Journal of Agricultural Science, *Cambridge* (2000), **134**, 277–284. *Printed in the United Kingdom*

Rotation and nitrogen fertilizer effects on pearl millet, cowpea and groundnut yield and soil chemical properties in a sandy soil in the semi-arid tropics, West Africa

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(*Revised MS received 25 October 1999*)

SUMMARY

A 5-year study was conducted from 1988 to 1992 at three sites in Niger to determine the effects of crop rotation of a cereal and legumes and nitrogen fertilizer on chemical properties of the soil (0–20 cm) and yield of pearl millet (*Pennisetum glaucum* (L.) R.BR.), cowpea (*Vigna unguiculata* (L.) Walp.), and groundnut (*Arachis hypogea* L.). Four N levels and rotation treatments including continuous fallow were investigated. Soil samples taken from the top 20 cm depth at the end of the experiment from treatments without nitrogen application which included continuous fallow, fallow–millet rotation, groundnut–millet rotation, cowpea–millet rotation, and continuous millet were analysed for soil pH, organic carbon, total nitrogen and exchangeable bases. Fertilizer N significantly increased yield of pearl millet, cowpea and groundnut. Continuous monocropping of pearl millet resulted in lower yields across N levels compared to legume–millet rotations. Legume yields were also consistently lower in monoculture than when rotated with millet. There was a decline in organic matter under continuous millet, cowpea–millet rotation and groundnut–millet rotation. The fallow–millet rotation supplied more mineral N than the legume–millet rotations. Nitrogen availability was greater in cowpea–millet rotation than continuous millet. Crop rotation was more productive than the continuous monoculture but did not differ in maintaining soil organic matter. The legume–millet rotation at 30 kg/ha N appears to be the most viable for millet production. Research should focus on understanding the effect of legume/cereal intercrops and rotations on soil productivity.

INTRODUCTION

Intensity of land use in West African semi-arid tropics associated with increasing human population pressure, puts a high demand on maintenance and improvement of soil fertility. The period of the traditional bush-fallow system of restoring soil productivity has reduced leading to continuous cultivation. This makes farming more fertilizer-dependent for high yields. Long-term fertilizer experiments in West Africa have shown that fertilizer application is an effective means of increasing crop yields (Pieri 1986, 1989).

Traditional cropping systems in semi-arid West Africa are dominated by cereal-based systems, with mixtures of pearl millet, sorghum, cowpea and groundnut being the most important. Intercropping is used by farmers to minimize risks and spread labour peaks (Norman 1974). It enables them to spread risks over two crops and also to exploit the long rainy season during a good year. In these mixtures, legumes are often grown between cereal rows at very low densities. In the case of cowpea grain yield is further limited by the numerous insect pests. In these combinations legume grain and fodder yields are very poor (Ntare 1989; Reddy *et al*. 1992). Similarly, yields of intercropped millet are less than those in sole millet since they are affected by factors such as low plant density, planting dates and spatial arrangements of the component crops (Ntare *et al*. 1989). In many areas crop residues of cereals and legumes are the

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Table 1. *Physical and chemical properties of soils at the experiment sites measured from a bulk sample before planting*

Soil properties	Sadore	Bengou	Tara
Clay (%)	1·00	3·9	1·3
pH (KCl)	4·10	4·3	4·1
Exchangeable acidity (cmol/kg)	0·23	0·20	0·39
Organic matter (%)	0·22	0·20	0·45
Total N (ppm)	74	226	197
Effective cation exchange capacity (cmol/kg)	0·54	1·87	1·20
Base saturation (%)	57	89	58
Total P (mg/kg)	68	96	129
Available P (Bray P1) (mg/kg)	2·3	6·9	3·3
Maximum P sorbed (b) (mg/kg)	52	101	129

