	180	180	1300
N0P30K30	849	2865	608	964	713	2299	440	710	2300
N30P30K30	1119	3597	906	1211	892	3071	720	930	3000
N60P30K30	1155	3278	758	1224	838	3159	900	880	3200
N90P30K30	1244	3731	980	1323	859	3423	1320	900	3400
N120P30K30	1147	4184	1069	1364	1059	3293	1400	1000	3300
N60P0K30	274	2372	262	366	279	1434	290	230	1500
N60P15K30	816	2639	614	1100	918	3089	710	920	3100
N60P45K30	1135	3719	1073	1568	991	3481	1200	980	3500
N60P30K0	1010	3213	908	1281	923	3377	920	910	3400
S.E.	107	349	120	232	140	320	162	250	400
C.V(%).	24	22	26	30	24	22	28	32	25

N.B. Nutrient applied are N, P_205 and K_20 kg/ha
TDM= Total dry matter

2.2.2 The use of alternative locally available phosphate rock

Despite the fact that deficiency of P is acute on the soils of West Africa, very little P fertilizers is used by local farmers, partially because of the high cost of the imported fertilizers. The use of locally available phosphate rock indigenous in the region could be an alternative to use of high cost imported P fertilizers. The effectiveness of phosphate rock (PR) depends on its chemical and mineralogical composition [40; 41; 42]. The most important feature of the empirical formula of francolite is the ability of carbonate ions to substitute for phosphate in the apatite latice. Smith and Lehr (1966) [43] concluded from their studies that the level of isomorphic substitution of carbonate for phosphate within the latice of the apatite crystal influences the solubility of the apatite in the rock and therefore controls the amount of phosphorus that is released when PR is applied to soil. The most reactive PR are those having a molar PO_4/CO_3 ratio less than 5. West African PR's are not very reactive. Chirn (1977) [44] found that the solubility of PR in neutral ammonium citrate (NAC) was directly related to the level of carbonate substitution. Diamond (1979) [45] proposed a classification of phosphate rock for direct application based on citrate solubility as >5.4% high; 3.2–4.5% medium and <2.7% low. Based on this classification only Tilemsi PR has a medium reactivity.

Environmental conditions, crop types, and management practices control the P supply and hence the effectiveness of a given PR in a given crop management environment, [46]. The ability of the soil to provide H+, soil with low P and Ca, soil moisture, the acidification of the rhizosphere, plants with high root density and high Ca uptake play an important role in P availability from PR [40; 44; 46; 4748].

Bationo et. Al. (1987) [21] have shown that direct application of PR indigenous to the region may be an economical alternative to the use of more expensive imported water-soluble P fertilizers for certain crops and soils. Bationo et. Al. (1987) [21] while evaluating Parc-W and Tahoua PR indigenous to Niger found that PR is only 48% as effective as single superphosphate (SSP), whereas the effectiveness of the more reactive Tahoua rock was as high as 76% of SSP. Further studies [22] showed that Tahoua PR is suitable for direct application, but Parc-W has less potential for direct application. The data from a long-term benchmark experiment show that SSP outperformed the other sources and its superiority to sulphur-free Triple Superphosphate (TSP) indicates that with continuous cultivation, sulphur deficiency develops. For both pearl millet grain and total dry matter yields, the relative agronomic effectiveness was almost similar for TSP as compared to the partially acidulated Parc W phosphate rock (PAPR) with 50% acidulation (PAPR50) indicating that partial acidification of Parc-W PR can significantly increase its effectiveness [1].

2.2.3 Phosphorus (P) placement and P replenishment with Phosphate rock

The data on **Table IX** clearly shows that hill placement of small qualities of P fertilizers will have a higher phosphorus use efficiency (PUE) as compared to the broadcasting of 13 kg P/ha as recommended by the extension services.

Single Superphosphate (SSP), Tahoua Phosphate Rock (TPR) and Kodjari Phosphate Rock (PRK) were broadcast (BC) and/or hill placed (HP). For pearl millet grain P use efficiency for broadcasting SSP at 13 kg P/ha was 18 kg/kg but hill placement of SSP at 4 kg P/ha gave a PUE of 83 kg/kg P. Whereas the PUE of TPR broadcast was 16 kg grain/kg P, the value increased to 34 kg/kg P when additional SSP was applied as hill placed at 4 kg P/ha. For cowpea fodder PUE for SSP broadcast was 96 kg/kg P but the hill placement of 4 kg P/ha gave a PUE of 461 kg/kg P. Those data clearly indicate that P placement can drastically increase P use efficiency and the placement of small quantities of water-soluble P fertilizers can also improve the effectiveness of phosphate rock (**Table IX**).

Table IX: Effect of P sources and placement on pearl millet and cowpea yield (kg/ha) and P use efficiency (PUE) (kg/kg P)

Treatments	Millet in 2001		Cowpea in 2001		Millet in 2002		Cowpea in 2002	
P sources and methods of placement	Grain yield	PUE	Fodder	PUE	Grain yield	PUE	Fodder	PUE
1 Control	468		1406		634		1688	
2 SSP (BC)	704	18	2656	96	887	19	2375	134
3 SSP (BC) + SSP (HP)	979	30	4468	180	1898	74	3125	147
4 SSP (HP)	798	83	3250	461	1026	98	2969	584
5 15-15-15 (BC)	958	38	4250	219	1110	37	3813	245
6 15-15-15 (BC) + 15-15-15 (HP)	1559	64	6500	300	2781	126	5156	266
7 15-15-15 (HP)	881	103	4062	664	1196	141	3531	724
8 TPR (BC)	680	16	2531	86	744	8	2094	112
9 TPR (BC) + SSP (HP)	1048	34	3781	140	1039	24	3375	161
10 TPR (BC) + 15-15-15 (HP)	1065	35	4281	169	1242	36	3844	189
11 PRK (BC)	743	21	2468	82	745	9	2469	141
12 PRK (BC) + SSP (HP)	947	28	4750	197	1002	22	3219	152
13 PRK (BC) + 15-15-15 (HP)	1024	33	5125	219	1171	32	3688	180
SE	46		120		60		222	
CV	18%		11%		10%		14%	

