Expl Agric. (2000), volume 36, pp. 243–264
Printed in Great Britain

LONG-TERM EFFECTS OF TILLAGE, PHOSPHORUS FERTILIZATION AND CROP ROTATION ON PEARL MILLET–COWPEA PRODUCTIVITY IN THE WEST-AFRICAN SAHEL

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(*Accepted 18 August 1999*)

SUMMARY

The millet (*Pennisetum glaucum*)-based cropping systems that dominate the Sudano–Sahelian Zone of West Africa cannot, as they are currently practised, meet the growing food needs of the region. They must therefore be intensified in a sustainable manner. The present study was initiated in 1986 and continued until 1996 to evaluate the effects of phosphorus (P) fertilization, tillage and rotation with sole cowpea (*Vigna unguiculata*) on an operational scale with two cropping systems, namely, sole millet and millet–cowpea intercropping. A randomized complete block design with four replications was used. The effects of P fertilization, ridging with animal traction and planting on ridges (AT), and rotation with sole cowpea increased the productivity of millet substantially in 10 of the 11 years. Based on the 11-year average, P fertilization alone improved grain yield by 52%, and AT with P fertilization improved grain yield by nearly 135%. Combining AT, P fertilization and the sole cowpea rotation resulted in a 200% increase in grain yield compared with the traditional system of production. Millet productivity did not show a significant decline when intercropped with cowpea. Stability and relative stability analysis showed that the traditional system was more stable than the various agronomic packages, but had the least yield. Conversely, the agronomic package with the highest yield advantage over the traditional system was the least stable. A major portion of the annual variation in the environmental index for grain yield and total dry matter was attributed to the seasonal variation in rainfall and organic matter depletion. Organic matter levels declined linearly with years of cultivation. Significant differences were found in the rate of depletion between the various agronomic treatments tested. After 11 years, nearly 60% of the organic matter was depleted irrespective of the agronomic treatments.

INTRODUCTION

In the Sahel, rainfall is low (300–600 mm), variable and undependable. The coarse-textured soils occupying 46% of the total area are often acidic, and low in organic matter, nutrients, and water holding capacity (Fussell *et al.*, 1987).

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During the past two decades, the yearly average growth rate of cereal production in the Sudano–Sahelian zone of West Africa has been 1% compared with an average population growth rate of 3% (Garba and Renard, 1991). The increase in production has resulted mainly from the extension of the area under cultivation and the use of marginal land previously devoted to livestock for grazing and browsing. Farmers have reduced and, in some cases, ceased the traditional practice of regenerating the soil by fallowing. Consequently the resource base is degrading.

Pearl millet (*Pennisetum glaucum*), the major staple crop, is grown on nearly 14×10^6 ha in the Sudano–Sahelian zone, accounting for nearly 57% of the world pearl millet production (FAO, 1993). Millet is traditionally intercropped with cowpea (*Vigna unguiculata*). Both crops are sown at very low densities (<5000 hills ha^{-1}) with no fertilizer. Sole cowpea is seldom planted in this region and crop rotation with a sole legume is not practised. Land preparation consists of clearing the soil surface before the rainy season, generally in April–May, and burning the dry organic residues. The productivity with this traditional system is very low and grain yields seldom exceed 300 kg ha^{-1}.

Several studies in the past, based on data from small experimental plots, have indicated that application of limited quantities of phosphorus, primary tillage and planting on ridges, and rotation with sole cowpea improve the productivity of millet-based systems (Fussell *et al.*, 1987; Bationo *et al.*, 1992; Reddy *et al.*, 1994). The applicability of these results to more realistically sized plots has not been assessed, however. Furthermore, these agronomic packages have not been evaluated for their effects upon sustainability or stability.

The objective of this long-term experiment (1986–96) was to evaluate on large plots a variety of systems combining low-cost inputs. These inputs included improved varieties of millet and cowpea, application of limited quantities of phosphorus (P) (13 kg ha^{-1} a^{-1}), ridging with animal traction and planting on ridges, rotation of sole millet or millet intercropped with cowpea with sole cowpea, and application of crop residues. This long-term study was also used to evaluate the stability of these production technologies or agronomic packages with various levels of agronomic inputs.

MATERIALS AND METHODS

The site

The experiment was established in 1986 and continued until 1996 at the ICRISAT Sahelian Center (ISC), located at Sadoré, 45 km south of Niamey, Niger, West Africa (lat 13°15′N long 2°18′E) and at an altitude of 240 m asl. The climate at Sadoré is characterized by a short rainy season from June to September (about 90 d). The average rainfall is 560 mm, is irregular and normally comes in the form of thunderstorms. Monthly rainfall for the years 1986 to 1996 is presented in Table 1. During the crop growing season, maximum temperatures varied in the range of 30–40 °C. Potential evapotranspiration (PET) exceeds the total rainfall

Table 1. Monthly, annual and growing season rainfall (mm) from 1986 to 1996 (11 seasons) at the ICRISAT Sahelian Center, Sadoré, Niger.

	Rainfall										
Month	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996
January	—	—	—	—	—	—	—	—	—	—	—
February	—	—	—	—	—	—	—	—	—	—	—
March	1	19	—	—	—	8	12	—	—	—	—
April	1	—	9	—	—	14	44	8	13	6	23
May	84	2	1	35	77	94	85	—	14	20	3
June	61	15	90	36	51	121	165	86	145	82	97
July	177	82	173	92	104	142	227	197	153	108	121
August	189	225	239	234	99	191	53	229	306	206	217
September	119	56	187	198	69	13	—	21	126	68	68
October	25	48	—	28	—	21	—	—	38	7	15
November	—	—	—	—	—	—	—	—	—	—	—
December	—	—	—	—	—	—	—	—	—	—	—
Total	657	448	699	623	400	603	585	542	794	495	544
Growing season	546	379	689	560	322	467	445	534	730	463	503

in all months except July–August which are the peak months of the rainy season (Sivakumar, 1986). The site is located on a sandy plain with Aeolian sands 2–8 m in depth covering one of a series of stepped surfaces comprised of cemented laterite gravels (West *et al.*, 1984). The surface horizon (25–30 cm in depth) is a yellowish red sand underlain by a thick (> 1 m) red loam or red sand horizon. Soils are coarse textured, with sand content exceeding 95%. Organic matter content is about 0.4%. The soils are acidic in nature (pH_{H_2O} 4.5–5.0), and low in nutrients (cation exchange capacity = 1.5 cmol kg^{-1}) and water holding capacity (< 10%) (West *et al.*, 1984).

Experimental details

The experiment was designed as a randomized complete bock (RCBD) with 13 treatments (Table 2), replicated four times, involving various combinations of hand cultivation (HC), ridging with animal traction and planting on ridges (AT), limited P fertilizer application and rotation with sole cowpea (C). These were tested with two cropping systems: millet–cowpea intercrop (M/C) and sole millet (M). Plot size was 500 m^2 (50 m × 10 m), and the area sampled for yield of each experimental plot was 75 m^2 (25 m × 3 m). In 1989, an additional treatment of crop residues (millet straw) was introduced by dividing each treatment plot into half. Thus, the plot size was reduced to half (250 m^2, 25 m × 10 m), and similarly the sampled area became half (37.5 m^2, 12.5 m × 3 m). In 1994, nitrogen treatment (15 kg N ha^{-1} as calcium ammonium nitrate) was introduced by further dividing each experimental plot into two, thereby creating additional treatments with nitrogen and without nitrogen.