Table 2. *Crop rotation and their different phases in 1989–1992*

Treatments number	1988	1989	1990	1991	1992
1	Fallow	Fallow	Fallow	Fallow	Fallow
2	Fallow	Millet	Fallow	Millet	Fallow
3	Millet	Fallow	Millet	Fallow	Millet
4	Millet	Millet	Millet	Millet	Millet
5	Millet	Cowpea	Millet	Cowpea	Millet
6	Cowpea	Millet	Cowpea	Millet	Cowpea
7	Cowpea	Cowpea	Cowpea	Cowpea	Cowpea
8	Groundnut	Groundnut	Groundnut	Groundnut	Groundnut
9	Millet	Groundnut	Millet	Groundnut	Millet
10	Groundnut	Millet	Groundnut	Millet	Groundnut

main source of livestock feed. Groundnut and cowpea fodder is an important source of cash income during the long dry months in the Sahel.

Under the increasing demographic and ecological pressures in the region, the traditional systems of crop production are unable to meet people's food needs. Ensuring some degree of yield stability for the farmers who face increasing climatic risks has become a priority for national governments and research institutions in the region. The only way to sustain productivity in these agricultural risky areas is through the use of production systems which are based on increased yield and/or biomass.

Despite the recognized 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.

Increasing yield by practicing crop rotation has been known for many years (Bullock 1992), but is rarely practiced by farmers in West Africa. Past research on crop rotation involving millet has mainly compared the effects of rotation and continuous cropping on yields (Lombin 1981; Stoop & Staveren 1981; Reddy *et al*. 1992). Information on the effects of these cropping systems on the soil characteristics is limited.

It is not well understood what causes rotation effects. It has been assumed by many that the positive effects of rotations arise from the added N from legumes in the cropping system. Some workers, however, have attributed the positive effects of rotations to the improvement of soil biological and physical properties (Hoshikawa 1990) and the ability of some legumes to solubilize occluded P and highly insoluble calcium-bound phosphorus by legume root exudates (Gardener *et al*. 1981; Arihara & Ohwaki 1989). Other advantages of crop rotation include soil conservation (Stoop & Staveren 1981), organic matter restoration (Spurgeon & Grissom 1965) and pest and disease control (Curl 1963; Sinnadurai 1973). However, these factors do not explain the entire yield increase associated with rotations in all cases. Some short-term rotations result in a degradation of those same factors yet the rotation effects are still realized.

The objective of our study was to investigate the effect of continuous monoculture, crop rotation, N fertilizer practices on yield and soil chemical properties.

MATERIALS AND METHODS

An experiment was conducted at three sites in Niger from 1988 to 1992. The sites were Sadore (13° 15′ N latitude, 2° 18′ E longitude, 240 m altitude and average annual rainfall of 560 mm), Bengou (11° 59′ N latitude, 3° 30′ E longitude, 260 m altitude and average rainfall of 850 mm) and Tara (11° 59′ N latitude, 3° 30′ E longitude, 240 m altitude and average annual rainfall of 700 mm). Sadore is in the Sahelian bioclimatic zone, an extensive semi-arid belt immediately south of the Sahara desert. The soil at Sadore is sandy loam classified as sandy silicious, Isohypothermic Psammentic Paleustalf (West *et al.* 1984). The top soil is 94% sand and 3% clay. At Bengou the soil is an Alfisol (clayey-skeletal, mixed Isohypothermic family of Udic Rhondastalf) with 12% clay, 70% sand in the top soil. The soil at Tara is classified as Haplic Acrisol with 86% sand in the top soil and 8% clay (Fechter *et al.* 1991). Bengou and Tara are only 30 km apart. At all the sites the land was under several years of fallow before the establishment of the experiments.

Analysis of a bulk soil sample taken from the top 20 cm soil depth of the experimental fields before establishment of the trial shows that the soils are low in clay, organic matter, total nitrogen, phosphorus and cation exchange capacity (Table 1). These soil properties are comparable to those reported by Manu *et al.* (1991).