SSP: Single Superphosphate ,15-15-15: N2 P2O5 K2O compound fertilizer
TPR: Tilemsi Phosphate Rock, PRK: Kodjari phosphate rock
BC: Broadcast at 13 kg P/ha, HP: hill placed at 4 kg P/ha
PUE: P use efficiency kg yield/kg P applied

In long-term soil management trials, application of nitrogen, crop residue and ridging and rotation of pearl millet with cowpea were evaluated to determine their effect on PUE. The results show that soil productivity of the sandy soils can dramatically increase with the adoption of improved crop and soil management technologies, whereas the absolute control recorded 33 kg ha^{-1} of pearl millet grains, 1829 kg ha^{-1} was obtained when phosphorus nitrogen and crop residue was applied to the ridged and fallowed leguminous cowpea upon the previous season. Results indicate for the grain yield that PUE increases from 46 with only P application to 133 when P is applied in combination with nitrogen, crop residue and the crop is planted on ridge in a rotation system (Table X).

Table X: Effect of mineral fertilizers, crop residue (CR) and crop rotation on pearl millet yield wasts (kg/ha) and phosphorus use efficiency (PUE) Sadore, Niger, 1998 rainy season.

Treatment	Without CR, Without N				Without CR, With N				With CR, Without N				With CR, With N			
	TDM		Grain		TDM		Grain		TDM		Grain		TDM		Grain	
	Yield	PUE	Yield	PUE	Yield	PUE	Yield	PUE	Yield	PUE	Yield	PUE	Yield	PUE	Yield	PUE
Control	889		33		2037		58		995		61		1471		98	
13 kg P/ha	2704	140	633	46	4339	177	1030	75	4404	185	726	51	240	4594	1212	86
13 kg P/ha + ridge	2675	137	448	32	4057	155	946	68	3685	210	785	56	4530	235	1146	81
13 kg P/ha + rotation	5306	340	1255	94	6294	327	1441	106	5392	338	1475	109	6124	358	1675	121
13 kg P/ha + ridge + rotation	5223	333	1391	104	5818	291	1581	117	6249	404	1702	126	7551	468	1829	133
SE	407		407		407		407		407		407		407		407	

CR Crop Residue; N Nitrogen; TDM Total Dry Matter; PUE (kg grain/kgP); TDM= Total dry matter

2.3 Organic matter management

2.3.1 Introduction

Maintaining soil organic matter is a key to sustainable land use management. Organic matter acts as source and sink for plant nutrients. Other important benefits resulting from the maintenance of organic matter is low-input agro-systems include retention and storage of nutrients, increasing buffering capacity in low activity clay soils, and increasing water holding capacity. Nye and Greenland (1960) estimated that the annual increase in nitrogen under forest fallow was 30 kg N ha^{-1} in the soil and 60 kg N ha^{-1} in the vegetation. For the savanna ecosystems, the annual increase was 10 kg N ha^{-1} in the soil and 25 kg N ha^{-1} in leaves and vegetation. Bationo et. Al. (1995) [49] 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) [6] reported that in the Sudano-Sahelian zone, 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) [7] found that a difference of 1 g kg-1 in organic carbon results in a difference of 4.3 mol kg^{-1}. In many cropping systems few if any agricultural residues are returned to the soil. This leads to decline soil organic matter, which frequently results in lower crop yields or soil productivity.

The concentration of organic carbon in the top soil is reported to average 12 mg kg^{-1} for the forest zone, 7 mg kg^{-1} for the Guinean zone, 4 mg kg-1 in the Sudanian zone and 2 mg kg^{-1} for the Sahelian zone. The soils of the Sudano-Sahelian zone are inherently low in organic carbon. This is due to the low root growth of crops and natural vegetation but also the rapid turnover rates of organic materials with high soil temperature and microfauna, particularly termites. A survey of millet producing soils, [35] 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.

2.3.2 Effect of soil management practices on organic carbon contents

There is much evidence for rapid decline of Corg levels with continuous cultivation of crops in the SSZWA [49]. 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% (1989, Table XI). The data in Table XI 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. The K-value in cotton cereal rotations were 2.8%, lower than the 2.8%, lower than the 2.8% in continuous cotton system. At Nioro-du-Rip in Senegal, soil tillage increased annual Corg losses from 3.8% to 5.2% and annual Corg losses declined from 5.2% without NPK to 3.9% with NPK application.

Table XI: 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.

2.3.3 Effects of crop residues and manure on soil productivity

The Sahelian zone

In long-term crop residue and management trials in the Sahelian zone a very significant effect between crop residue and mineral fertilizer was reported [50]. From this experiments started since 1984 [51] the grain yield declined to 160 kg ha^{-1} in unmulched and unfertilized plots. However, grain yield could be increased to 770 kg ha^{-1} with a mulch of 2 t crop residue per hectare and 1030 kg ha^{-1} with 13 kg P plus 30 kg N ha^{-1}. The combination of crop residue and mineral fertilizers resulted in grain yield of 1940 kg ha^{-1}. The application of 4 t of crop residue per hectare maintained soil organic carbon at the same level as that in an adjacent fallow field in the top soil but continuous cultivation without mulching results in drastic reduction of Corg (Figure 3). In the Sudanian zone, all available reports show a much smaller or even negative effect of crop residue use as soil amendment [49]. In the Sahelian zone the application of crop residue increased soil pH, and exchangeable bases and decrease the capacity of the soil to fix phosphorus.

