Post Stratification Clarifies Treatment Effects on Pearl Millet Growth in the Sahel

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ABSTRACT

Spatial variation in the growth of pearl millet [*Pennisetum glaucum* (L.) R. Br.] over short distances is a problem in field experiments in the Sahel, but the causes are still poorly understood. Data from a 3-yr experiment with millet were used to compare four data types for their usefulness for reducing variation not related to treatment: (i) soil chemical data, (ii) residuals of the first year's yield data, (iii) a traditional fertility classification system, and (iv) plant vigor scores. The completely randomized experiment consisted of four factors combined to 48 treatments, replicated twice. There were three levels of millet crop residues (CR), two levels of broadcast P, and four genotypes; the fourth factor had two levels and varied over years. Whereas chemical analyses of the topsoil did not explain overall variation, residuals of plant scores used as covariates led to a reduction in residual variation of 32% for straw and 51% for grain yield in 1991. Most satisfactory, however, was the use of residuals of plant scores to classify plots into two strata of relatively low and high inherent soil productivity (a retrospective procedure called *post stratification*). In low-productivity plots, a CR application of 2000 kg ha^{-1} (compared with 500 kg ha^{-1}) increased millet straw yield by an average of 42% and grain yield by 48% for the first 2 yr. In contrast, under high productivity, yields were barely influenced by treatments. The application of P, however, was equally effective in both productivity strata. The results show that vigor scores can be useful to clarify treatment effects on millet growth. The different responses of crop residues and P in the two productivity strata also indicate that nonchemical parameters such as soil mechanical resistance may contribute to soil microvariability in the Sahel.

SPATIAL VARIABILITY OF THE SOIL, reflected in poorly understood differences in plant growth over short distances, may hinder the analysis of data from field experiments and the detection of treatment effects (Moormann and Kang, 1978; Wendt et al., 1993; Wilding and Hossner, 1989). The problem is particularly severe when research is conducted with millet on recently cleared acid sandy soils of the Sahel with an unknown history of land use by local farmers. In sub-Saharan Africa, therefore, field experiments (especially experiments of plant physiologists, nutritionists, and breeders that go beyond basic agronomy) are frequently conducted at sites of high uniformity that are not typical for the region. On-station research has shown that one way to increase uniformity of plant growth in the Sahel is ridging, which improves plant stands and total biomass (Klaij and Hoogmoed, 1993). However, the search for spatial uniformity by researchers misses the opportunity to test interactions between treatment effects and inherent soil productivity.

That treatment effects can also interact with spatial vari-

Abbreviations: CR, crop residue; DAS, days after sowing; DM, dry matter; SSP, single superphosphate.

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ability in plant growth has been recently demonstrated (Buerkert and Stern, 1995). These results showed that the application of crop residues as surface mulch, and broadcast P fertilization, decreased within- and between-plot variation not only in mechanical topsoil resistance but also in millet growth as described by plant density, plant height, and relative total dry matter.

The lack of a clear understanding of soil-induced spatial microvariability in millet growth on acid sandy soils of the Sahel is reflected in contradicting explanations of the phenomenon. Based on simple correlations between millet height and results of soil analyses, Scott-Wendt et al. (1988) claimed that Al toxicity was the probable cause of poor millet growth on bad spots in the field. However, Ahlrichs et al. (1991) and Kretzschmar et al. (1991) conclusively demonstrated in soil and in solution culture under controlled conditions that millet is very tolerant to high levels of Al. Taken together, the results of these authors indicate that variable P availability associated with different levels of exchangeable Al in the surface soil may explain a large proportion of the differences in millet growth. This has been supported by Wendt et al. (1993), who concluded from their analyses of topsoil samples at 19 productive and unproductive sites in Niger that spatial variability in millet growth was due to sorption of P by exchangeable Al and crystalline Fe oxides. Herrmann et al. (1994) have stated that differences in early growth variability in millet may be linked to differences in soil microbial activity and nitrate concentration at the beginning of the rainy season. Wind erosion may further contribute to soil microvariability by denuding crusted soil surfaces of more fertile material and depositing it elsewhere (Chase and Boudouresque, 1987; Wendt et al., 1993). Geiger et al. (1992) provide additional evidence of the increase in fertility on spots where dust is entrapped by mechanical barriers such as crop residues. On the acid sandy soils of the Sahel, localized small differences in a single nutrient such as P, or in organic matter, moisture, or temperature may, in combination with other factors, have large effects on millet growth. Under these conditions, which lead to an irregular patchy microenvironment rather than a combination of regular gradients, standard experimental design techniques such as simple blocking or Latin square designs are inadequate to separate treatment effects from environmental variation. Generally, geostatistical techniques such as semivariograms and kriging (Perrier and Wilding, 1986; Warrick et al., 1986) are now widely available to cope with significant soil trends. On the acid sandy soils of the Sahel, however, the variation in crop growth is very unpredictable. Plots of the same treatment that are only a few meters apart may differ by more than sevenfold in their dry matter production. Under such conditions, coefficients of variation may exceed 100%, even in long-term experiments (Rebafka et al., 1994).

Coping with the random patchiness of the spatial variation found in the Sahel may, thus, require other approaches than for the spatially interdependent growth differences found with cereals on eroded hillsides or soils derived from eolian sediments. Under those conditions, environmental variation could be accounted for with geostatistical tools (Samra et al., 1990; Bhatti et al., 1991).

Ideally, the variability in crop growth in the Sahel might be predicted by quantifying and modeling the interacting chemical, physical, and biological processes involved. Until such modeling becomes possible, proxies to describe soil productivity are required to define uncontrolled variation, which may mask treatment effects.

The work presented here compares several approaches to determining effects of soil variability on treatment responses in millet: (i) initial chemical properties of topsoil from the 0- to 0.2-m depth sampled at the plot level were used as covariates, (ii) residuals of the number of millet heads as well as the straw and grain yields of 1991 served for an ex post facto subdivision of the experiment into eight blocks, (iii) the use of a farmer's knowledge about specific (but no longer detectable) characteristics of his field such as former trees, bushes, and animal grazing areas for an alternative blocking of the plots, and (iv) the use of residuals from plant vigor estimates collected at early tillering according to a well-defined scoring key and used as covariates or as criteria for post stratification. It was our hypothesis that by using these techniques, the experimental error could be substantially reduced and treatment effects be made more evident. To test this hypothesis, the effects of crop residue and broadcast P application on millet straw and grain yields were measured and interpreted. Effects of the other treatments and their interactions changed little with the techniques used and are therefore only briefly reported. Nearest-neighbor analyses using various averages of residuals from neighboring plots as covariates and an analysis of covariance with row and column positions as covariates were also performed for comparison.