Table 2. Treatment outline of the long-term experiment at the ICRISAT Sahelian Center, Sadoré, Niger.

Treatment number	Treatment†	Cropping		
		First year	Second year	Third year
1	Traditional	M/C	M/C	M/C
2	Inter + AT + R_0	M/C	M/C	M/C
3	Inter + AT + R_1	M/C	C	M/C
4	Inter + AT + R_2	C	M/C	C
5	Inter + HC + R_0	M/C	M/C	M/C
6	Inter + HC + R_1	M/C	C	M/C
7	Inter + HC + R_2	C	M/C	C
8	Sole + AT + R_0	M	M	M
9	Sole + AT + R_1	M	C	M
10	Sole + AT + R_2	C	M	C
11	Sole + HC + R_0	M	M	M
12	Sole + HC + R_1	M	C	M
13	Sole + HC + R_2	C	M	C

†Inter = millet and cowpea intercropping (M/C); sole = sole millet (M) or cowpea (C); R_0 = continuous cropping; R_1 or R_2 = millet in rotation with sole cowpea; AT = ridging using animal traction and planting on ridges; HC = hand cultivation.

The plot size became 125 m^2 (25 m × 5 m), and the sampled area was reduced to 18.75 m^2 (12.5 m × 1.5 m).

Millet was planted in hills. The spacing for hills was 1.5 m × 1.0 m for the traditional system, 1.5 m × 0.66 m for sole millet and intercropped millet (AT and HC), 1.5 m × 1.32 m for intercropped cowpea (M/C), and 0.75 m × 0.35 m for sole cowpea (C). Thus, plant density was 6666 hills ha^{-1} (6 plants per hill) for traditional system millet, and 5000 hills ha^{-1} (2 plants per hill) for traditional system cowpea. For all the improved agronomic treatments, the millet plant density was 10 000 hills ha^{-1} (3 plants per hill), and the cowpea plant density in improved intercropped systems was the same as in the traditional treatment. For sole cowpea, the plant density was 44 444 hills ha^{-1} (2 plants per hill).

Millet and cowpea as sole crops were planted after the first 20 mm rain of the growing season. Cowpea in the intercrop treatments was planted two weeks after millet. Several seeds were planted per hill to allow subsequent thinning to the desired plant density. Two or three weeks after planting, millet was thinned to six plants per hill in the traditional treatment, and 3 plants per hill in the improved agronomic treatments.

For control plots cultivated by the traditional system no fertilizer was applied. For all the improved agronomic treatments, the annual P fertilizer applications (13 kg P ha^{-1}) were 60 kg of triple superphosphate (TSP) ha^{-1} in 1986, and 65 kg TSP ha^{-1} in 1987 and 1988. Single superphosphate (SSP) was applied at the rate of 167 kg ha^{-1} from 1989 onwards. Phosphorus fertilizer was broadcast by hand at the beginning of the growing season.

Millet variety ITMV 8001 was used for both sole and intercrop production systems until 1994, when it was replaced by ICMV 89305. For intercropped cowpea, Sadoré Local, which is a local landrace, was used. For sole cowpea treatments, TVX 3236 was used from 1986 to 1994 when it was replaced with TM 578.

Fields were kept weed-free by manual hoeing or by using a donkey-drawn cultivator in the AT plots. Sole cowpea was protected from insect attack by spraying with insecticide Cymbus Super® with Electrodyn® at least twice during the cropping season. For millet–cowpea or sole millet production systems, no plant protection was given.

At maturity, the sample area of each experimental plot was harvested manually, and grain yield (GY) and total dry matter (TDM) were determined by drying samples at 70 °C in a forced-draught oven for 48 h, followed by weighing. For cowpea as an intercrop, the growing season does not permit the late-maturing local landraces to mature; only hay was harvested and added to millet dry matter to determine the TDM of the production system. For sole cowpea, pods were hand picked and, after threshing, the grain yield was determined.

Soil samples were collected at a depth of 30 cm at the beginning and end of the crop season, and analysed for pH_{H_2O}, phosphorus (Bray I) (Bray and Kurtz, 1945), and organic matter (OM) (Nelson and Sommers, 1982).

The results of crop residue and nitrogen application treatments will be presented elsewhere, and therefore are not discussed here.

Data analysis

Yearly data for grain yield and total dry matter was subjected to analysis of variance as per RCBD (GENSTAT, 1993). Combined analysis of the data for 11 years was done using restricted maximum likelihood estimation (REML) analysis using a fixed-effects model (GENSTAT, 1993). The significance of various factors was assessed using Wald Statistic as explained in GENSTAT 5, release 3, 1993, pp. 564–566.

Stability analysis

Two approaches were adopted to analyse the stability of these production systems. The first was that of Finlay and Wilkinson (1963), where the productivity of various treatments (expressed as GY or TDM) is regressed on an environmental index (EI), defined as the average yield of all treatments in a given year. In this approach, the regression coefficient is the indicator of stability. This approach, originally developed to assess the stability of a genotype's productivity based on multi-location evaluations, was also advocated for evaluating the stability of cropping systems or agronomic treatments over time (Raun *et al.*, 1993).

The second approach, known as 'relative stability', is an analysis of functional linear relationships between pairs of cropping systems (Mead *et al.*, 1986; Lightfoot *et al.*, 1987; Guerta *et al.*, 1994). Relative stability is assessed by comparing slopes of regression lines that result when the average yield of the pair $(A + B)/2$ is regressed on the yield difference (A − B) between the two treatments (Mead *et al.*, 1986). A slope close to zero would indicate that the two treatments change similarly and are equally stable. A positive slope indicates that 'B' is more stable than 'A'. A strongly negative slope indicates that 'A' is more stable than 'B'. A probability level < 0.05 for the slope from the relative stability equation indicates that the slope is significantly different from zero. Relative stability analysis is expected to give a more reliable estimate than the Finlay and Wilkinson (1963) approach for evaluating the stability of any given pair of production systems over time (Mead *et al.*, 1986; Lightfoot *et al.*, 1987; Raun *et al.*, 1993).

RESULTS

Total dry matter of millet

Total dry matter of millet (TDM) was significantly lower in the traditional system of production compared with the agronomic treatments in all the years except in 1986, where there were no significant treatment effects (Tables 3 and 4). In the best agronomic package, that is, in AT combined with the sole cowpea rotation, TDM was nearly three times higher than in the traditional system (based on the 11-year average). The sole millet system produced higher biomass than the intercropped system only in years 1992 and 1994 (Table 4). The positive effects of the sole cowpea rotation and AT in improving the TDM of millet were significant from 1987 to 1996. Rotation with sole cowpea improved the subsequent M or M/C productivity by up to 50% compared with continuous M or M/C systems of production (based on the 11-year average). The CS × ROT interaction was significant in years 1992 and 1995. AT improved the TDM by up to 35% compared with HC in M/C or M. The CS × AT interaction was not significant in any of the years during this 11-year period. The ROT × AT interaction was significant in 1995 only and the CS × ROT × AT interaction was never significant.