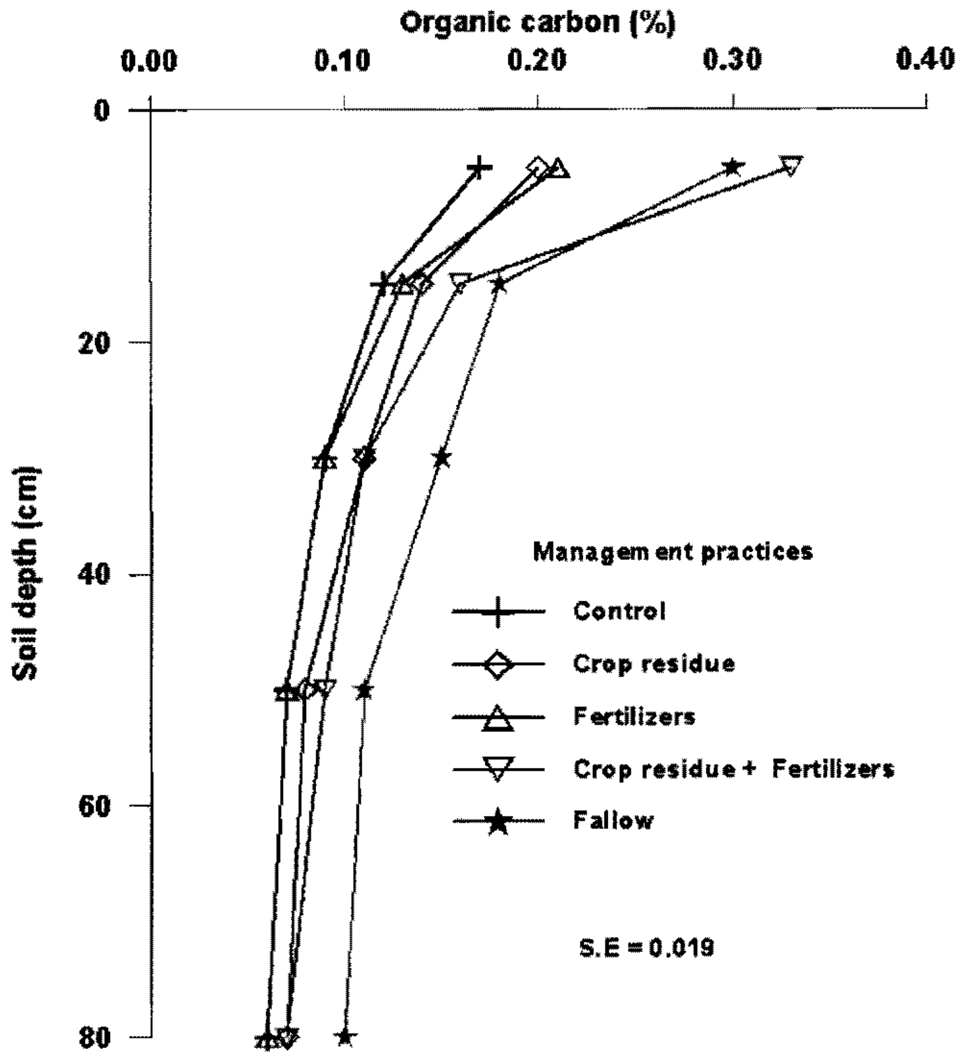

Figure 3: Effect of different management practises on soil organic carbon content after 14 years of cultivation, Sadore, Rainy season 1997

On the nutrient poor West African soil, manure, the second farm-available soil amendment can substantially enhance crop yields. For Niger, McIntire et al. (1992) reported grain yield increase between 15 and 86 kg for millet and between 14 and 27 kg for groundnut per ton of applied manure. Similar manure effects have been reported from other Sahelian countries. However, given the large variation in the nutrient concentration of the manure types applied comparisons between results from different experiments should be made with precaution. Powell et. Al. (1998) [52] found a very significant effect of manure and urine application on pearl millet in the Sahelian zone.

At the farm level, the maintenance of Corg levels in the soils of the region will largely depend on an increase in C fixation by plants. Given the strong limitation of plant growth by the low availability of mineral nutrients, a yield-effective application of mineral fertilizers is crucial. It would not only allow large increase in crop production and the amount of by-products but also to improve soil coverage by forage grass and weeds.

2.3.4 Placement of manure

The placement of manure affects the yield achieved. For instance, a complete factorial experiment was carried out in Niger, West Africa, with three levels of manure (0, 3, 6t/ha) three level of P (0, 6.5 and 13 kg/P ha) using two methods of application (broadcast and hill placement). For pearl millet grain hill placement of manure performed better than broadcasting and with no application of P fertilizer, broadcasting 3 t/ha of manure resulted on pearl millet grain yield of 700 kg/ha whereas the point placement of the same quantity of manure gave about 1000 kg/ha **(Figure 4)**. A similar effect was observed with cowpea.