A pearl millet cultivar CIVT (110 days), an early maturing cowpea cultivar TN5–78 (75 days) and an early maturing groundnut cultivar 55–437 (90 days) were used at all the sites. These crop cultivars are recommended for cultivation in Niger. Crop rotations in the study are presented in Table 2.

Experimental design was a randomized complete block design in a split-plot treatment arrangement with four replications. The main plot treatment factor was rotation and fertilizer level was the split-plot. The subplot size was 50 m². Recommended planting densities were 30000 plants/ha for millet, 80000 plants/ha for cowpea and groundnut. Planting varied according to the start of the rains at each site, but in general planting was in June and harvesting occurred in October. In each year all plots received 13 kg P/ha as single superphosphate and 25 kg K/ha as KCl. Nitrogen in the form of urea was applied at the rates of 0, 15, 30 and 45 kg N/ha. Two splits were applied, with one half at 21 days after planting (DAP) and the second half at 45 DAP. All fertilizers were broadcast and incorporated. No supplementary irrigation was applied. The monthly rainfall distribution during the experiment is shown in Table 3. Plant stands at harvest, millet grain and stover (stems and leaves) yields, cowpea and groundnut stover were measured. The crop residues were removed each year following traditional practices.

Table 3. *Monthly rainfall (mm) distribution during the crop cycle of the experiments*

	Sadore					Tara					Bengou				
Month	1988	1989	1990	1991	1992	1988	1989	1990	1991	1992	1988	1989	1990	1991	1992
May	1·0	35	77	94	44	NA	NA	14	210	37	73	5	33	40	0·0
June	91	36	51	121	85	NA	NA	147	99	102	177	102	60	120	80
July	173	92	10	142	165	NA	NA	189	152	162	235	156	207	180	189
August	239	234	99	191	227	NA	NA	98	158	228	277	189	156	225	268
September	187	198	69	13	53	NA	NA	38	16	66	161	157	113	117	93
October	0·0	28	0·0	21·0	0·0	NA	NA	0·0	40	0·0	7	24	0·0	10	5
Total	691	623	306	582	574			486	675	595	930	633	569	584	635

NA, Not available, no meteorological station had been installed.

Table 4. *Effect of nitrogen on pearl millet, cowpea and groundnut yield at three sites in 1988*

	Millet grain			Cowpea fodder			Groundnut fodder		
N Rates kg N/ha	Sadore	Bengou	Tara	Sadore	Bengou	Tara	Sadore	Bengou	Tara
0	915	1172	550	4069	2213	2974	1470	1128	1088
15	1098	1358	671	4474	2510	2963	1944	1243	1681
30	1194	1424	727	4288	2548	3025	2105	1278	1820
45	1233	1539	804	4264	3008	3500	2486	1359	2093
S.E. (D.F. 27)	60·0	58·3	52·3	218·3	153·7	161·3	132·7	55·0	104·3
CV (%)	23	18	32	15	17	15	19	13	18