Grain yield of millet

Grain yield (GY) was significantly higher in all the agronomic treatments than in the traditional system of production for all years except the first, 1986, which was the first year of cropping after clearing the bush (Table 5). Based on the 11-year average, productivity under the traditional system was less than half that of the best combination of agronomic packages used in this study. The GY in the sole millet production (M) system was significantly higher than in the millet–cowpea intercrop (M/C) system only in 1994. In other years, there were no significant differences between M and M/C production systems (Table 6). The sole cowpea rotation effect on subsequent millet GY was significantly higher than in continuous M or M/C production systems in 1988, 1989, 1992, 1994 and 1996. The CS × ROT interaction was significant in years 1992, 1994 and 1995. The ROT × AT interaction was significant in years 1986, 1987, 1992 and 1994. Based on the 11-year average, nearly 50% increase in millet GY was observed for

Table 3. Pearl millet total dry matter (t ha^{-1}) as affected by phosphorus application, cropping systems, tillage methods and crop rotation in 1986–1996 at the ICRISAT Sahelian Center, Sadoré, Niger†.

		Millet–cowpea intercrop system				Sole millet system				
		Tillage (AT)		Hand cultivation		Tillage (AT)		Hand cultivation		
Year	Traditional system	Continuous	Rotation	Continuous	Rotation	Continuous	Rotation	Continuous	Rotation	s.e.d.
1986	4.09	3.96	3.98	3.38	4.17	4.52	2.92	4.50	4.08	0.64
1987	1.21	1.89	2.95	1.52	1.77	1.87	2.52	1.69	1.72	0.44
1988	1.65	3.29	5.92	2.69	4.24	3.29	5.00	2.19	4.18	0.54
1989	1.00	2.74	3.30	1.14	1.70	1.83	2.87	1.29	2.07	0.32
1990	1.00	3.60	3.90	2.83	2.99	2.86	3.50	2.07	3.17	0.45
1991	0.86	2.69	4.12	0.80	1.95	2.32	3.19	0.98	1.04	0.43
1992	1.52	2.88	3.64	1.95	3.26	1.95	3.62	1.47	3.78	0.35
1993	1.24	2.99	4.07	1.88	3.39	2.66	4.36	2.24	2.70	0.33
1994	1.68	4.65	8.63	2.67	5.29	4.59	8.28	3.17	6.81	0.75
1995	0.80	3.37	4.89	2.53	3.09	2.62	4.02	2.72	3.32	0.38
1996	1.04	2.00	3.97	1.56	2.36	2.08	3.73	1.79	3.83	0.21
Mean	1.46	3.10	4.47	2.09	3.11	2.78	4.00	2.19	3.34	

† ANOVA using randomized complete block design.

Table 4. Analysis of variance for total dry matter of millet (1986–1996) for various management practices at the ICRISAT Sahelian Center, Sadoré, Niger.

Source of variation	df	Variance ratio†										
		1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996
Control	1	0.02	7.02*	41.27**	15.35**	69.60**	32.26**	49.12**	31.53**	63.51**	46.76**	80.28**
Cropping systems (CS)	1	0.60	0.43	0.17	0.08	0.83	1.36	4.68*	0.45	8.99*	3.68	0.42
Rotation (ROT)	1	0.89	6.07*	73.31**	17.43**	5.45*	21.74**	71.21**	42.45**	90.59**	23.34**	13.69**
Tillage (AT)	1	0.38	7.28*	19.15**	22.41**	16.13**	91.61**	10.75**	14.38**	24.39**	22.22**	13.48**
CS × ROT	1	5.39	0.75	0.78	0.88	3.27	0.47	16.04**	0.00	0.46	9.52*	0.11
CS × AT	1	1.54	0.18	0.15	0.37	0.01	0.00	0.05	0.00	2.00	0.02	0.47
ROT × AT	1	2.55	2.39	0.73	0.77	1.38	2.20	0.28	1.50	0.63	5.44*	3.41
CS × ROT × AT	1	0.11	0.01	2.03	0.17	0.00	0.15	0.01	0.06	0.31	0.04	3.12
Replications	3											
Residual	24											
Total	35											

†Variance ratio is the ratio between the mean sum of squares of the factor and the residual mean sum of squares; *significant at $p = 0.05$; **significant at $p = 0.01$.

Table 5. Pearl millet grain yields ($t\ ha^{-1}$) as affected by phosphorus application, cropping systems, tillage methods and crop rotation in 1986–1996 at the ICRISAT Sahelian Center, Sadoré, Niger†.

Year	Traditional system	Millet–cowpea intercrop system				Sole millet system				s.e.d
		Tillage (AT)		Hand cultivation		Tillage (AT)		Hand cultivation		
		Continuous	Rotation	Continuous	Rotation	Continuous	Rotation	Continuous	Rotation	
1986	0.83	0.87	0.74	0.78	0.90	0.97	0.61	0.80	0.84	0.14
1987	0.28	0.38	0.71	0.36	0.40	0.46	0.58	0.50	0.42	0.11
1988	0.23	0.60	0.99	0.39	0.81	0.58	0.84	0.47	0.75	0.14
1989	0.13	0.48	0.62	0.24	0.35	0.48	0.59	0.35	0.48	0.09
1990	0.10	0.62	0.54	0.34	0.47	0.44	0.49	0.34	0.39	0.08
1991	0.12	0.37	0.41	0.07	0.22	0.32	0.46	0.12	0.17	0.11
1992	0.24	0.31	0.58	0.29	0.40	0.40	0.71	0.27	0.54	0.11
1993	0.29	0.73	0.71	0.57	0.51	0.58	0.76	0.46	0.46	0.11
1994	0.18	0.84	1.59	0.35	0.88	1.09	1.67	0.75	1.81	0.13
1995	0.08	0.67	0.64	0.32	0.51	0.56	0.64	0.50	0.46	0.07
1996	0.06	0.12	0.28	0.10	0.23	0.16	0.33	0.14	0.31	0.06
Mean	0.23	0.54	0.71	0.35	0.52	0.55	0.70	0.43	0.60	

†ANOVA using randomized complete block design.

Table 6. Analysis of variance for grain yield of millet (1986–1996) for various management practices at ICRISAT Sahelian Center, Sadoré, Niger.

Source of variation	df	Variance ratio										
		1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996
Control	1	0.01	5.68*	17.92**	20.74**	36.03**	8.36**	61.42**	9.56**	90.20**	39.60**	18.89**
Cropping systems (CS)	1	0.03	0.22	0.27	1.18	0.98	0.28	2.08	1.84	19.56**	1.55	1.27
Rotation (ROT)	1	1.34	3.28	23.13**	12.14**	1.52	2.88	21.67**	0.07	72.03**	0.45	58.98**
Tillage (AT)	1	0.19	4.23*	4.24*	14.69**	6.93*	23.19**	14.04**	0.82	4.96*	2.04	0.34
CS × ROT	1	1.17	2.06	0.92	0.34	0.10	0.12	7.81**	1.63	4.04*	6.28*	0.00
CS × AT	1	0.00	0.82	0.42	0.15	1.26	0.02	3.14	0.63	5.28*	0.53	0.79
ROT × AT	1	5.06*	4.73*	0.04	0.00	0.01	0.03	5.91*	0.03	4.56*	0.01	0.21
CS × ROT × AT	1	0.27	0.12	0.00	1.09	0.21	0.21	0.12	0.23	0.76	0.02	0.02
Replications	3											
Residual	24											
Total	35											

†Variance ratio is the ratio between the mean sum of squares of the factor and the residual mean sum of squares; *significant at $p = 0.05$; **significant at $p = 0.01$.

plots rotated with sole cowpea, compared with continuous M or M/C production systems. AT had significantly positive effects on GY in 1987, 1988, 1989, 1990, 1991, 1992 and 1994. A nearly 35% increase in GY can be attributed to AT. The CS × AT interaction was significant only in 1994.