MATERIALS AND METHODS

Data on straw and grain yields were used from an experiment conducted on a reddish acid sandy Lambucheri soil at ICRISAT Sahelian Center, Sadoré, Niger (13°15′ N, 2°18′ E; 240 m altitude). This soil was classified by West et al. (1984) as a sandy, siliceous, isohyperthermic Psammentic Paleustalf according to the U.S. soil taxonomic system (Soil Management Support Services, 1988), or as an Arenosol according to the FAO system (FAO–UNESCO, 1988). Millet seed was tested for germination and planted during the rainy season of 1991, 1992, and 1993. On a field that had been fallowed for the previous 8 yr, planting density was 10 000 planting holes per hectare; the holes (or pockets) were dug to a depth of 0.05 m using a traditional hoe of 0.15-m blade width. Each pocket contained 75 viable seeds and was covered again immediately after planting. Annual rainfall, distributed unimodally between mid-May and mid-September, was 603 mm in 1991, 586 mm in 1992, and 542 mm in 1993. Treatments applied every year in the factorial experiment were (i) genotypes, (ii) crop residues, (iii) P application, and (iv) a fourth factor, which varied over the 3 yr. The genotypes were the cultivars Sadoré Local, CIVT (Composite Inter-Variétal de Tarna), and ITMV8001 in all 3 yr, with ICH412, SOSAP, and ICMV89305 as the fourth genotype in 1991, 1992, and 1993, respectively. All have a growing period from 90 to 110 d. There were three levels of millet crop residues, broadcast on the soil surface as stalks at rates of 500 and 2000 kg DM ha^{-1}, or as ash at the rate of 2000 kg ha^{-1}. Phosphorus was applied broadcast as single superphosphate (SSP) at two rates: 0 and 13 kg P ha^{-1}. The fourth factor varied by year: in 1991, it consisted of broadcast N application (0 and 30 kg N ha^{-1} as urea); in 1992, banded molybdenum application (0 and 200 g Mo ha^{-1} as ammonium molybdate); and in 1993, a P application into the pockets (0 and 500 g P ha^{-1} as SSP).

The field was gently undulated, but did not have a systematic slope in any particular direction. The soil was visually homogeneous, except for several irregular spots (about 10 m^2 in size) that were slightly different in color. Some of these spots may have derived from termite mounds, trees, or bushes, but these could not be identified initially. Since the preexisting information provided no reason for a specific blocking, the 48 treatments, replicated twice, were completely randomized. Plot size was 10 by 10 m, containing 10 planting rows. Weeding was done manually at thinning (21 DAS) and at booting (50 DAS). Partial protection against damage from the cotton stainer (*Dysdercus voelkeri* Schmidt) during flowering was achieved with two applications of deltamethrin [(*S*)-α-cyano-*m*-phenoxybenzyl (1*R*, 3*R*)-3-(2,2-dibromovinyl)-2,2-dimethylcyclopropanecarboxylate] at a rate of 1 kg ha^{-1}.

Soil Sampling

Samples of the topsoil (0- to 0.2-m depth) were taken from each plot before application of treatments in early May 1991 by bulking four subsamples per plot taken at random. Samples were air dried, sieved to pass a 2-mm screen, and analyzed for pH (1:2.5 0.01 *M* KCl), organic C (Walkley and Black, 1934), total N by the micro-Kjeldahl method (Bremner and Mulvaney, 1982), Bray P (Olsen and Sommers, 1982), and exchangeable Al and total acidity according to McLean (1982). Exchangeable bases were extracted with 1 *M* NH_4Ac; cations were determined by atomic absorption spectrophotometry (Ca and Mg) and flame emission spectrophotometry (K and Na). Water-soluble P was determined after Sissingh (1971), but incubation time was reduced to 5 min at a soil/water ratio of 1:10.

To examine treatment effects on the mechanical resistance of the surface soil, penetrometer measurements were taken before the onset of the growing season in 1993 at two depth intervals. In each plot, 20 measurements were done independently at the 0- to 0.02-m and 0- to 0.05-m depths. The hand-held penetrometer (Eijkelkamp, The Netherlands) was equipped with tips of diameter 35 and 15 mm for the upper and lower depth, respectively. The individual measurements were analyzed for treatment effects on resistances averaged per plot and for the proportion of variances arising from within- and between-plot components.

Use of Residuals of Yield Components in 1991

The full statistical model, with all treatment factors and their interactions, but without any covariate, was fitted to the number of heads, straw, and grain yield in 1991. For grain yield, the distribution of residuals indicated a gradient from west to east, which may have been due to an existing fallow area in the west that provided sanctuary to the cotton stainer, the major pest in this season (Fig. 1). Therefore, the distance of the plots from the west was used as a blocking factor, leading to eight blocks of 12 plots each. To examine the spatial variability in millet growth in more detail, two additional approaches were tested: (i) the row (west to east) and column (north to south) positions of each plot were taken as covariates and (ii) residuals of straw and grain yields were used in a nearest-neighbor analysis (Bartlett, 1938, 1978), for which different nearest-neighbor values were calculated simultaneously using a PC-SAS (SAS Inst., Cary, NC) macro provided by Dr. David Marx of the University of Nebraska. The nearest-neighbor values computed by the macro were averages of residuals from plots at both sides (west to east and north to south) and also at the four corners of each plot. Those values were used as covariates in subsequent analyses.

Blocking after Recording and Mapping of Field History

The farmer who cultivated the site before it was fallowed in 1983 was able to identify the previous position of trees and bushes, termite mounds, hard pans, and areas of elevated soil fertility due to the presence of huts or animal enclosures. The reliability of this information was verified at several locations where roots of old trees could be dug out at the indicated spots. Based on the farmer's information, a field map was drawn using a Geographical Information System (GIS) and the following categories were defined: (i) plots that formerly had hard pans, which are associated with bad millet growth; (ii) plots with former bushes and trees; (iii) plots with termite mounds; (iv) areas of former trash disposal that were associated with good millet growth; and (v) all other plots. These five categories were used to derive incomplete blocks. A plot was assigned to a particular block if >50% of its area belonged to it (Fig. 2).

N

STOVER DRY MATTER

													Mean
	0.45	-0.46	0.17	0.46	0.38	0.47	1.16	0.22	0.45	0.47	0.05	-0.11	0.31
	0.11	0.77	0.27	0.44	-0.23	0.06	0.10	-1.37	0.64	0.17	0.03	-0.77	0.02
	0.23	0.35	-0.29	0.04	-0.13	-0.54	0.99	0.45	0.76	1.37	-1.16	0.08	0.18
	-0.31	0.20	-0.19	0.97	0.34	-0.03	0.05	0.85	0.31	-0.47	0.33	-0.38	0.14
	-0.64	-0.33	0.19	-0.02	-0.08	0.29	-0.02	-0.47	0.54	-0.05	-0.99	-0.45	-0.17
	-0.45	-0.18	-0.19	0.76	-0.04	-0.85	-0.05	-0.35	-0.10	-0.97	0.37	-0.44	-0.21
	3.20	0.05	0.29	-0.05	-0.45	-0.29	-0.37	-0.20	0.19	-0.76	-0.22	-0.34	0.09
	-0.17	0.13	0.02	-3.20	-0.76	-0.27	-0.06	0.02	0.45	0.18	-0.17	-0.45	-0.36
Mean	0.32	0.07	0.03	-0.08	-0.12	-0.15	0.22	-0.11	0.41	-0.01	-0.22	-0.36	0.00