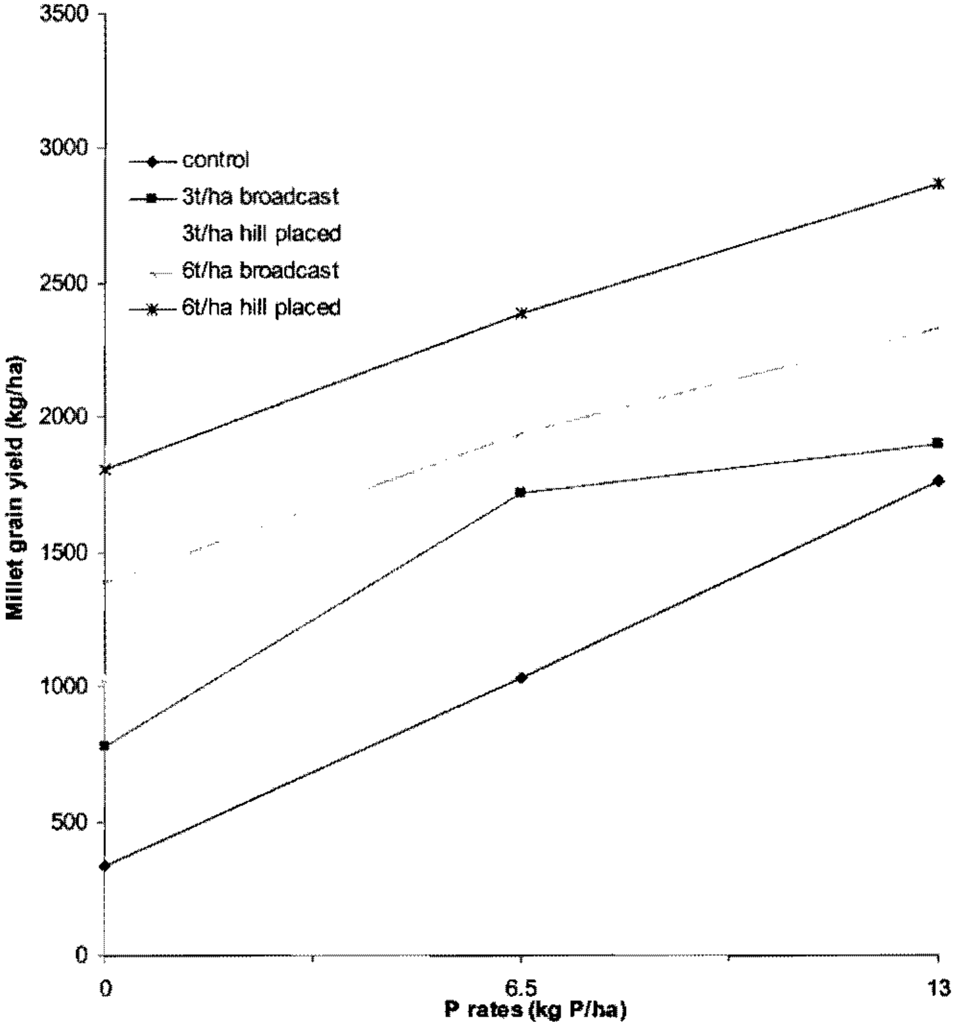

Figure 4: Millet grain yield response to P and manure applied at different rates and methods, Karabedji, Niger, 2002 rainy season

2.4 Combining organic and inorganic plant nutrients in production

Combined application of organic resources and mineral inputs forms the technical backbone of the Integrated Soil Fertility Management approach. The data in Table XII 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. Successive levels of manure from 2-8 tonnes per ha, with reduction in inorganic P applied resulted to increased yield upto 5718kg/ha.

Table XII: Optimum combination of plant nutrients for cowpea fodder in the Sahel (kg/ha)

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%

In Mali, low quality manures derived from livestock fed predominantly with rice residues were used in combination with urea-N at 0, 30, 60, 90 and 120kg ha-1. The research showed that application of 90-120 kg N gave the highest paddy yield (approx 7.5 t ha-1) thereby doubling yield over the control. Integration with manure did not significantly increase the rice yields at any N levels; rather there was a slight additive effect of applying the low quality material.

In Burkina Faso, low quality manure (<1.0%N) applied at 1, 2, 3 and 4 tons dry matter per hectare was combined with urea-N at 0, 40, 80 and 120 KgNha-1. Applications of N alone doubled rice grain yield over the unfertilized control. There was an additive increase when organic matter was integrated with inorganic-N at all manure levels, however this increase was not significant.

At Zaria, Nigeria, low quality manure that is typical of farmer organic resource input was applied at 1, 2, 3 and 4 t dm ha-1 and combined with 0, 30, 60 and 90 kg N ha-1 in a split plot design arrangement where the main plots were treated with N at 4 levels and the sub-plots received manure inputs at 4 levels. The results were only insignificant additive effects of manure and fertilizer combinations were not significant indicating that these manures contributed little to the N demand for the maize crop. However, these low quality manures can contribute significantly to overcome P deficiency to maize crop as shown in Figure 5.

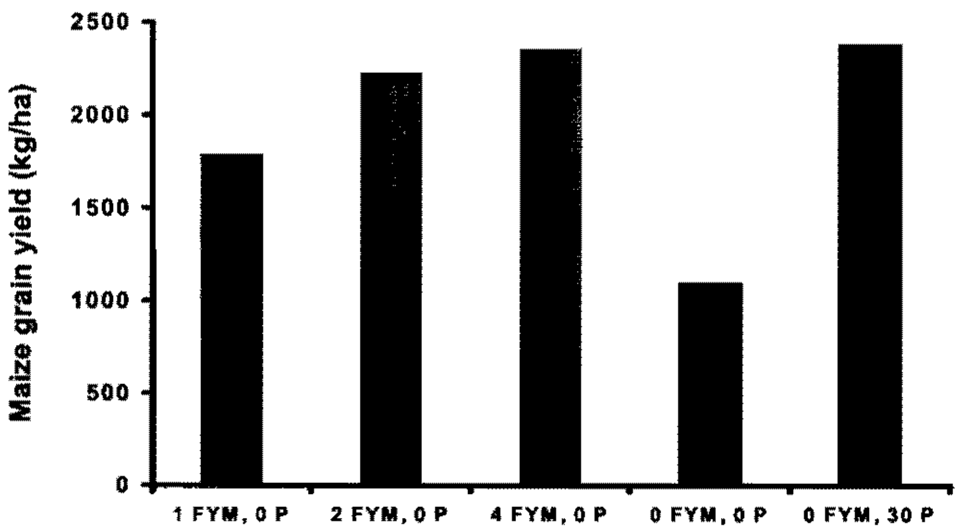

Figure 5. Use of low quality manure (<1%N) to alleviate P deficiency in maize crops in Zaria, Nigeria, 2001

2.4.1 Interactions of N, P and manure.

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) established in Banizoumbou to assess the fertilizer equivalency of manure for N and P established a very significant effect of N, P and manure on pearl millet yield **(Table XIII)**. 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 factors at this site. Manure account for 8% in the total variation.