Combined analysis of grain yield and total dry matter production over 11 years

Analysis of variance showed significant differences in GY and TDM production among years (Table 7). 'Year' was the largest single contributing factor to the total variance in GY and TDM over 11 years. This was anticipated because the key factors determining productivity in this environment, that is, seasonal rainfall amount and distribution, temperature fluctuations and insect populations varied widely across years. Rotation with sole cowpea was the second largest contributing factor to the variance in GY and TDM, followed by tillage. Among the interactions, CS × Year, ROT × Year and AT × Year had significant effects on the GY and TDM of millet. This indicated the relative inconsistency of the effects of tillage and rotation on the productivity of millet across years. There were no significant differences in millet productivity between M and M/C production systems. However the CS × Year interaction was significant. Only in 1994 were there significant differences in millet productivity between the M and M/C cropping systems (Tables 4 and 6).

Table 7. Combined analysis of variance for millet grain yield and total dry matter for the years 1986 to 1996 using restricted maximum likelihood estimation (REML) analysis with fixed-effects model, at the ICRISAT Sahelian Center, Sadoré, Niger.

		Wald statistic	
Source†	df	Grain yield	Total dry matter
Cropping System (CS)	1	1.7	0.9
Rotation (ROT)	2	63.6**	117.9**
Tillage (AT)	1	26.2**	42.9
Year (Yr)	10	602.0**	401.3**
CS × ROT	2	1.1	1.5
ROT × AT	2	2.8	2.7
CS × AT	1	2.1	4.2
CS × Yr	10	43.5**	19.0**
ROT × Yr	9	104.8**	118.8**
AT × Yr	10	24.0**	59.6**
CS × ROT × AT	2	1.1	2.1
CS × ROT × Yr	9	8.3	17.0
CS × AT × Yr	10	14.7	8.5
ROT × AT × Yr	9	10.3	9.1

† CS = millet–cowpea or sole millet; ROT = sole cowpea, continuous sole millet or millet–cowpea intercropping; AT = animal traction for ridging and planting on ridges or hand cultivation; * significant at $p = 0.05$; ** significant at $p = 0.01$.

Stability of various production systems

Stability analysis assumes that the treatment effect is a linear function of temporal variability which would compensate for some of the limitations encountered in conventional analysis of variance (Raun *et al.*, 1993). The underlying concept of assessing stability through regression of each treatment's yield on an environmental index (EI) is that a stable system will react less to changes in the environment than will an unstable system (Lightfoot *et al.*, 1987). Systems for which the slope of the linear regression is smaller may be considered as more stable or less responsive.

Grain yield and TDM were significantly linearly correlated with the environmental index for various agronomic treatments (Table 8). However, the slope of the regression line increased with increasing agronomic inputs. The treatment

Table 8. Linear regression equations for grain yield and total dry matter for various agronomic treatments on the environmental index† in millet–cowpea and sole millet production systems (1986–1996) (conventional stability analysis), at the ICRISAT Sahelian Center, Sadoré, Niger.

Treatment‡	Intercept	Slope (b)	s.e.	*r*
		Grain yield millet–cowpea intercrop system		
Traditional	−0.11	0.72	0.25	0.68*
AT	0.06	1.03	0.17	0.90**
AT1	0.10	1.31	0.35	0.78**
HC	−0.03	0.81	0.18	0.84**
HC1	−0.02	1.14	0.11	0.96**
		Grain yield sole millet system		
Traditional	0.03	0.41	0.24	0.49
AT	0.04	1.02	0.08	0.97**
AT1	0.10	1.19	0.22	0.87**
HC	0.05	0.76	0.12	0.90**
HC1	−0.21	1.62	0.19	0.95**
		Total dry matter millet–cowpea intercrop system		
Traditional	−0.33	0.63	0.29	0.59
AT	0.67	0.85	0.13	0.82**
AT1	0.25	1.48	0.36	0.81*
HC	−0.06	0.75	0.18	0.82**
HC1	−0.54	1.28	0.10	0.97**
		Total dry matter sole millet system		
Traditional	−0.16	0.50	0.28	0.52
AT	0.20	0.96	0.12	0.94**
AT1	0.66	1.24	0.36	0.75**
HC	−0.66	0.85	0.19	0.83**
HC1	−0.60	1.46	0.22	0.91**

† Environmental index is defined as the average yield of all treatments in a given year;
‡ Traditional = traditional production system; AT = tillage with ridge planting, continuous sole millet or millet–cowpea intercrop; AT1 = tillage with ridge planting rotated with sole cowpea; HC = hand planting with continuous sole millet or millet–cowpea intercrop; HC1 = hand planting with sole cowpea rotation.

with no agronomic inputs, the traditional system, had the lowest slope, whereas the best agronomic treatment, which included tillage (AT), P fertilization, and sole cowpea rotation had the highest slope. For the M production system, the agronomic package with HC, P fertilization and sole cowpea had the highest slope value for GY and TDM.

Relative stability analysis further confirmed the trends obtained with the conventional stability analysis. Slope values were negative when the traditional system was compared with improved agronomic treatments, both for GY and TDM. This showed that the traditional system was more stable than the agronomic treatments. Two-tail *t*-tests for slopes different from zero ($p < 0.05$), were used in all comparisons. For GY, the traditional system was significantly more stable than HC with the sole cowpea rotation in the M production system; the AT continuous millet system was more stable than HC with the sole cowpea rotation, and the slope was significantly different from zero. For the M/C production system, the traditional system tended to be more stable compared with the improved agronomic treatments, as is indicated by the negative slope values; however, none were statistically significant. For TDM production, the AT with continuous M/C was significantly more stable than AT with the sole cowpea rotation. Also, for TDM, AT with the sole cowpea rotation was more stable than HC with the continuous cultivation of M/C. The relative stability of the M/C systems was greater than that of the M systems for all agronomic treatments, as indicated by negative slopes.

Variation in environmental index for grain yield and total dry matter and its relation to seasonal rainfall and depletion of soil organic matter levels during the growing season

The environmental index for GY ranged from 0.1 to 1.1 t ha^{-1} during the 11-year period for both M/C intercrop and M production systems. For TDM, the environmental index varied from 1.9 to 5.7 t ha^{-1}. Environmental indices for GY and TDM were positively correlated with seasonal rainfall ($r = 0.64$: $n = 22$; $r = 0.72$: $n = 22$ respectively) (Fig. 1), and also with the annual depletion of OM (that is, the change in OM from the beginning of the growing season to the end of the growing season) ($r = 0.67$: $n = 22$). Stepwise forward regressions indicated that seasonal rainfall and depletion of OM during the growing season together explained 61% of the variation in environmental index for GY and nearly 50% of the variation in environmental index for the TDM.

Seasonal rainfall and its relationship to the productivity of different agronomic treatments

When the productivity (GY or TDM) of various agronomic treatments over 11 years was regressed on seasonal rainfall, the degree of association between these factors improved with increasing inputs; thus, the '*r*' value was the lowest in the traditional system of production ($r = 0.14$: $n = 11$), whereas it was highest in the treatment where AT was combined with the sole cowpea rotation ($r = 0.72$: $n = 11$). The relationships were significant only in treatments where it was rotated with sole cowpea (AT + ROT $r = 0.72$: $n = 11$; HC + ROT $r = 0.62$: $n = 11$).