GRAIN YIELD

													Mean
	0.30	-0.40	0.07	0.40	0.28	0.22	0.55	0.18	0.38	0.34	-0.06	0.03	0.19
	0.03	0.14	0.05	0.17	-0.01	0.21	0.19	-0.36	0.49	0.51	0.02	-0.14	0.11
	0.07	0.22	-0.09	0.02	0.02	-0.12	0.50	0.27	0.56	0.36	-0.55	0.14	0.11
	-0.24	0.14	-0.08	0.29	0.25	-0.02	0.36	0.45	0.24	-0.22	0.26	-0.28	0.10
	-0.49	-0.56	0.08	0.06	-0.14	-0.22	0.05	-0.34	0.12	0.08	-0.50	-0.27	-0.15
	0.00	-0.06	0.07	0.41	-0.02	-0.45	0.06	-0.22	-0.19	-0.29	0.49	-0.17	-0.03
	0.91	-0.08	0.09	-0.36	-0.30	0.22	-0.49	-0.14	-0.07	-0.56	-0.18	-0.25	-0.10
	-0.51	-0.03	-0.05	-0.91	-0.41	-0.05	-0.21	-0.06	-0.00	0.06	-0.07	-0.38	-0.22
Mean	0.00	-0.04	0.02	0.01	-0.04	-0.03	0.13	-0.03	0.19	0.04	-0.07	-0.17	0.00

Fig. 1. Residuals of 1991 straw and grain yields (differences between individual plot yields and the respective treatment averages, in Mg ha^{-1}) plotted on a schematic field map. Plots with negative residuals (shaded) have lower yields than predicted by the model.

Scoring of Early Millet Growth

Treatment effects are likely to be cumulative over the growing season and, if applied on the same plot each year, over the whole duration of the experiment. Therefore, plant data to be used as integrating proxies of differences in inherent soil productivity should be taken as early as possible after treatment application. Thus, in each year 3 d after thinning (24 DAS), when plants had recovered from the thinning stress and were ready to tiller, pockets were evaluated for vigor. Vigor was defined as the physical appearance of a millet pocket, including height and greenness of leaves. Following this definition, the range of vigor apparent in the field was determined by giving the row with the lowest average vigor across the whole experiment a value of 1 and the row with the highest vigor a value of 7. Afterwards, rows for intermediate vigor values were also defined and marked in the field for further reference. Subsequently, each row of all plots was evaluated according to the scale set by the

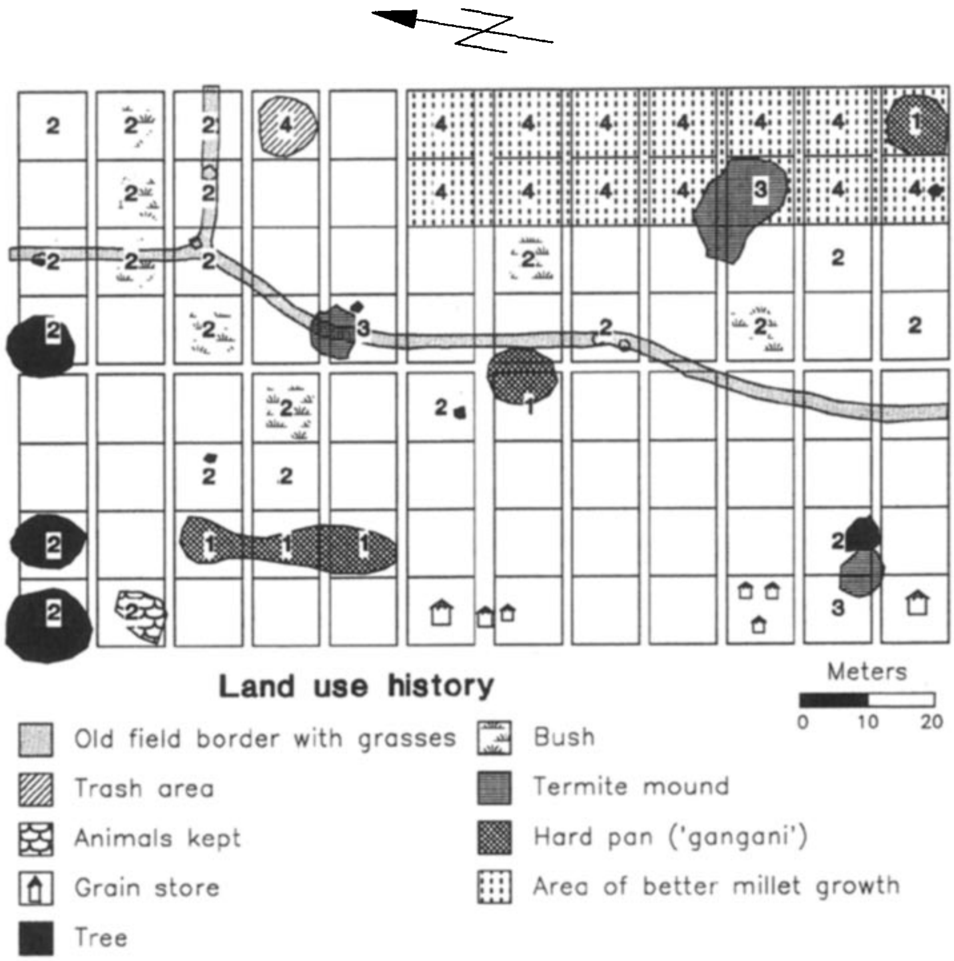

Fig. 2. Map of land-use history drawn after land clearing in 1991 according to the classification system of the farmer who cultivated the field before it was left fallow for 8 yr in 1983. Five incomplete blocks were defined ex post facto: (1) plots that formerly had hard pans, associated with bad millet growth, (2) plots that formerly had bushes and trees, (3) plots with termite mounds, (4) areas of former trash disposal, associated with good millet growth, and (5) all other plots (here, any plot without a block number indicated).

reference rows. The number of pockets per row was also recorded. By multiplying the number of pockets per row with the corresponding vigor estimate of the row, an average score ranging from 1 to 70 was obtained for each of the 960 rows in the experiment. To minimize effects of personal bias, continuing millet growth, and changing exposure of the pockets to the sun, the scoring of the whole experiment was done by one person on a single clear day between 1000 and 1500 h. At final harvest, four central rows of millet were harvested in each plot, and dry matter of grain and straw was determined after oven-drying to constant weight at 65°C.

To obtain covariates uncorrelated with treatment effects, not the scores themselves, but the residuals of average scores per plot were used as covariates in the analysis of millet straw and grain yields. Those residuals were obtained after fitting the full statistical model with all treatments and interactions in an ordinary analysis of variance of the vigor scores.