Table XIII: Fertilizers equivalency of manure at Banizoumbou, Niger, in two cropping seasons in 2001 and 2002

Parameters	Growing season in 2001		Growing season in 2002	
	Grain (kg/ha)	Total dry matter (kg/ha)	Grain (kg/ha)	Total dry matter (kg/ha)
Absolute control	290	1275	338	1238
Control for N	1210	4550	1008	3895
Control for P	635	2280	916	3545
% N in manure	0.71	0.71	1.6	1.6
% P in manure	0.18	0.18	0.32	0.32
Yield at 2t/ha of manure without N	1530	5450	1167	4746
Yield at 4t/ha of manure without N	1695	4855	1609	5640
Yield at 2t/ha of manure without P	810	2910	1229	4659
Yield at 4t/ha of manure without P	1070	3625	1411	5294
Equivalent N for 2t/ha of manure	41.53	38.90	8	13
Equivalent N for 4t/ha of manure	*	21.1	49	33
Equivalent P for 2t/ha of manure	3	2.71	8.7	7.2
Equivalent P for 4t/ha of manure	7.5	5.57	11.8	9.6
N fertilizer equivalency at 2t/ha of manure	292	273	25	41
N fertilizer equivalency at 4t/ha of manure	*	74	77	52
P fertilizer equivalency at 2t/ha of manure	83	75	136	113
P fertilizer equivalency at 4t/ha of manure	104.1	77	92	75

Grain production with manure and no P was lower than with manure and no N indicating the importance of P in this site. Addition of both manure and nitrogen fertilizer increases the yields though using equivalent N for 2t/ha of manure was even better.

Superior results following combination of crop residues and inorganic fertlizer have 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 XIV)**. In this split-split-plot design the split-split plot consisted of crop residue application or no crop residue application consisting of leaving half of the total crop residue produced in the plot and the sub-sub plot was with or without nitrogen application.

Table XIV: Effect of fertilizer, crop residue, tillage and rotation on cowpea and millet yield, Sadore, Niger 1998-2002

Main treatments in the operational scale	**-CR-N**				**-CR+N**				**+CR-N**				**+CR+N**			
	MG	**I. MT**	**CG**	**CF**	**MG**	**II. MT**	**CG**	**CF**	**MG**	**III. MT**	**CG**	**CF**	**MG**	**IV. MT**	**CG**	**CF**
1= Traditional practices	118	822	40	256	177	1207	50	348	197	1141	51	416	295	1467	43	427
2= Animal traction (AT) +no rotation +Intercropping + P	463	2248	54	235	567	2556	50	263	596	2766	52	247	736	3410	59	278
3= Animal traction (AT) + rotation +Intercropping + P	777	3591	68 *94*	431 *490*	923	4011	96 *99*	542 *539*	939	4117	106 *115*	602 *720*	1107	4788	111 *120*	713 *871*
4= Hand Cultivation (HC) +no rotation +Intercropping + P	389	1971	48	326	596	2618	68	536	627	2920	43	392	768	3498	66	659
5= Hand Cultivation (HC) + rotation +Intercropping + P	769	3578	72 *132*	199 *744*	868	4139	86 *122*	235 *883*	981	4430	49 *150*	234 *1084*	1104	5044	54 *153*	262 *1314*
6= Animal traction (AT) +no rotation +Pure millet + P	484	2110			646	2751			626	2669			846	3520		
7= Animal traction (AT) + rotation + Pure millet + P	802	3427	90	352	957	4108	66	440	1033	4348	84	420	1141	5155	87	673
8= Hand Cultivation (HC) +no rotation + Pure millet + P	526	2219			785	3028			708	2875			1065	3835		
9= Hand Cultivation (HC) + rotation + Pure millet + P	818	3524	156	1044	1030	4139	138	1269	1135	4305	120	1001	1301	4929	126	1216
SE	43	149	12	83	43	149	12	83	43	149	12	83	43	149	12	83
CV	27%	21%	69%	66%	27%	21%	69%	66%	27%	21%	69%	66%	27%	21%	69%	66%

Numbers in italic are sole cowpea yield in rotation.

2.5 Relationships between cropping systems and fertility management

2.5.1 Intercropping

Fussell and serafini (1985) [53] reported yield advantages from 10-100% in millet-cowpea systems. Yield stability has been proposed as a major advantage of intercropping as farmers want to rely on management practices that increase yields, when this is possible, while improving the stability of the production in both good and poor rainfall years. Relative stability of intercropping and cropping using stability analysis have been compared [54 and 55] and found that in the groundnut/cereal systems in northern Nigeria, intercropping systems were found to be more stable. Ntare (1989) [56] reported yield advantages of 20-70% depending on the different combinations of pearl millet and cowpea cultivars. Although traditional intercropping cover over 75% of the cultivated area in the SSZWA, there is a scarcity of information on the efficiency of fertilizers under these systems. The number of days before planting the second crop will depend on the importance of the next rains after the first cereal crops have been planted. With a basal application of P fertilizers the cereal growth is rapid and can suppress completely the second crop if its planting occurs after three weeks after the cereal crops have been sown. In contrast if the legume crops is planted early it will compete more with the cereal crop for light, water and nutrients and can significantly reduce the yield of the cereal crop.

2.5.2 Relay and sequential cropping

In the Sudanian zone with longer growing season and higher rainfall there is greater opportunity than in the Sahelian zone to manipulate the systems with appropriate genotypes and management systems. Field trials have been conducted 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 [57; 58].

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 [59].

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.

2.5.3 Crop rotation

Despite the recognised need to apply chemical fertilizers for high yields, the use of fertilizers in West Africa is limited by lack of capital, inefficient distribution systems, poor enabling policies and other socio-economic factors. Cheaper means of improving soil fertility and productivity are therefore necessary.

^{15}N has been used to quantify the amounts of nitrogen fixed by cowpea and groundnut under different soil fertility levels. The nitrogen derived from the air (NDFA) varies from 65 to 88% for cowpea whereas the values varied from 20 to 75% for groundnut. In the complete treatment where all nutrients were applied cowpea stover fixed up to 89 kg N ha^{-1} whereas for same treatment groundnut fixed only 40 kg N ha^{-1} in this Sahelian environment. In order to determine ^{15}N recovery from different cropping systems, labelled nitrogen fertilizers were applied to microplots of pearl millet grown continuously, in rotation with cowpea, in rotation with groundnut, intercropped with cowpea, and intercropped with groundnut. The data indicates that nitrogen use efficiency increased from 20% in continuous pearl millet cultivation to 28% when pearl millet was rotated with cowpea [17]. 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 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.