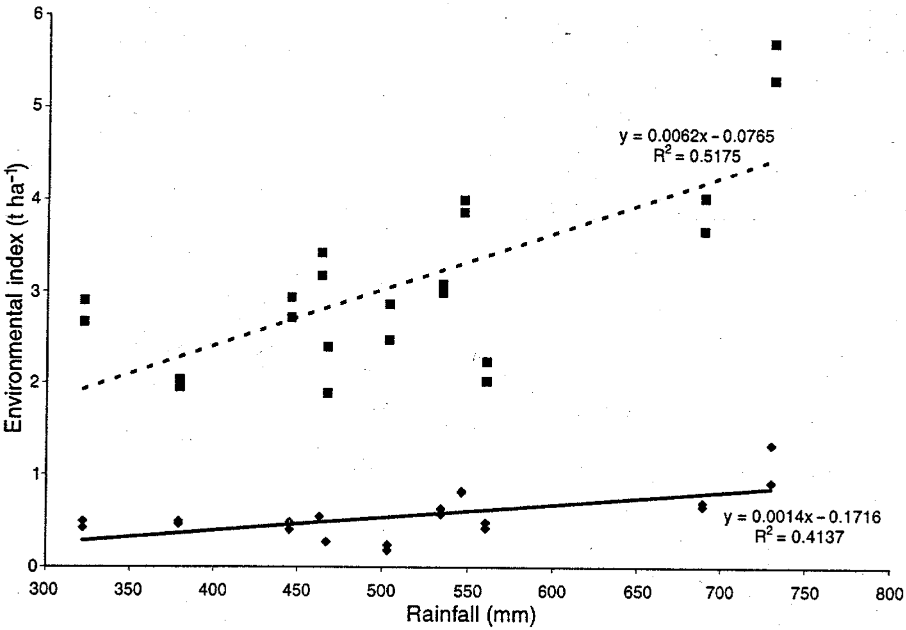

Fig. 1. Relationship between seasonal rainfall (mm) and environmental index for grain yield (◆, t ha^{-1}) and total dry matter (■, t ha^{-1}) over an 11-year period.

The trends were similar for both the cropping systems. The 'b' value increased with the degree of inputs of the treatments, and the trends were similar to the responses observed when regressed on the environmental index (data not presented). Thus, the best combination of inputs such as AT, P fertilization and rotation with sole cowpea had the highest 'b' value when regressed on seasonal rainfall for both the cropping systems, indicating that the best package of practices would respond most strongly and predictably to changes in seasonal rainfall.

For ROT systems, the benefits of cowpea on the GY and TDM of subsequent millet was positively correlated with seasonal rainfall in both tillage treatments (AT and HC) (Fig. 2a; b), thus indicating that seasonal rainfall could account for most of the annual variation in rotation effects. Annual variation in the benefits of AT on GY was positively correlated with seasonal rainfall only in M; there was no significant relationship between seasonal rainfall and the benefits of AT with ROT; also, the annual variation in AT benefits in TDM productivity of M or M/C systems could not be accounted for by the seasonal variation in rainfall (Fig. 2a; b).

Trends in productivity of various agronomic treatments over time

In the traditional system of production, there was a significant decline in productivity over years of cultivation, as the relationship between productivity

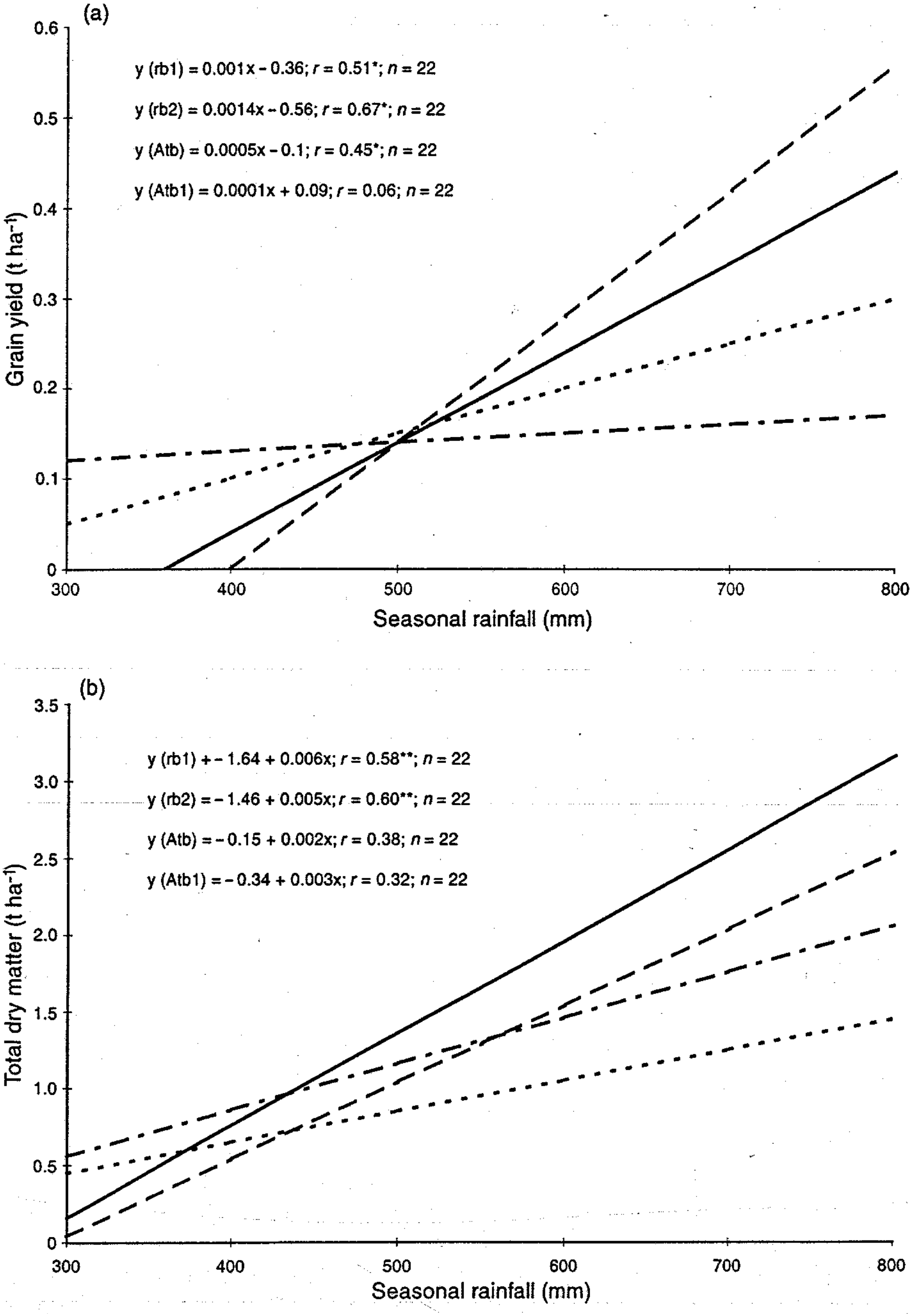

Fig. 2. Relationship between seasonal rainfall (mm) and rotation benefits (—— rb1 = rotation benefits with ridge planting; — — rb2 = rotation benefits with hand cultivation) and ridge benefits (- - - ATb = ridge benefits without rotation; — - — AT1b = ridge benefits with rotation) as grain yield (t ha^{-1}) and total dry matter (t ha^{-1}) over 11 years in millet production systems.

and years of cultivation was exponentially negative for GY ($r = -0.78$: $n = 11$) and TDM ($r = -0.70$: $n = 11$). This is in agreement with the general observation of a decline in productivity within two to three years of cultivation, and explains why farmers traditionally left worn lands fallow for 7 to 10 years to regain some of the fertility before cultivating them again (Pieri, 1992). In contrast, there was no reduction in productivity over time in any of the improved treatments for either cropping system. Thus, agronomic inputs not only improved the productivity of the land, but also sustained productivity over a longer period of time.