The same residuals of scores taken in 1991 and averaged across the eight central rows of each plot were also used for post stratification into two groups of soil productivity (the strata), where the term *soil productivity* is not meant to describe any particular measurable parameter of the soil or a combination of those, but refers to observed differences in early plant growth not related to treatments. With the scores sorted in ascending order, the lower and upper halves of the corresponding plots were assigned to a low and a high inherent productivity stratum, respectively. The experiment was thus effectively split into two parts. The analyses for the two unbalanced data sets were run separately for all 3 yr of the experiment to examine treatment effects under different conditions of inherent soil productivity over time. In addition to this split of the data into two strata, the farmer's fertility classification scheme was used as a blocking factor in 1991, the first year of the experiment. Because treatments were applied to the same plots each year, for an evaluation of treatment effects over years, data of straw and grain yield were considered to be repeated measurements and analyzed using the repeated measures approach provided in the software package SAS version 6.08 (Littell et al., 1991; SAS Inst., 1985). The same package was also used to test all data for normal distribution, homogeneity of variances, and additivity of the statistical models. GENSTAT 5 release 3 (Lawes Agric. Trust, 1993) was used for all other computations within years.

RESULTS

Statistical Analysis of Overall Effects

Plots of residuals for all analyses of variances and covariances indicated that variances were homogeneous. There were, however, distortions from the normal distribution for data of straw and grain yield in 1991 and for grain yield in 1993. In all cases, a square root transformation helped to overcome this, but subsequent analyses of the transformed data did not lead to noticeable changes

Table 1. *F*-values and probabilities of year and treatment effects on pearl millet straw and grain yield in 1991, 1992, and 1993.

ANOVA†	Straw *F*-value	Straw Pr>*F*‡	Grain *F*-value	Grain Pr>*F*
	kg ha^{-1}			
Stratum§	13.7	<0.001	12.0	0.001
Genotype	19.4	<0.001	3.6	0.017
CR	5.8	0.005	6.3	0.003
P	39.4	<0.001	33.4	<0.001
4th factor¶	4.5	0.036	0.8	0.386
Stratum × CR	1.5	0.232	1.9	0.164
Stratum × P	0.9	0.358	0.2	0.690
Genotype × CR	2.7	0.020	3.2	0.008
Genotype × P	1.3	0.291	0.5	0.654
CR × P	0.7	0.524	2.3	0.106
Year#	0.7	0.480	76.3	<0.001
Year × Stratum	0.7	0.519	9.7	<0.001
Year × Genotype	8.9	<0.001	10.4	<0.001
Year × CR	19.8	<0.001	8.0	<0.001
Year × P	3.6	0.035	3.8	0.027
Year × 4th factor	0.0	0.979	0.5	0.620

† Three-way interactions with the year factor were not significant except for Year × Genotype × P for grain yield (Pr > *F* < 0.01).
‡ Probability of a treatment effect (significance level).
§ The classification of plots in two strata of low and high productivity is based on residuals of vigor scores taken in 1991.
¶ The fourth factor varied by year: 1991, broadcast N; 1992, banded Mo; 1993, P placed into planting pockets. It was never significant, nor were there interactions with the other treatments.
# Probabilities of year effects and their interactions with the treatment factors are based on multivariate tests using Wilks' Lambda.

in the *F*-values of any factor or interaction. Given that both statistical techniques (analysis of variance and covariance) are robust to nonnormality, results presented here are, for simplicity, based on untransformed data.

The repeated measures analyses showed that productivity strata defined with the help of the score residuals, genotype, crop residues (CR), and broadcast P application explained a significant proportion of total variation (Table 1). There were significant interactions of genotype × year (which may also reflect the change in genotypes) and of genotype × CR for both straw and grain yield. Whereas average straw yields remained similar over years, average grain yields, the effects of stratum on grain yields, and of both CR and P on straw and grain yields, changed over time (Table 1).

Use of Soil Data, Yield Residuals, and Post Stratification Techniques in 1991

Of all the analyzed soil parameters used as covariates in 1991, only pH and Bray P explained a significant portion of total variation in straw yield, with *F*-values of 4.7 and 4.1. For grain yield, only pH was significant, with an *F*-value of 4.2. Even with these covariates, however, the residual mean squares (the measure of unexplained variation) decreased by only 13% for straw and 5% for grain yield compared with the standard analysis of variance. This led to coefficients of variation of 43% for straw and 39% for grain yield. The amount of variation attributed to the main factors remained unchanged (data not shown).

Standard analyses of variance showed large differences between genotypes and an increase of 24% for straw and of 38% for grain yields across genotypes with broadcast P fertilization (Table 2). However, in contrast to previous experiments with crop residue application (Bationo et al., 1993), this statistical analysis did not show any CR effect in the first year. Coefficients of variation were 46% for straw and 40% for grain yield (Table 2). There were no interactions between treatments.

Individual and average residuals for straw and grain yield are shown according to their field position in Fig. 1. The

Table 2. Analyses of variance (ANOVA) and covariance (ANCOVA) for pearl millet straw and grain yield in 1991 (first year).

Source of variation	df	ANOVA MS	ANOVA Pr>*F*†	ANCOVA MS‡	ANCOVA Pr>*F*	Yield: Crop residue 500	ash	2000	P 0	13	Genotype§ 1	2	3	4
		× 10^6¶		× 10^6¶		kg ha^{-1}								
						Straw yield (overall mean: 2038 kg ha^{-1})								
CR	2	0.795	0.418	0.795	0.283	1914	2215	1985#						
P	1	4.536	0.029	4.536	0.009				1821	2255				
Genotype	3	10.730	<0.001	10.730	<0.001						2856	1946	1227	2123
N	1	1.821	0.160	1.821	0.091									
Covariate††	1	–	–	14.180	<0.001		(237)‡‡		(193)			(273)		
Residual	47–48	0.896		0.613										
Total	95	1.314												
CV, %		46		38										
						Grain yield (overall mean: 1070 kg ha^{-1})								
CR	2	0.169	0.404	0.169	0.166	1010	1049	1151						
P	1	2.817	<0.001	2.817	<0.001				899	1241				
Genotype	3	0.732	0.013	0.732	<0.001						1291	1028	868	1092
N	1	0.136	0.394	0.136	0.227									
Covariate	1	–	–	4.538	<0.001		(107)		(87)			(124)		
Residual	47–48	0.183		0.090										
Total	95	0.246												
CV, %		40		28										

† Probability of a treatment effect (significance level).
‡ Mean squares (MS) in the analysis of covariance are based on Type I sums of squares.
§ Genotypes were 'Sadoré Local', 'CIVT', 'ICH412', and 'ITMV8001'.
¶ Actual values = reported values × 10^6.
# Treatment means are adjusted for covariates.
†† Residuals of scores (vigor 1 to 7 times the number of pockets per row).
‡‡ Data in parenthesis indicate standard errors of the difference.

gradient from west to east was most pronounced for grain yield. The post stratification of the experiment in the west-east direction contributed significantly to the explanation of total variation. This was indicated by an F-value of 4.4 for the blocks, with seven degrees of freedom, and the decrease of residual mean squares for grain yield by 23%, to 140 000, and of the coefficient of variation from 40 to 35%.