The different cropping systems have a significant effect on the soil organic carbon. The soil organic carbon levels was 0.22% in the continuous systems whereas it is increased to 0.27% in the rotation systems. As a result of this soil pH was higher in the rotation systems as compared to the continuous monoculture.

An on-going experiment in the Sahel region involving a combination of rotation, inorganic and organic nutrient sources has clearly indicated the high potential to increase the staple pearl millet yields in the very poor Sahelian soils (**Table XV**)

Table XV: Effect of fertilizers, soil tillage, crop residue, cropping system on pearl millet grain yield; Sadore 2001-2 cropping season.

Treatments	Pure millet grain yield (kg/ha) in 2001								Pure millet grain yield (kg/ha) in 2002							
	- Rotation				+ Rotation				- Rotation				+ Rotation			
	- Crop residue		+ Crop residue		- Crop residue		+ Crop residue		- Crop residue		+ Crop residue		- Crop residue		+ Crop residue	
	-N	+N	-N	+N	-N	+N	-N	+N	-N	+N	-N	+N	-N	+N	-N	+N
Traditional	146	181	331	473					104	104	156	183				
Phosphorus + HC	873	1145	1247	1649	703	1067	1649	1866	244	337	438	594	583	667	724	807
Phosphorus + AT	708	816	935	1114	904	1225	1381	1529	280	355	456	574	586	788	781	903

HC: hand cultivation, planting on flat; AT: Animal traction, planting on ridges

3. Farmers evaluation of soil fertility restoration technologies

3.1 Effects of soil fertility restoration technologies on land productivity from farmers managed trials in the SSZWA

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 on 56 plot per treatment 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 plus hill placement of 4 kg P/ha as NPK compound fertilizers.

There was no difference between hill placement of DAP and 15-15-15 indicating that with the 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 about additional 300 kg/ha of pearl millet grain (**Figure 6**). 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. Similar results have been found by [60 and 61]

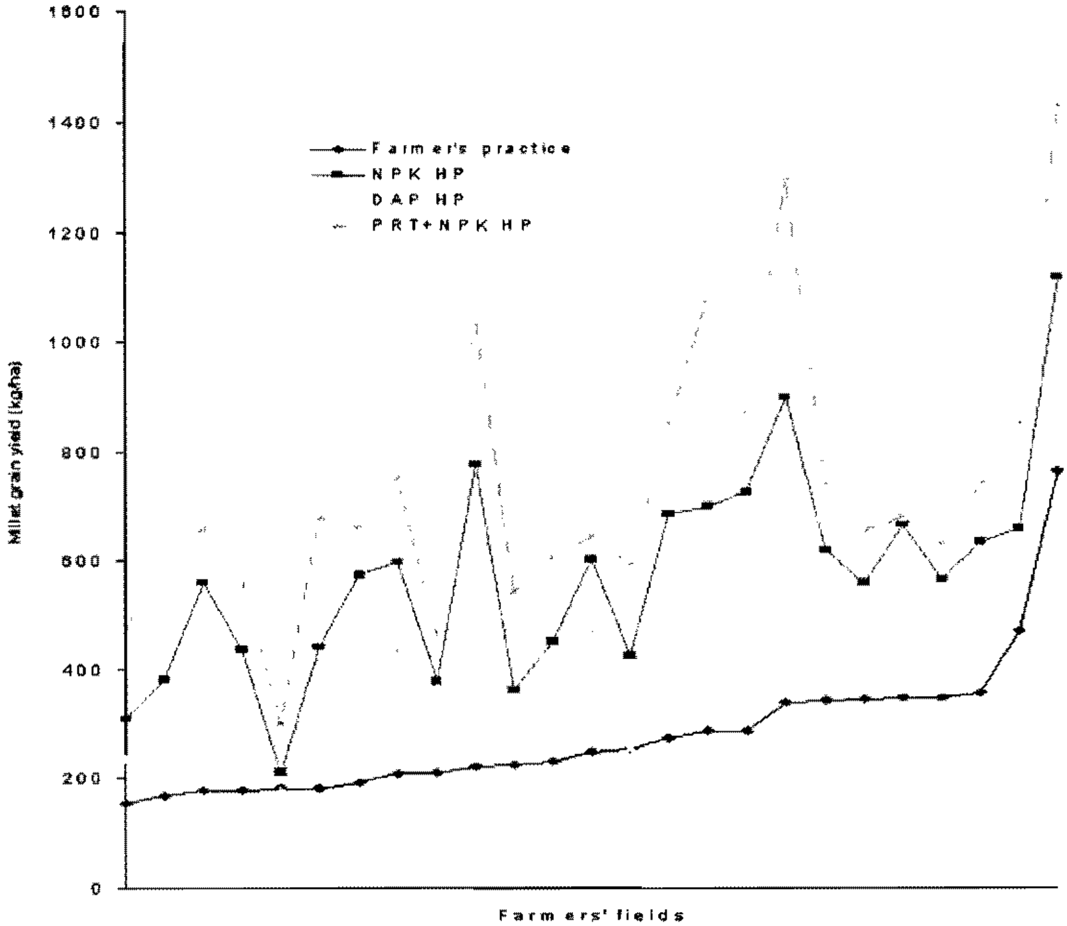

Figure 6: Millet grain response to different management practices, Gaya, Niger, 2002 rainy season

4. New research opportunities in the SSZWA

4.1 New strategies for integrated nutrient management

In the past, integrated nutrient management concentrated mainly on the utilization of available organic and inorganic sources of plant nutrients in a judicious and efficient way. Integrated nutrient management is recently perceived much more broadly as the judicious manipulation of all soil nutrient inputs and outputs and internal flows.

Future research needs to adopt this new holistic approach to integrated nutrient management. For a given cropping system or watershed, this will require the establishment of the nutrient balances. Interventions to limit nutrient losses through erosion can be in some cases as important as research on increasing the efficiency of organic and inorganic plant nutrients for a sustainable land use. This new approach will enhance more carbon sequestration and increase more bio-mass production on the farms for domestic use and there will be more bio-man available for livestock feeds and for soil mulching.