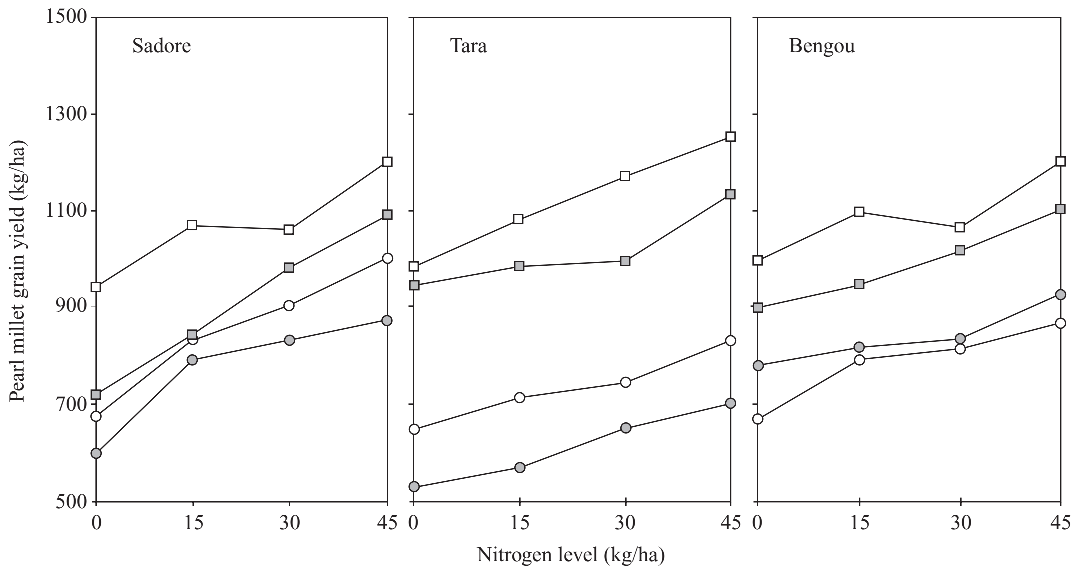

Fig. 1. Effect of nitrogen and rotation on pearl millet grain yield (kg/ha) at Sadore, Tara and Bengou: millet–millet (●), fallow–millet rotation (○), groundnut–millet rotation (■), and cowpea–millet rotation (□).

In 1992, after harvest, soil samples were taken from the top 20 cm depth of subplot without nitrogen application of continuous fallow, fallow–millet rotation, groundnut–millet rotation, cowpea–millet rotation and continuous millet for chemical analysis. Soil pH was measured in 1 N KCl using a 2:1 solution to soil ratio and exchangeable acidity was measured as described by McLean (1982). Organic carbon was measured by the wet chemical digestion procedure of Walkley & Black (1934). Total nitrogen was determined by the Kjeldahl procedure (Bremmner & Mulvaney 1982). Exchangeable bases (Ca, Mg, K and Na) were displaced with NH_4OAc. Calcium and Mg were determined by atomic absorption spectrophotometry, while K and Na were determined using flame photometry. In order to estimate soil-N availability the soils were incubated and total mineral nitrogen determined at 7, 21, and 35 days (Keeney 1982).

The data were analysed as a split-plot using analysis of variance. Due to the large volume of data for individual years, data was pooled over years and means are presented as graphs.

RESULTS AND DISCUSSION

Crop yields

In the combined analysis of variance (data not shown) millet grain and total dry matter yields were significantly affected by years, rotation and nitrogen application at all sites. The only significant interactions were years × rotation and years × nitrogen. Strong year effects on legume yield were observed but the significance of the other treatments and the related interactions were variable. The effects of rotation on cowpea and groundnut were significant at Tara and Bengou.

In 1988, a year in which no rotation effect had been established the application of N significantly increased