Similar results were obtained with the row-column analysis, where a significant row effect with an F-value of 20.3 for grain yield led to a reduction in residual mean squares to 130 000 and a coefficient of variation of 34%. The nearest-neighbor analysis with average residuals of all eight surrounding plots as a covariate (F-value of 10) led to a reduction of the residual mean squares for grain yield to 154 000 and of the coefficient of variation to 38%. All three techniques, however, were essentially ineffective in reducing the unexplained variation for straw yield and did not, for either straw or grain yield, lead to a noticeable change in the F-values of any of the factors in the experiment.

In contrast, the use of residuals of the 1991 scores as covariates, averaged for the four harvested rows, greatly helped to define variability and to clarify the effects of crop residue application. Compared with the standard analysis of variance, the residual mean squares decreased by 32% for straw and 51% for grain yield (Table 2). This led to a drop of the coefficients of variation to 38% for straw and 28% for grain yield. The reduction in treatment unrelated variation caused an increase in the amount of variation explained by CR application (Table 2). Residuals of scores in other years, however, were less useful. Similarly, use of the farmer's classification of pretreatment plot history in blocking, alone or combined with residuals of scores used as covariates, did not significantly reduce residual mean squares or increase F-values for any of the experimental factors.

Effects of Crop Residue Application in Plots of Low and High Productivity in 1991, 1992, and 1993

After 3 yr, the application of CR had strongly influenced the mechanical resistance of the surface soil before the onset of the rainy season. Irrespective of the productivity stratum, increasing the rate of mulched CR from 500 to 2000 kg ha^{-1} decreased the mechanical resistance at the 0- to 0.02-m depth by 53% and at the 0- to 0.05-m depth by 23% (Table 3). Ash application led to the largest resistances at both depths. In plots of the low-productivity stratum, the soil mechanical resistance of the upper layer was on the average 18% larger than in plots with high inherent productivity. Still in the low-productivity stratum, variance components within plots were twice as large as between plots irrespective of depth. Variance components in the high-productivity stratum at the upper soil layer were four and at the lower layer 2.5 times higher within than between plots (data not shown).

During the first 2 yr of the experiment, differences in treatment effects on millet straw and grain yield between CR application rates of 500 kg ha^{-1} and 2000 kg ha^{-1} were evident only in plots of the low-productivity stratum. This response to CR application was similar at both levels of applied P. In 1991, low-productivity plots with 2000 kg applied CR ha^{-1} produced 1980 kg ha^{-1} straw and 1020 kg ha^{-1} grain, which is 13 and 20% less than the respective average yields of high-productivity plots (Table 4). Adding blocks according to the farmer's fertility classification in 1991 further reduced variation on low- but not on high-productivity plots. In 1992 and 1993, the farmer's classification into blocks did not contribute to the total variation and blocks were therefore not included in the model (Table 4). In 1993, compared with the control, the addition of 2000 kg CR ha^{-1} led to significant yield increases in both strata. Nevertheless, CR effects were still larger in low-productivity plots (Table 4). Compared with the low level of CR application, burning of crop residues at 2000 kg ha^{-1} in low-productivity plots was very effective in increasing straw and grain yields in the first year, less effective in the second year, and resulted in the lowest yield of the three CR treatments in the third year. This declining effectiveness of ash application was similar for both levels of broadcast P, irrespective of soil productivity (Table 4). The changing response of millet to ash application over time was reflected in the significant year × CR interaction (Table 1) and the lack of a year × CR × stratum interaction (data not shown). The broadcast application of P increased millet straw yields between 23 and 61% and grain yields between 30 and 54%. This increase was smallest in 1991 but, in marked contrast to CR application, similar in both productivity strata irrespective of the year (Table 4). There was no evidence of an interaction between the effects of CR and P for either straw or grain yield.

Splitting the experiment into two strata reduced the variation unrelated to treatment as measured by the residual mean squares of both straw and grain yield (Table 5). Therefore, across years, the coefficients of variation for straw and grain yield dropped when analyses of variance were performed separately for low- and high-productivity strata compared with the combined analyses. The only exceptions were straw yields at the high-productivity stratum in 1991.

Table 3. Soil mechanical resistance at two depths as measured with a manually operated penetrometer before the onset of the rainy season 1993 (third year).

ANOVA	Mechanical resistance, by soil depth: 0–0.02 m, Mean†	0–0.02 m, Pr>F‡	0–0.05 m, Mean	0–0.05 m, Pr>F
	kN m^{-2}		kN m^{-2}	
Crop residues (CR)§		<0.001		<0.001
500	190		2000	
2000	90		1550	
2000_{ash}	270		2400	
SED¶	20		220	
Productivity		0.019		0.346
low	200		1900	
high	170		2010	
SED	18		180	
CR × Productivity		0.002		0.672

† Values are means of 20 measurements taken and analyzed for the two depths separately in each of 96 plots.
‡ Probability of a treatment effect (significance level).
§ Crop residue levels: millet stalks broadcast at rates of 500 or 2000 kg DM ha^{-1}, or as 2000 kg ash ha^{-1}.
¶ SED, standard error of the difference.

Table 4. Treatment means and probabilities of treatment effects on straw and grain yield of pearl millet in three years, separated for productivity strata.

Crop residue†	1991 Straw yield 0 P‡	1991 Straw yield 13 P	1991 Grain yield 0 P	1991 Grain yield 13 P	1992 Straw yield 0 P	1992 Straw yield 13 P	1992 Grain yield 0 P	1992 Grain yield 13 P	1993 Straw yield 0 P	1993 Straw yield 13 P	1993 Grain yield 0 P	1993 Grain yield 13 P
	t ha^{-1}											
	Low productivity											
500	1.0	1.7	0.5	0.8	1.2	2.1	0.6	1.0	1.3	2.2	0.4	0.7
2000	2.0	2.0	1.0	1.0	1.8	2.7	1.0	1.3	2.6	3.0	1.0	0.9
2000_{ash}	1.7	2.1	0.8	1.2	1.5	2.5	0.7	1.2	0.8	1.6	0.2	0.6
SED§	0.2		0.1		0.2		0.1		0.2		0.1	
Effects	Pr > *F*¶											
CR	0.012		<0.001		0.042		0.020		<0.001		<0.001	
P	0.017		0.003		<0.001		<0.001		<0.001		0.004	
Genotype	<0.001		0.014		<0.001		0.016		<0.001		<0.001	
4th factor#	0.208		0.426		0.823		0.900		0.189		0.820	
Block	<0.001		<0.001		–		–		–		–	
	High productivity											
500	1.8	2.4	1.0	1.4	1.9	2.9	0.9	1.1	1.5	2.8	0.5	0.7
2000	2.0	2.4	1.1	1.3	1.8	2.7	1.0	1.4	2.6	3.5	0.8	0.9
2000_{ash}	2.3	3.0	1.0	1.7	1.9	2.9	0.9	1.3	1.2	2.2	0.4	0.7
SED	0.4		0.2		0.2		0.1		0.2		0.1	
Effects	Pr > *F*											
CR	0.467		0.318		0.834		0.298		0.012		<0.001	
P	0.104		0.002		<0.001		<0.001		0.017		0.003	
Genotype	0.011		0.229		<0.001		0.436		<0.001		0.014	
4th factor#	0.040		0.069		0.028		0.338		0.208		0.426	
Block	0.281		0.167		–		–		–		–	

† Crop residue (CR) levels: millet stalks broadcast at rates of 500 or 2000 kg DM ha^{-1}, or as 2000 kg ash ha^{-1}.
‡ Phosphorus broadcast at 0 or 13 kg ha^{-1}.
§ SED, standard error of the difference.
¶ Probability of a treatment effect (significance level).
# The fourth factor varied by year: 1991, broadcast N; 1992, banded Mo; 1993, P placed into planting pockets.