4.2 Integration of socio-economic and policy research with the technical solution

In the past several technical solutions to the problem of land degradation in the SSZWA have been researched and tested, and may have shown the potential for addressing the problem in some places. Unfortunately a review of the state of the art indicated that very few of these technologies have been adopted by the resource poor farmers. Therefore future research should focus more on problems driven by socio-economic factors and enabling policy environment in order to enhance farmers' capacity to invest in soil fertility restoration. The adoption of the participatory approach will be essential. In this way, the technologies generated have a better chance of adoption by land users.

4.3 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.

4.4 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.

4.5 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-Azbuscular Mycorrhizal (VAM) for better utilization of P applied as indigenous phosphate rock.

4.6 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.

References

[1] Bationo, A. Chien, S.H. and Mokwunye, A.U. 1986. Chemical characteristics and Agronomic value of some phosphorus rocks in West Africa. Papier presented at International Symposium on Drought in sub saharan Africa. Nairobi, Kenya, May 19-23, 1986.

[2] Stoorvogel, J.J., E.M.A. Smaling. 1990 Assessment of soil nutrient depletion in sub-Saharan Africa: 1983-2000. Volume 1. Main report. The Winand Staring Centre, Wageningen, The Netherlands.

[3] Buerkert, A., J.P.A. Lamers, H. Marschner, and A. Bationo. 1996a. Inputs of mineral nutrients and crop residue mulch reduce wind erosion effects on millet in the Sahel. In: B. Buerkert, B.E. Allison and M. von Oppen (Eds.). Wind Erosion in West Africa. The problem and its control. Proc. Intern. Symp., Univ. Hohenheim, Stuttgart, Germany, 5-7 Dec. 1994. pp. 145-160.

[4] Sterk, G., L. Herrmann and A. Bationo. 1996. Wind-blown nutrient transport and soil productivity changes in southwest Niger. Land Degradation and Development 7: 325-335.

[5] Buerkert, A. K. Michels, J.P.A. Lamers, H. Marshner and A. Bationo. 1996b. Anti-erosive, soil physical, and nutritional effects of crop residues. In: B. Buerkert, B.E. Allison and M. von Oppen (Eds.). Wind Erosion in Niger. Kluwer Academic Publishers in cooperation with the University of Hohenheim. Dordrecht, The Netherlands. p. 123-138.

[6] 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.

[7] 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

[8] Kowal, J.M. and Kassam, A.H. 1978. Agricultural ecology of Savanna; a study of west Africa. Oxford, UK: Clarendon Press. 403 pp

[9] Charreau C. 1974. Soils of tropical dry and dry-wet climatic areas of west Africa and their use and management. A series of lectures. Agronomy Mimeo 74-26. Ithaca, New York, USA: Cornell University, Department of Agronomy, 434 p

[10] Lal, R. 1980. Soil erosion as a constraint to crop production. Page 405-423. In Priorities for alleviating soil related constraints to food prodution in the tropics> Los Baños, Laguna, Philippines: International Rice Research Institute.

[11] Mughogho S K, Bationo A, Christianson C B and Vlek P L G 1986 Management of nitrogen fertilizers for tropical African soils, in A U Mokwunye and P L G Vlek (eds) Management of nitrogen and phosphorus fertilizers in sub-Saharan Africa, Martinus Nijhoff, Dordrecht, The Netherlands

[12] Bationo A, Christianson CB and Baethgen WE (1989) Plant density on plant millet production in a sandy soil of Niger, Agronomy J 82:290-295

[13] Christianson C B and P L G Vlek 1991 Alleviating soil fertility constraints to food production in West Africa: Efficiency of nitrogen fertilizers applied to food crops. In A U Mokwunye (ed). Alleviating soil fertility constraints to increased crop production in West Africa. Kluwer Academic Publishers, Dordrecht. The Netherlands

[14] Ganry F, Rideau J and Nicoli J (1973) The effect of nitrogenous fertilizers and organic materials on yields and nutritional value of Souna III millet. Technical report – Institute for Agricultural Tropical Research in Senegal (Bambey, Senegal)

[15] Gigou J, Ganry F and Pichot J (1984) The nitrogen balance in some tropical agrosystems. Paper presented at the International Symposium on Nitrogen Management in Farming Systems in the Tropics, Ibadan, Nigeria, October 1984.

[16] Christianson CB, Bationo A, Henao J and Vlek PLG (1990) Fate and efficiency of N fertilizer applied to millet in Niger. Plant and soil 125:221-231

[17] 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.