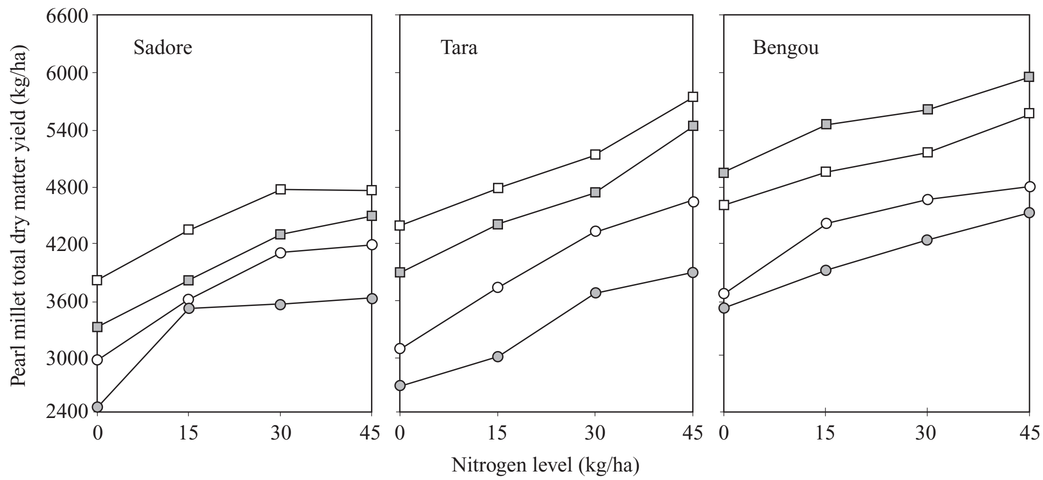

Fig. 2. Effect of nitrogen and rotation on pearl millet total dry matter yield (kg/ha) at Sadore, Tara and Bengou: millet–millet (●), fallow–millet rotation (○), groundnut–millet rotation (■), and cowpea–millet rotation (□).

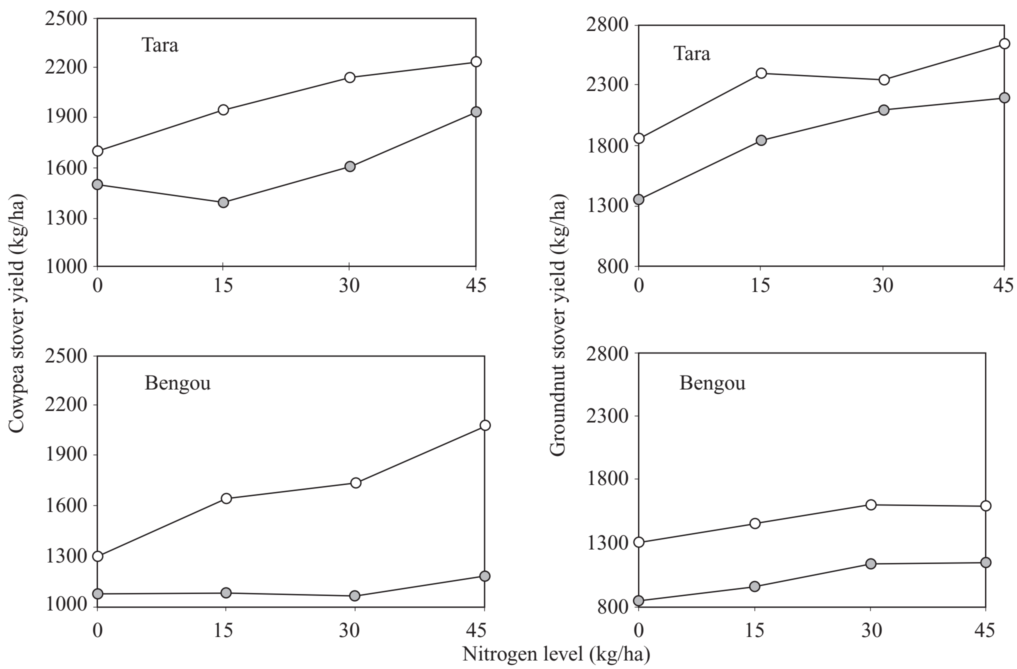

Fig. 3. Effect of nitrogen and rotation on legume stover yield (kg/ha) at Tara and Bengou: cowpea–cowpea sequence (●), and millet–cowpea rotation (○).

millet and legume yields (Table 4). In the case of legumes only fodder yield is reported because of extremely low grain yield of cowpea due to insect damage and low groundnut pod yield due to poor pod filling. Cowpea fodder yield increases were observed at Tara and Bengou while for groundnut the effect of N was significant at the three locations. These significant responses for legumes indicate that the predominantly sandy soils of the Sudano–Sahelian zone may be deficient in molybdenum, required for efficient symbiotic N_2 fixation (Hafner *et al.* 1992).