DISCUSSION

The combined analysis over years confirmed the usefulness of classifying plots into two productivity strata, which produced distinctly different mean yields until 1993. The significant year × stratum interaction for grain yield (Table 1) might have been caused by the strong attack of the cotton stainer in 1991, which decreased grain yield more in plots of high than of low productivity. This differential damage was most likely caused by effects of soil productivity on the speed of millet development. At the time of pest attack, in high-productivity plots the plants had already reached the sensitive stage of grain filling, while in low-productivity plots the plants were still flowering. The markedly lower grain yield in 1993 was caused by a heavy attack of the millet head caterpillar [*Heliocheilus* (=*Raghuva*) *albipunctella*]. The different effect of P on millet straw and grain yields across years (Table 1) may reflect the cumulative effect of P application on soil P supply to millet. Due to the change in genotype and the fourth factor with years, both are partially confounded, but *F*-values of 1.77 for grain and 1.48 for straw gave no indication of an interaction. Altering the order in which factors entered into the unbalanced ANOVAs each year led to only very small changes in the *F*-values. This confirms the validity of the reported effects.

Table 5. Overall means, residual mean squares (RMS), and coefficients of variation from analyses of variance without (combined) and with (low, high) productivity stratification in three years.

Productivity	Straw yield Mean	Straw yield RMS	Straw yield CV	Grain yield Mean	Grain yield RMS	Grain yield CV
	kg ha^{-1}	× 10^3†	%	kg ha^{-1}	× 10^3†	%
1991						
combined	2038	896	46	1070	183	40
low	1757	254	29	886	46	24
high	2319	1347	50	1253	177	34
1992						
combined	2150	569	35	1030	151	38
low	1950	406	33	951	134	38
high	2350	409	27	1108	127	32
1993						
combined	2104	402	30	653	59	37
low	1930	260	26	646	166	33
high	2279	632	27	661	61	32

† Actual values = reported values × 10^3.

After 8 yr of fallow, some replicated plots at the described site, spaced less than 70 m apart, differed almost sevenfold in the production of aboveground total dry matter. Even two directly adjacent replicates showed differences in dry matter of 39%. These values are in close agreement with Chase et al. (1989), who found differences in millet dry matter of up to eight times in adjacent plots. Under such conditions, the testing of treatments with smaller effects (which may still be relevant to farmers) becomes very difficult.

Contrary to the findings of Scott-Wendt et al. (1988) and Wendt et al. (1993), neither the contents of exchangeable Al nor Bray or water-soluble P in the upper 0.2 m of soil sufficiently explained the variations in millet growth unrelated to treatments on our recently cleared soil, even if samples were taken at the plot level. This is in contrast to results from the humid tropics in Indonesia, where Trangmar et al. (1987) found that variation in rice on recently cleared forest land was well correlated with soil chemical parameters. On the same Sahelian soil that we used, Geiger et al. (1992) showed that, even after 5 yr of CR and fertilizer application, differences in soil chemistry between treatment and control plots could be shown only in the top 0.2 m of the soil profile; lower soil layers were very similar. This indirectly indicates that even sampling to greater depth might not have been helpful in explaining the spatial variability of millet growth. However, only further research could clarify whether sampling the surface layer at 0.05-m intervals (as suggested by Wendt et al., 1993) and using more dynamic analytical methods such as desorption studies of water-soluble or resin-extractable P could increase the explanatory value of soil chemical parameters for spatial variability in millet dry matter production.

Mapping spatial differences in soil fertility and plant growth with a cover crop in a uniformity trial is an effective but expensive approach to designing meaningful field experiments under conditions of highly unpredictable spatial variation in crop growth. To be of prolonged use, it also requires that the pattern of variability remain reasonably constant over years. Whenever uniformity trials are not feasible on sandy soils of the Sahel, the use of scoring techniques to estimate the vigor and plant stand of young millet pockets may be useful to determine patterns of soil variability over short distances. However, if early plant growth is used as an integrating indicator for unknown soil properties in an experiment with applied treatments, effects of soil variability are likely to be confounded with early treatment responses even in the first year of the experiment. Such a correlation between treatment effects and early growth was evident for our data of 1991, where the analysis on the scores showed strong effects of genotype and broadcast P application. Any use of the scores themselves as covariates, even with a successful reduction in unexplained variation and a simultaneous adjustment in means of straw and grain yield, therefore remains unsatisfactory. Residuals of plant vigor scores obtained from an analysis of variance, however, are unbiased estimates of environmental variation unrelated to treatments.

Our data show that the use of 1991 residuals of scores as covariates was efficient in reducing variation and adjusting CR effects, but splitting the experiment into two productivity strata allowed an even more sensible interpretation of the results. Since the stratum definition was based on residuals of 1991 scores, it reflected the spatial variability in native productivity of the soil at the beginning of the experiment. Defining strata according to residuals of scores from 1992 and 1993 was not helpful in reducing residual mean squares or clarifying treatment effects. This was probably due to both decreasing soil variability with continuous cultivation and increasing treatment effects on early millet growth (and, therefore, scores) over years. Whereas stratification allowed a more precise testing of the effects of CR and broadcast P in a variable environment, it adds little to our knowledge about the cause-and-effect relationships involved in the spatial variability of millet growth. The advantages and drawbacks of post stratification, which has been found to lead to substantial gains in precision in institutional surveys, have been discussed by Holt and Smith (1979) and Smith (1991). Even if in some cases there may be a risk of what is called data dredging, both authors conclude that the technique is robust and relatively free of assumptions, offers protection against extreme sample configurations, and reflects the structure of a population rather than a sample. To what degree efforts to model spatial heterogeneity directly (Gleeson and Cullis, 1987; Zimmerman and Harville, 1991) may be useful in providing more insights into the random nature of spatial variation in millet growth of the Sahel remains open to further investigation.