Soil organic matter and other soil chemical properties

Soil OM levels declined linearly with years of cultivation (from 3.6 to 1.5 g kg^{-1} dry weight) ($r = 0.94$: $n = 11$), and reached their lowest levels after 11 years of cropping (Fig. 3a; b). There were significant treatment differences in soil OM levels ($p < 0.001$) among the two production systems in all the years from 1987. However, OM declined for all treatments and had reached the lowest levels by 1996 (Fig. 3a; b). The differences between treatments were greatest in 1990. Among treatments, soil OM levels were highest for AT with ROT, and lowest for the traditional system in most years.

Organic matter depletion (the difference between OM levels at the beginning of the cropping season and OM levels at the end of the cropping season) was highest in 1986, 1993 and 1994 (Fig. 3a). There was no significant change in soil pH from year to year of cultivation. Soil P levels increased (from 6.6 mg kg^{-1} in the first year to 18.22 mg kg^{-1} by the 11th year) (means of all treatments) with the years of cultivation, which was due to the cumulative net addition of P to the soil P pool every year in all the agronomic treatments. Soil P levels declined steadily (from 6.6 mg kg^{-1} in the first year to 2.6 mg kg^{-1} by the 11th year) in the traditional system where there was no external P input.

DISCUSSION

The traditional system of production was consistently low in productivity compared with the improved agronomic treatments, thus confirming the earlier reports of the positive effects of P application, ridging and planting on ridges, and rotation with sole cowpea on the productivity of the two cropping systems. The degree of comparative advantage over the traditional system, however, depended on the level of agronomic inputs and rainfall.

Substantial improvements in productivity (50% to 80% increase based on the 11-year averages) were obtained in both cropping systems where hand cultivation (HC) was combined with P fertilization and a continuous cropping of either M or M/C. Much greater improvements (about 200% increase based on the 11-year average), were obtained where planting on ridges (AT), P fertilization and sole cowpea rotation were combined.

Although the traditional system of production was more stable than the improved systems, it had very low productivity. The traditional system's produc-

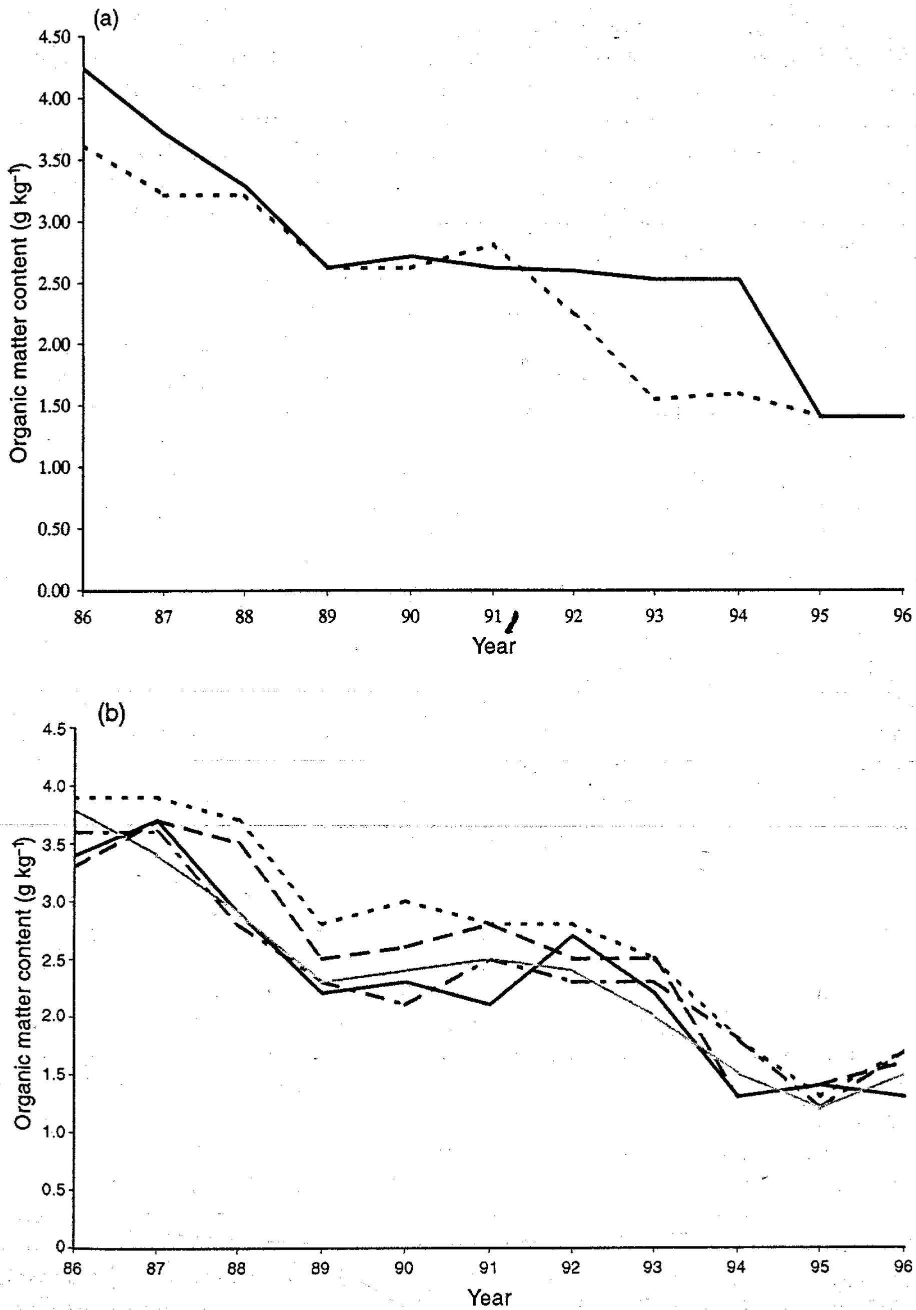

Fig. 3. Soil organic matter content (g kg^{-1}) (a) at the beginning (——) and end (- - -) of the season in sole millet and millet–cowpea production systems (mean of all treatments) and (b) in different production systems (— traditional cropping; — —AT; - - -AT1; — - - —HC; ——HC1, described in Table 8) (mean of sole millet and millet–cowpea intercrop treatments) over a period of 11 years (1986–1996).

tivity showed no relationship with the seasonal variation in rainfall, which was one of the most important factors determining environmental index. The nutrient availability in the traditional system was very low in the absence of external inputs. Water was therefore rarely the limiting factor for productivity, validating earlier perceptions of low input systems (Payne *et al.*, 1990; Payne, 1997). As improved agronomic treatments were introduced, however, water availability appeared to be increasingly the limiting factor. This was evident from the significant positive relationship between seasonal rainfall and productivity in treatments where P fertilization, AT and rotation with sole cowpea were combined.