Grain yield of millet following cowpea was higher ($P < 0{\cdot}01$) than millet following groundnut at the three sites (Figs 1 and 2). Similarly, millet total dry

Table 5. *Soil chemical properties after harvest at the end of the experiment*

Rotation	pH			Organic matter (%)			Total N (mg/kg)			Effective cation exchange capacity (cmol/kg)			Base saturation (%)		
	Sadore	Bengou	Tara	Sadore	Bengou	Tara	Sadore	Bengou	Tara	Sadore	Bengou	Tara	Sadore	Bengou	Tara
F–F	4·7	4·7	5·0	0·76	0·46	0·56	351	230	219	1·95	1·15	1·25	96	94	97
F–M	4·9	4·7	5·0	0·74	0·44	0·59	302	251	207	1·83	1·35	1·16	98	93	94
M–M	4·6	4·4	4·3	0·52	0·37	0·44	235	178	165	1·91	1·11	0·88	95	83	81
C–M	4·7	4·3	4·3	0·56	0·35	0·47	260	206	197	1·84	1·15	0·88	97	80	76
G–M	4·6	4·3	4·2	0·58	0·27	0·45	263	192	130	1·88	1·25	0·81	93	80	70
S.E. (D.F. 27)	0·11	0·09	0·10	0·030	0·040	0·033	12·0	10·67	21·3	0·123	0·107	0·077	0·016	3·66	2·67
CV(%)	4	4	4	9	20	13	8	10	23	13	17	15	3	9	6

F–F, Continuous fallow, F–M, Alternate fallow millet, M–M, Continuous millet; C–M, cowpea–millet rotation; G–M, groundnut–millet rotation.

matter was higher ($P < 0.01$) in the cowpea–millet rotation, except at Bengou where the total dry matter was highest in the groundnut–millet rotation. With no application of N fertilizer, millet grain yield after cowpea increased by 57% at Sadore, 28% at Bengou and 87% at Tara. Much less millet yield increases due to rotation with groundnut were observed (20% at Sadore, 15% at Bengou and 79% at Tara). Millet total dry matter followed similar trends (Figs 1 and 2). Yield advantages due to rotation of millet and cowpea were also reported by Klaij & Ntare (1995). Even at higher levels of N, continuous cropping of millet produced the lowest yields of both millet grain and total dry matter. This suggested that factors other than N alone contributed to the yield increases in the millet–legume rotations.

The response of legumes to rotation with millet is also apparent at Tara and Bengou (Fig. 3), where legume yields were consistently lower in continuous monoculture than when rotated with millet. No rotation effects on legumes were observed at Sadore.

Soil chemical properties

It should be noted in this section that the effects of rotations on soil chemical properties are compared to the fallow, since we did not sample individual plots before sowing. Rotations resulted in significantly lower soil pH, ECEC and base saturation at Sadore and Tara, but these were slightly changed at Bengou (Table 5). When compared to continuous millet, rotated plots maintained the same level of soil acidity.

Soil organic matter was significantly reduced in rotations at Sadore and Bengou. The fallow–millet rotation maintained organic matter content at the same level as that of continuous fallow at all sites because the biomass produced in the fallow–millet rotation was incorporated in the soil. In other rotations, the crop residues were removed as per traditional practice. Compared to continuous millet, legume–millet rotations maintained a similar level of organic matter. Comparable results were obtained by Klaij & Ntare (1995) who reported that crop rotation did not help maintain soil organic matter levels at Sadore.

There was a general decline in total N in rotated plots at all locations. This decline was significant at Bengou and Tara when compared to the fallow.

The decline in organic matter under the continuous millet, cowpea–millet and groundnut–millet rotations when compared to fallow may explain the corresponding decline in ECEC at Bengou and Tara. This finding is in agreement with Bationo & Mokwunye (1991) who reported that in the West African semi-arid tropics, ECEC is more related to organic matter than the clay content of the soils.