The relatively low effectiveness of the nearest-neighbor technique in this trial is in sharp contrast to results of Kempton and Howes (1981) and Scharf and Alley (1993), who found this technique very useful for reducing environmental variation and clarifying treatment effects in a large number of cereal trials in the UK and the USA. The limited reduction of environmental variation in grain yield obtained with either the nearest-neighbor or the row–column technique parallels the effect of dividing the experiment into eight incomplete blocks. It seems as if each of these three techniques captured the amount of variation caused by the relatively systematic attacks of the cotton stainer on the crop. The relatively larger effectiveness of using residuals of plant vigor scores for an analysis of grain and straw data, however, seems to be more appropriate to account for the irregular nature of large soil-related changes in millet growth over short distances on acid sandy soils of the Sahel. This pattern of sudden changes in biomass production apparently cannot be well predicted by measuring yield trends close by. The patchiness of soil fertility in the Sahel also has important implications for the size of experimental plots, as discussed in detail by Buerkert and Stern (1995). If one is interested only in average treatment effects, plots should be large and preferably should comprise several hundreds of square meters. If, however, the effect of a particular treatment across different productivity strata is of interest, plots should be scaled down to the size of the patches of diverging productivity.

The value of the subjective fertility assessment by the farmer was highest in the first year of the experiment, when decomposing roots from trees or bushes or old termite mounds showed stronger effects than treatments. Over time, cumulative treatment effects most likely overtook and progressively reduced variation due to prefallow land-use history.

The initial analysis of plots from the whole experiment had not revealed any overall CR effect. The response to CR was clarified by the classification of the data into the two productivity strata. The different response of millet to broadcast CR and P application across the two productivity strata may help to elucidate some of the mechanisms involved in spatial growth variability. The plots with the worst scores in 1991 appeared to be in small depressions covered by a fine crust that slowed down infiltration during strong rainstorms. These observations coincided with the farmer's assessment of these spots, of which he classified some particularly as *gangani*, or hardpans. The relationship between depressions and poor millet growth has been described by Scott-Wendt et al. (1988). Hoogmoed and Stroosnijder (1984) have reported that thin and hydrophobic crusts, such as found in these depressions, may form very quickly after a few rainstorms and have only one-tenth of the hydraulic permeability of the underlying layers of sand.

Our measurements of the mechanical resistance of the topsoil revealed that even after three consecutive years of millet cultivation, the resistance of plots grouped in 1991 into the low-productivity stratum was still higher than in high-productivity plots (Table 3). The data also show that one effect of crop residues applied as surface mulch is a decrease in soil mechanical resistance, probably the result of larger termite activity and the deposition of coarser soil particles on the surface of CR plots. It has been shown that one of the consequences of CR application in millet is increased root growth (Hafner et al., 1993), and this effect seems to be more important on spots where, in addition to adverse soil chemical conditions such as low plant-available P, soil physical conditions hamper root elongation. As no measurements of mechanical resistance were taken before land clearing in 1991, possible differences in the initial mechanical resistance between the two productivity strata could not be verified. However, it seems likely that the demonstrated higher efficiency of CR application on millet straw and grain yield in the low-productivity stratum was related to the poorer physical conditions of its plots. This assumption is indirectly supported by the similar response of millet to P application in both strata, which indicates that the differences in the productivity strata were not primarily caused by different amounts of plant available P in the soil. The fact that variability in resistance measurements within plots was larger than between plots indicates the patchiness of the soil surface conditions and mirrors the results found with the variation in millet height and aboveground dry matter (Buerkert and Stern, 1995).

Most current research focuses on blanket application of crop residues and mineral P fertilizer to sustain production on acid sandy soils of the Sahel (Bationo and Mokwunye, 1991; Bationo et al., 1993). However, given the multiple uses of crop residues by small-scale farmers of the Sahel and their scarce on-farm availability (Nicou and Charreau, 1985; Lamers and Feil, 1993; Bationo et al., 1995) crop residue application needs to be optimized. The data presented here suggest that concentrating available CR on spots of low productivity may be a short-term solution for restoring soil fertility on acid sandy soils of the Sahel. This is already practiced by some farmers in the region. However, our data also indicate that the transfer of crop residues from areas of high to low productivity may lead to a rapid decline of soil fertility in the former. A similarly rapid decline in millet yield after cessation of crop residue application has been found by Rebafka et al. (1994) and indicates how fragile the current agricultural systems are. All available data show that the continuous cultivation of acid sandy soils in the Sahel and a sustainable food production for the rapidly increasing agropastoral population in sub-Saharan Africa requires inputs of mineral fertilizers such as P. Only improved soil fertility will lead to higher grain and straw yields, which also would allow the application of crop residues on areas of both currently high and low productivity in farmers' fields to prevent soil degradation.

CONCLUSIONS

The results presented here show that the short-term response of millet growth to CR application strongly depend on inherent soil productivity. They demonstrate the advantages of dividing a field into strata representing different soil productivity classes, and not simply into regular blocks, to better understand treatment effects. Until the mechanisms governing soil microvariability on the acid sandy soils of the Sahel are fully understood and the parameters involved can be easily determined, scoring of young millet plants may be a cheap and efficient approach to estimating differences in the expression of soil fertility in millet growth. This approach should be further tested and adapted to other soils and crops in the region to define the limits of its value in clarifying treatment effects and reducing experimental error.

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REFERENCES

Ahlrichs, J.L., R.R. Duncan, G. Ejeta, P.R. Hill, V.C. Baligar, R.J. Wright, and W.W. Hanna. 1991. Pearl millet and sorghum tolerance to aluminium in acid soils. p. 947–951. *In* R.J. Wright et al. (ed.) Plant-soil interactions at low pH. Kluwer Acad. Publ., Amsterdam.

Bartlett, M.S. 1938. The approximate recovery of information from field experiments with large blocks. J. Agric. Sci. 28:418–427.

Bartlett, M.S. 1978. Nearest neighbour models in the analysis of field experiments. J. R. Stat. Soc. B. 40:147–174.

Bationo, A., A. Buerkert, M.P. Sedogo, B.C. Christianson, and A.U. Mokwunye. 1995. A critical review of crop residue use as a soil amendment in the West African semi-arid tropics. *In* J.M. Powell et al. (ed.) Proc. Conf. Livestock and Sustainable Nutrient Cycling in Mixed Farming Systems of Sub-Saharan Africa, Addis Ababa. 22–26 Nov. 1993. (in press)

Bationo, A., B.C. Christianson, and M.C. Klaij. 1993. The effect of crop residue and fertilizer use on pearl millet yields in Niger. Fert. Res. 34:251–258.

Bationo, A., and A.U. Mokwunye. 1991. Role of manures and crop residues in alleviating soil fertility constraints to crop production: With special reference to the Sahelian and Sudanian zones of West Africa. Fert. Res. 29:117–125.

Bhatti, A.U., D.J. Mulla, F.E. Koehler, and A.H. Gurmani. 1991. Identifying and removing spatial correlation from yield experiments. Soil Sci. Soc. Am. J. 55:1523–1528.