Several studies have indicated that inter-cropping is likely to be more stable than sole cropping (Rao and Willey, 1980; Rao *et al.*, 1979). The relative stability analysis confirmed this for our conditions, even though they were much harsher than those in the studies of Rao and Willey (1980). Inter-cropping introduced no increased risk of crop failure to pearl millet, while affording increased economic opportunities through the production of cowpea hay.

The fact that nearly 60% of soil OM was depleted in all the treatments demonstrates that OM depletion can be a serious constraint to the development of sustainable production systems. However, our results do not support the notion that intensifying agricultural production in this region would deplete OM more rapidly than low input systems.

In the traditional system of production, the annual nutrient balance of the soil is negative beginning the first year of cultivation, after which production declines quite sharply. The combined technologies of P fertilization, planting on ridges and cereal/legume rotation result in a higher production of above and below ground biomass and contribute to a more positive nutrient balance. Nevertheless, the supply of soil OM declines at about 2% per year in most tropical ferruginous soils and by some 4% or even 7% in very sandy soils under continuous cropping (Pieri, 1992). It is probably not possible to maintain the OM at initial levels, although it is possible to control the rate of decline to a certain critical level, which in this case appears to be about 1.5 g kg^{-1}.

The addition of crop residues, when farmers can afford it, can help to mediate the decline in OM. In very sandy soils, however, and especially under the climate prevailing in the Sudano–Sahelian zone, this may aggravate the deficit nutrient balance further through overstimulation of microbiological activity, which can cause high rates of mineralization, such as occur when straw is ploughed in (Pieri, 1992). There is still no general understanding of how much (or how little) organic matter is needed to protect soil structure (Latham, 1997).

Rotation with sole cowpea and AT benefits were much higher in the better environments than in the poor environments. Some of the reported beneficial effects of ridging include reduced soil bulk density, concentration of fertility, improvement of plant stand and early growth, reduction of weed incidence, and better water use (Kowal and Stockinger, 1973; Klaij and Hoogmoed, 1989; 1993). Increase in millet grain yields of up to 20% due to ridge-planting has been reported (Nicou and Charreau, 1985). Our results show that AT could improve millet productivity by up to 50% over hand planted plots. However, use of animal traction without fertilizer application leads more to the extension of the area cultivated than to increased production per unit labour or area (Pieri, 1992), and thereby aggravates further the risk of soil degradation.

Nitrogen contribution by the legume could be one of the main reasons for the substantial effects of sole cowpea rotation on subsequent millet productivity. Since this production environment is highly unstable (in terms of seasonal rainfall and distribution), and since huge N losses of up to 53% have been associated with N fertilizer application (Christianson *et al.*, 1990), millet–cowpea rotations could provide a low risk means of improving soil fertility for farmers in the Sahel (Radke *et al.*, 1988). However, institutional support is needed for such a large scale adoption of sole cowpea into existing farming systems. Insecticide protection is vital for grain production in sole cowpea cultivation. Furthermore, marketing of the cowpea seed has to be organized. An important bottleneck constraining cowpea production relates to labour requirements. The various operations (sowing, weeding, harvesting) require some 225–235 person-days in the traditional system and sole millet, some 264–276 in the millet–cowpea intercrop, and 482–524 in the sole cowpea system. Harvesting the grain of sole cowpea by hand takes 180 person-days, compared with 35 person-days for the same operation in sole millet (Renard *et al.*, 1988). An economic evaluation of the technologies conducted in 1990 suggested that the application of P in a hand cultivated rotation of millet with cowpea, or a hand cultivated annual millet–cowpea intercrop, might be the packages to recommend to the farmers (Baidu-Forson, 1990).

Such recommendations are especially relevant for farmers who have little or no experience in the use of animal traction technology, cultivate only two ha or less, or cannot afford large cash expenses. Choice between the annual millet–cowpea intercrop and the rotation of millet with cowpea depends on the availability of adequate household labour and cash, as well as on the true opportunity costs of these resources. For maximum benefit from nitrogen fixation by cowpea, farmers would have to alternate planting sites for millet and cowpea, rather than managing all sites as an annual millet–cowpea intercrop. This intensified management method may prove to be complicated for inexperienced farmers. Moreover, the respective dates of planting and plant densities have to be managed carefully if neither millet nor cowpea is to be unduly disadvantaged. On the other hand, it is inconceivable that a farmer who has only one field will plant it entirely to millet or plant pure cowpea every other year. Instead, each farmer would need to partition his fields to rotate pure cowpea and pure millet cultivation. The exact proportions allocated to either crop will depend on household food security and income goals.

In on-farm experiments conducted from 1989 to 1991 (Baidu-Forson *et al.*, 1994), 75% of the farmers in the village of Diakindi, 7 km south of Sadoré, accepted the use of P and the improved millet variety, but adoption depended on the availability of these inputs. Animal traction and improved cowpea varieties were not widely accepted and therefore are not likely to be adopted by most farmers.

Other on-farm tests in progress in other parts of Niger confirm the adoption of P fertilization and improved millet varieties, so long as these inputs are available. The positive effect of cowpea–millet rotation upon yield and soil properties is also quite striking.

This long-term study showed that the depletion of OM was as rapid in the traditional system of production as in the agronomic treatments or packages, which might make it unsustainable even in the improved systems of production, despite a two-fold improvement in productivity over the traditional system. Spreading a fraction of the millet straw over the soil surface or incorporating it into the soil can improve the OM levels.

Alternatively, forage legumes could be introduced into the rotations. Experiments conducted at the Sahelian Center (Kouamé *et al.*, 1994; Garba and Renard, 1994) and elsewhere in West Africa (De Leeuw *et al.*, 1994) have clearly shown the benefits of the cereal–stylosanthes intercrop and of the rotation of millet with cereal–stylosanthes. At the Sahelian Center the latter resulted in an average yield advantage of millet following millet–stylosanthes that ranged from 8% to 74%.

Acknowledgements. We acknowledge the technical assistance of Mr M. Manzo and his contribution in managing this experiment for 11 years. Dr Roger Stern and Ms Fiona Underwood have contributed substantially to the data organization and, with the appropriate statistical advice, to the data analysis. Also, we acknowledge the assistance of Dr S. V. R. Shetty and Dr C. Johansen, who provided helpful and thoughtful suggestions and comments.

REFERENCES

Bationo, A., Christianson, C. B., Baethgen, W. E. & Mokwunye, A. U. (1992). A farm-level evaluation of nitrogen and phosphorus fertilizer use and planting density for pearl millet production in Niger. *Fertility Research* 31:175–184.

Baidu-Forson, J. (1990). *Economic Evaluation of On-Station Operational Scale (OPSCAR) Trials Conducted at Sadoré, Niger. Resource Management Program, Economics Group, Progress Report 96.* Patancheru, India: ICRISAT.

Baidu-Forson, J., Renard, C., Deuro, N., Reddy, C. & Kadi, M. (1994). *Evaluation Agro-économique de Nouveaux Systèmes de Production en Milieu Paysan au Niger. Programme d'Exploitation des Ressources. Compte Rendu des Travaux No. 4.* Niamey, Niger: Centre Sahélien de l'ICRISAT.

Bray, R. H. & Kurtz, T. (1945). Determination of total, organic and available forms of phosphorus in soils. *Soil Science* 59:39–45.