Crop rotation significantly affected mineral nitrogen (Fig. 4). The fallow–millet rotation supplied

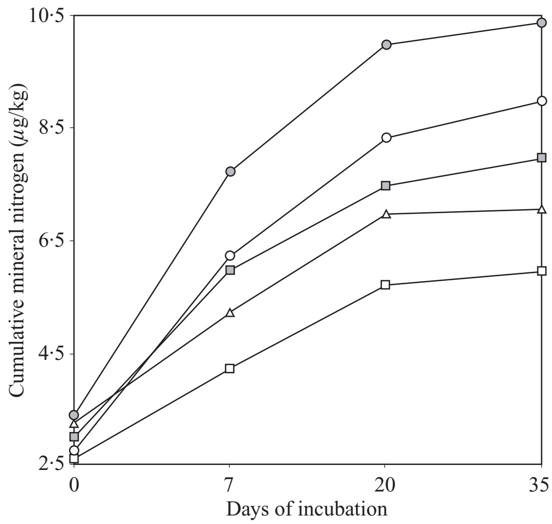

Fig. 4. Relationship between cumulative mineral nitrogen and time of incubation of soils from different crop rotations pooled over three sites: millet–millet (□), groundnut–millet rotation (△), cowpea–millet rotation (■), fallow–fallow (○) and fallow–millet rotation (●).

more nitrogen than the legume–millet rotation, but the latter was more productive for millet production. These results suggest that other factors in addition to biological nitrogen fixation may be involved in the positive effect of legume–cereal rotations (Crookston *et al*. 1988). Although total N and organic matter did not differ significantly between legume–millet rotation and continuous millet, N availability was significantly greater in the cowpea–millet rotation than in the continuous millet system. This could be due to the differential decomposition rates of roots of the different crops. Crop rotation is known to substantially increase soil microbial activity and this may lead to an increase in nutrient availability (Keecy *et al*. 1989).

Although the fallow–millet rotation seems to be productive it would only produce one crop every 2 years. Therefore, if the long-term yields of this rotation are converted to an annual basis they would not be significantly higher than yields of continuous millet. In some parts of the Sahel, land is still available to farmers and it is still possible to leave some part of it in fallow for 1 or 2 years. The legume–millet rotation at 30 kg/ha would appear to be the most viable for millet production in the region considering the importance of both millet and legume crop residues as animal feed. Since these residues are not incorporated into the soil, ways to maintain sufficient levels of soil organic matter need further investigation. Recycled manure could contribute to the replenishment of organic matter, but this is limited by the large quantities needed per hectare (10 to 20 tonnes) and the small size of animal herds owned by the farmers. Thus, sustainable fodder production should be intensified, with the aim of developing strategies to close the feed gap, and improve soil fertility.

The low yields associated with continuous millet are alarming considering that the area under rotation in West Africa is still negligible. In the traditional intercropping system, the density of cowpea is very low and its contribution to biological nitrogen fixation may be negligible. Steiner (1984) reported that in legume/non-legume association there was no direct evidence for a quantitatively significant transfer of N from legumes to the non-legume. It is mainly the following crops in the rotation that profit from the residual N effect (Singh *et al*. 1984). In this study the effect of the various crop rotations on soil organic matter was rather negative when compared to continuous fallow and this has important implications on the sustainability of these rotations particularly in the fragile Sahelian environment.

The results of this study show that legumes such as cowpea and groundnut have a positive effect on succeeding millet yields. Both cowpea and groundnut grain as well as fodder are saleable whereas in pearl millet, only the grain contributes to the crop's value when it is not intercropped. As a result it should be possible to use purchased fertilizer on the legumes that have an impact on the pearl millet crop. This is one way of intensifying the cropping pattern. Research should focus on understanding the effects of cereal/legume intercrops and rotations on soil productivity and the N benefits to succeeding crops. These factors will aid in developing cropping system strategies for sustaining agriculture in the drought prone region of West Africa.

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