Bremner, J.M., and C.S. Mulvaney. 1982. Nitrogen: Total. p. 595–624. *In* A.L. Page et al. (ed.) Methods of soil analysis. Part 2. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Buerkert, A., and R.D. Stern. 1995. Effects of crop residue and phosphorus application on the spatial variability of non-destructively measured millet growth in the Sahel. Exp. Agric. 31 (in press).

Chase, R., and E. Boudouresque. 1987. Methods to stimulate plant regrowth on bare Sahelian forest soils in the region of Niamey, Niger. Agric. Ecosyst. Environ. 18:211–221.

Chase, R.G., J.W. Wendt, and L.R. Hossner. 1989. A study of crop growth variability in sandy Sahelian soils. p. 229–240. *In* C. Renard et al. (ed.) Soil, crop, and water management systems for rainfed agriculture in the Sudano-Sahelian zone. Proc. Int. Workshop, ICRISAT Sahelian Ctr., Niamey, Niger. 11–16 Jan. 1987. ICRISAT, Patancheru, AP, India.

Food and Agriculture Organization–United Nations Educational, Scientific and Cultural Organization. 1988. Soil map of the world. UNESCO, Paris.

Geiger, S.C., A. Manu, and A. Bationo. 1992. Changes in a sandy Sahelian soil following crop residue and fertilizer additions. Soil. Sci. Soc. Am. J. 56:172–177.

Gleeson, A.C., and B.R. Cullis. 1987. Residual maximum likelihood (REML) estimation of a neighbor model for field experiments. Biometrics 43:277–288.

Hafner, H., E. George, A. Bationo, and H. Marschner. 1993. Effect of crop residues on root growth and nutrient acquisition of pearl millet in an acid sandy soil in Niger. Plant Soil 150:117–127.

Herrmann, L., A. Hebel, and K. Stahr. 1994. Influence of microvariability in sandy sahelian soils on millet growth. Z. Pflanzenernaehr. Bodenk. 157:111–115.

Holt, D., and T.M.F. Smith. 1979. Post stratification. J. R. Stat. Soc., Ser A, 142:33–46.

Hoogmoed, W.B., and L. Stroosnijder. 1984. Crust formation on sandy soils of the Sahel: I. Rainfall and infiltration. Soil Tillage Res. 4:5–23.

Kempton, R.A., and C.W. Howes. 1981. The use of neighbouring plot values in the analysis of variety trials. Appl. Stat. 30:59–70.

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

Kretzschmar, R.M., H. Hafner, A. Bationo, and H. Marschner. 1991. Long- and short-term effects of crop residues on aluminum toxicity, phosphorus availability and growth of pearl millet in an acid sandy soil. Plant Soil 136:215–223.

Lamers, J., and P. Feil. 1993. The many uses of millet residues. ILEIA Newsl. 9(3):15.

Lawes Agricultural Trust. 1993. GENSTAT 5 Release 3 reference manual. Oxford Univ. Press, Oxford.

Littell, R.C., R.J. Freud, and P.C. Spector. 1991. SAS system for linear models. 3rd ed. SAS Inst., Cary, NC.

McLean, E.O. 1982. Soil pH and lime requirement. p. 199–224. *In* A.L. Page et al. (ed.) Methods of soil analysis. Part 2. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Moormann, F.R., and B.T. Kang. 1978. Microvariability of soils in the tropics and its agronomic implications with special reference to West Africa. p. 29–43. *In* M. Stelly (ed.) Diversity of soils in the tropics. ASA Spec. Publ. 34. ASA, Madison, WI.

Nicou, R., and C. Charreau. 1985. Soil tillage and water conservation in semi-arid West Africa. p. 9–32. *In* H.W. Ohm and J.G. Nagy (ed.) Appropriate technologies for farmers in semi-arid West Africa. Purdue Univ., West Lafayette, IN.

Olsen, S.R., and L.E. Sommers. 1982. Phosphorus. p. 403–430. *In* A.L. Page et al. (ed.) Methods of soil analysis. Part 2. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Perrier, E.R., and L.P. Wilding. 1986. An evaluation of computational methods for field uniformity studies. Adv. Agron. 39:265–312.

Rebafka, F.-P., A. Hebel, A. Bationo, K. Stahr, and H. Marschner. 1994. Short- and long-term effects of crop residue application and of phosphorus fertilization on pearl millet (*Pennisetum glaucum* (L.) R. Br.) yield on an acid sandy soil in Niger, West Africa. Field Crops Res. 36:113–124.

Samra, J.S., R. Anlauf, and W.E. Weber. 1990. Spatial dependence of growth attributes and local control in wheat and oat breeding experiments. Crop Sci. 30:1200–1205.

SAS Institute. 1985. SAS user's guide: Statistics. 5th ed. SAS Inst., Cary, NC.

Scharf, P.C., and M.M. Alley. 1993. Accounting for spatial yield variability in field experiments increases statistical power. Agron. J. 85:1254–1256.

Scott-Wendt, J., R.G. Chase, and L.R. Hossner. 1988. Soil chemical variability in sandy Ustalfs in semiarid Niger, West Africa. Soil Sci. 145:414–419.

Sissingh, H.A. 1971. Analytical technique of the Pw method used for the assessment of the phosphate status of arable soils in the Netherlands. Plant Soil 34:483–486.

Smith, T.M.F. 1991. Post stratification. Statistician 40:315–323.

Soil Management Support Services. 1988. Keys to soil taxonomy. Tech. Monogr. 6. 4th printing. Dep. of Agronomy, Cornell Univ., Ithaca, NY.

Trangmar, B.B., R.S. Yost, M.K. Wade, G. Uehata, and M. Sudjadi. 1987. Spatial variation of soil properties and rice yield on recently cleared land. Soil Sci. Soc. Am. J. 53(3):668–674.

Walkley, A., and I.A. Black. 1934. An examination of the Degtjareff methods for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Sci. 37:29–38.

Warrick, A.W., D.E. Myers, and D.R. Nielsen. 1986. Geostatistical methods applied to soil science. p. 53–82. *In* A. Klute (ed.) Methods of soil analysis. Part 1. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Wendt, J.W., A. Berrada, M.G. Gaoh, and D.G. Schulze. 1993. Phosphorus sorption characteristics of productive and unproductive Niger soils. Soil Sci. Soc. Am. J. 57:766–773.

West, L.T., L.P. Wilding, J.K. Landeck, and F.G. Calhoun. 1984. Soil survey of the ICRISAT Sahelian Center, Niger, West Africa. Texas A&M Univ./TropSoils, College Station, TX.

Wilding, L.P., and L.R. Hossner. 1989. Causes and effects of acidity in Sahelian soils. p. 215–227. *In* C. Renard et al. (ed.) Soil, crop, and water management systems for rainfed agriculture in the Sudano-Sahelian zone. Proc. Int. Workshop, ICRISAT Sahelian Ctr., Niamey, Niger. 11–16 Jan. 1987. ICRISAT, Patancheru, AP, India.

Zimmermann, D.L., and D.A. Harville. 1991. A random field approach to the analysis of field-plot experiments and other spatial experiments. Biometrics 47:223–239.