Christianson, C. B., Bationo, A., Henao, J. & Vlek, P. L. G. (1990). Fate and efficiency of N fertilizers applied to pearl millet in Niger. *Plant and Soil* 125:221–231.

De Leeuw, P. N., Mohamed-Saleem, M. A. & Nyamu, A. M. (Eds) (1994). *Stylosanthes as a Forage and Fallow Crop. Proceedings of the Regional Workshop on the Use of Stylosanthes in West Africa, Kaduna, Nigeria, 26–31 October 1992.* Addis Ababa, Ethiopia: ILCA.

FAO (1993). *Crop Production Year Book No. 46.* Rome, Italy: FAO.

Finlay, K. W. & Wilkinson, G. N. (1963). The analysis of adaptation in a plant breeding programme. *Australian Journal of Agricultural Research* 14:742–754.

Fussell, L. K., Serafini, P. G., Bationo, A. & Klaij, M. C. (1987). Management practices to increase yield and yield stability of millet in Africa. In *Proceedings of the International Pearl Millet Workshop, 7–11 April 1986*, 255–268. Patancheru, India: ICRISAT.

Garba, M. & Renard, C. (1991). Biomass production, yields and water use efficiency in some pearl millet/legume cropping systems at Sadoré, Niger. In *Soil Water Balance in the Sudano–Sahelian Zone. Proceedings of an International Workshop, Niamey, Niger, February 1991. IAHS Publication No. 19*, 431–439 (Eds M. V. K. Sivakumar, J. S. Wallace, C. Renard & C. Giroux). Wallingford, UK: International Association of Hydrological Sciences.

Garba, M. & Renard, C. (1994). Fixation de l'azote et bilan du phosphore dans quelques systèmes culturaux à mil–légumineuses à Sadoré (Niger). In *Stylosanthes as a Forage and Fallow Crop. Proceedings of the Regional Workshop on the Use of Stylosanthes in West Africa, Kaduna, Nigeria, 26–31 October 1992, ILCA, Addis Ababa, Ethiopia*, 203–213 (Eds P. N. De Leeuw, M. A. Mohamed-Saleem & A. M. Nyamu). Addis Ababa, Ethiopa: ILCA.

GENSTAT (1993). *GENSTAT Reference Manual, Release 3.* New York, USA: Oxford University Press Inc.

Guerta, E. A., Raun, W. R., Westerman, R. L. & Boman, R. K. (1994). Applications of stability analysis for single site long-term experiments. *Agronomy Journal* 86:1016–1019.

Klaij, M. & Hoogmoed, W. B. (1989). Crop response to tillage practices in a Sahelian soil. In *Soil, Crop and Water Management Systems for Rainfed Agriculture in the Sudano–Sahelian Zone. Proceedings of an International Workshop, 7–11 January 1987, ICRISAT Sahelian Center, Niamey, Niger*, 265–275 (Eds C. Renard, R. J. van den Beldt & J. F. Parr). Patancheru, AP 502 324, India: ICRISAT.

Klaij, M. C. & Hoogmoed, W. B. (1993). Soil management for crop production in the West African Sahel. II. Emergence, establishment and yield of pearl millet. *Soil and Tillage Research* 25:301–315.

Kouamé, C. N., Powell, J. M. & Renard, C. (1994). Development of millet–stylo cropping systems for sandy soils in the Sahel. In *Stylosanthes as a Forage and Fallow Crop. Proceedings of the Regional Workshop on the Use of Stylosanthes in West Africa, Kaduna, Nigeria, 26–31 October 1992*, 193–201 (Eds P. N. De Leeuw, M. A. Mohamed-Saleem & A. M. Nyamu). Addis Ababa, Ethiopia: ILCA.

Kowal, J. & Stockinger, K. S. (1973). Usefulness of ridge cultivation in Nigerian agriculture. *Soil and Water Conservation Journal* 28:136–137.

Latham, M. (1997). Crop residues as a strategic resource in mixed farming systems. In *Crop Residues in Sustainable Crop/Livestock Farming Systems*, 181–196 (Ed. C. Renard). Wallingford, UK: CAB INTERNATIONAL.

Lightfoot, C. W. F., Dear, K. B. G. & Mead, R. (1987). Intercropping sorghum with cowpea in dryland farming systems in Botswana. II. Comparative stability of alternative cropping systems. *Experimental Agriculture* 23:435–442.

Mead, R., Riley, J., Dear, K. & Singh, S. P. (1986). Stability comparison of intercropping and monocropping systems. *Biometrics* 42:253–266.

Nelson, D. W. & Sommers, L. E. (1982). Total carbon, organic carbon and organic matter. In *Methods of Soil Analysis Part 2*, 538–578 (Eds A. L. Page, R. H. Miller & D. R. Keeney). Madison, WI, USA: Agronomy Society of America.

Nicou, R. & Charreau, C. (1985). Soil tillage and water conservation in semi-arid West Africa. In *Appropriate Technologies for Farmers in Semi-arid West Africa*, 9–37 (Eds H. W. Ohm & J. G. Nagy). West Lafayette, Indiana, USA: Purdue University.

Payne, W. A. (1997). Managing yield and soil water use of pearl millet in the Sahel. *Agronomy Journal* 89:481–490.

Payne, W. A., Wendt, C. W. & Lascano, R. J. (1990). Root zone water balances of three low-input millet fields in Niger, West Africa. *Agronomy Journal* 82:813–819.

Pieri, C. J. M. G. (1992). *Fertility of Soils: A Future for Farming in the West African Savannah.* Berlin: Springer Verlag.

Radke, J. K., Andrews, R. W., Janke, R. R. & Peters, S. E. (1988). Low-input cropping systems and efficiency of water and nitrogen use. In *Cropping Strategies for Efficient Use of Water and Nitrogen. Special Publication No. 51*, 193–218. Madison, WI, USA: ASA, CSSA and SSSA.

Rao, M. R. & Willey, R. W. (1980). Evaluation of yield stability in intercropping studies on sorghum/pigeonpea. *Experimental Agriculture* 16:105–116.

Rao, N. G. P., Rana, B. S. & Tarhalkar, P. P. (1979). Stability, productivity and profitability of some intercropping systems in dryland agriculture. In *Proceedings of an International Workshop on Intercropping, Hyderabad, India, 10–13 January 1979*, 292–298 (Ed. R. W. Willey). Patancheru, India: ICRISAT.

Raun, W. R., Barreto, H. J. & Westerman, R. L. (1993). Use of stability analysis for long-term soil fertility experiments. *Agronomy Journal* 85:159–167.

Reddy, K. C., Visser, P. L., Klaij, M. C. & Renard, C. (1994). The effects of sole and traditional intercropping of millet and cowpea on soil and crop productivity. *Experimental Agriculture* 30:83–88.
Renard, C., Klaij, M. C. & Ntare, B. R. (1988). Results of the operational scale research project at the ICRISAT Sahelian Center. In *New Food Production Systems Technologies for the Sahel. Proceedings of a Meeting of Directors of Agricultural Research Institutes in West Africa.* INRAN–ICRISAT, Niamey, Niger, 7–8 September 1988, 86–102. Niamey, Niger: ICRISAT.
Sivakumar, M. V. K. (1986). *Climate of Niamey. Progress Report No. 1.* Niger: ICRISAT Sahelian Center.
West, L. T., Wilding, L. P. & Landeck, J. K. (1984). *Soil Survey of the ICRISAT Sahelian Center, Niger, West Africa.* College Station, Texas, USA: Texas A&M University.