[18] Goldsworthy PR 1967 Responses of cereals to fertilizers in northern Nigeria. II. Maize Expl Agric 3 263-273
[19] Pichot J and Roche P 1972 Le phosphore dans les sols tropicaux. Agron Trop 27: 939-965
[20] Thibout F, Traore MF, Pieri C and Pichot J 1980 L'utilisation agricole de phosphate naturels de Tilemsi (Mali): synthese de resultants de la recherché agronomique sur les cultures vivrieres et oleagineuses. Agron Trop 35: 240-249
[21] Bationo A, C B Christianson and A U Mokwunye (1987) Soil fertility management of the millet-producing sandy soils of Sahelian West Africa: The Niger experience. Paper presented at the Workshop on soil and crop management systems for rainfed agriculture in the Sudano-Sahelian zone, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Niamey, Niger.
[22] Bationo A, S H Chien, C B Christianson, J Henao, and A U Mokwunye (1990) A three year evaluation of two unacidulated and partially acidulated phosphate rocks indigenous to Niger Soil Sci. Soc. Am. J.54:1772-1777
[23] Hauck FW 1966 Fertilizer needs and effectiveness with tropical crops in West Africa, FFHC Bulletin, Rome: FAO
[24] Jones MJ 1973 A review of the use of rock phosphate as fertilizer in Francophone West Africa. Samara misc paper 43, Institute for Agricultural Research, P.M.B. 1044 Zaria
[25] Juo A S R, and R L Fox 1977 Phosphate sorption characteristics of some benchmark
[26] Kang BT and Osiname AO 1979 Phosphorus response of maize grown on alfisols of southern Nigeria, Agron J 71, 873-877
[27] Boyer S 1954 L'emploi des phosphates de thies dans l'agriculture Senegalaise, CR 2nd Conf Interafr de Sols. Leopoldvill, p 1395
[28] Nabos J, Charoy J and Pichot S 1974 Fertilization phosphates de sols du Niger, utilization des phosphates naturels de Tahoua. Agron Trop 29, 1140-1150
[29] Juo ASR and Kang BT 1978 Availability and transformation of rock phosphates in three forest soils from southern Nigeria. Comm Soil Sci and Plant Analysis 9, 495-505
[30] Mokwunye U 1979 Phosphorus fertilizers in Nigerian savanna soils. II. Evaluation of three phosphate sources applied to maize at Samaru. Trop Agric. (Trinidad) 56, 65-68
[31] Truong B, Pichot J and Bennard P 1978 Caracterisation et comparaison des phosphates naturels tricalciques d'Afrique de l'ouest en vue de leur utilization directe en agriculture. Agron Trop 33, 136-145
[32] Bache B W and N E Rogers 1970 Soil phosphate values in relation to phosphate supply to plants from some Nigerian soils. J. Agric. Sci., Camb. 74:383-390
[33] Mokwunye U 1974 Some reflections on the problem of "available" phosphorus in soils of tropical Africa, Samaru Conf. Pap. 3:1-11
[34] Jones M J and A Wild 1975 Soils of the West African savanna. Commonw. Bur. Soils Tech. Comm. No. 55, Harpenden, England
[35] 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.
[36] Sanchez P A and G Uehara, 1980 Management considerations for acid soils with high phosphorus fixation capacity. In The role of phosphorus in agriculture. F.E. Khasawneh (eds). Am. Soc. Agron., Madison, WI, pp. 471-509
[37] Udo E J, and J A Ogunwale 1972 Characteristics of phosphorus adsorption by some Nigerian soils. Soil Sci. Soc. Am. J. 36:879-883
[38] Syers J K, T D Evans, J D H Williams, and J T Murdock 1971 Phosphate sorption parameters of representative soils from Rio Grande du Sol, Brazil. Soil Sci. 112:267-275
[39] Fox R L, and E J Kamprath 1970 Phosphate sorption isotherms for evaluating the phosphate requirements of soils. Soil Sci. Soc. Am. Proc. 34:902-907
[40] Khasawneh, F.E. and E.C. Doll 1978. The use of phosphate rock for direct application to soils. Adv. Agrono. 30:155-206.
[41] Lehr, J.R. and McClellan, G.H. 1972. A revised laboratory reactivity scale for evaluating phosphate rocks for direct application, Bulletin 43, Tennessee Valley Authority, Muscle Shoals, AL, U.S.A.
[42] Chien S H and L L Hammond 1978 A simple chemical method for evaluating the agronomic potential of granulated phosphate rock. Soil Sci Soc Am J. 42:615-617

[43] Smith, J.P. and J.R. Lehr 1966. An X-ray investigation of carbonate apatites. J. Agric. Food Chem. 14:342-349.
[44] Chien, S.H. 1977. Thermodynamic considerations on the solubility of phosphate rock. Soil Science 123:117-121.
[45] Diamond, R.B. 1979. Views on marketing of phosphate rock for direct application. Halifa, Israel. March 20-23, 1978. pp. 448-463. Special publication. IFDC-S1. International Fertilizer Development Center, Muscle Shoals, Alabama, U.S.A.
[46] Mokwunye, A.U. 1995. Reactions in soils involving phosphate rocks. In Henny Gerner and A.U. Mokwunye (Eds.). Use of Phosphate Rocks for Sustainable Agriculture in West Africa. IFDC-Africa.
[47] Kirk, G.J.D. and P.H. Nye 1986. A simple model for predicting the rate of dissolution of sparingly soluble calcium phosphate in soil. I. The basic model. J. Soil Sci. 37:529-540.
[48] Hedley, M.J., P.H. Nye, and R.E. White 1982. Plant-induced changes in the rhizosphere of rape (Brassica napus var. Emerad) seedlings. II. Origin of the pH change. New Phy. 91:31-44.
[49] 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.
[50] Bakayoko M, Buerkert A, Lung A, Bationo A, and Romheld V 2000 Cereal/legume rotation effects on cereal growth in Sudano-Sahelian West Africa: soil mineral nitrogen, mycorrhizae and nematodes. Plant and Soil 218: 103-116.
[51] Bationo A Christianson BC and Klaij MC (1993) The effect of crop residue and fertiliser use on pearl millet yields in Niger. Fert Res 34:251--258.
[52] 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.
[53] 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
[54] Baker E F I 1980 Mixed cropping in northern Nigeria. IV. Extended trials with cereals and groundnuts. Experimental Agriculture 16:361-369
[55] 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
[56] Ntare B R 1989 Intercropping morphologically different cowpea with pearl millet in a short season environment in the Sahel. Experimental Agriculture 26. 41-47
[57] ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1985. Annual report 1984. Patancheru, A.P. 502 324, India: ICRISAT.
[58] ICRISAT, 1984-1988, Annual Report, 1984 to 1988. Patancheru, A.P. 5023, India,
[59] 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.
[60] Bationo A, Ayuk E D, Ballo and Kone M 1997. Agronomic and economic evaluation of Tilemsi phosphate rock in different agro-ecological zones of Mali. Nutrient Cycling in Agroecosystems 48: 179-189.
[61] Bationo, A., J. Ndjeunga, C. Bielders, V.R. Prabhakar, A. Buerkert and S. Koala. 1998. Soil fertility restoration options to enhance pearl millet productivity on sandy sahelian soils in south-west Niger. In: Peter Lawrence, Geneviève Renard and Matthias von Oppen (Eds.) The Evaluation of Technical and Institutional Options for Small Farmers in West Africa. Proceedings of an International Workshop held on April 21-22-1998 at the University of Hohenheim as part of the Special Research Programme 308. Adapted Farming in West Africa. Margraf Verlag, Weikersheim, Germany.