A Study of Crop Growth Variability in Sandy Sahelian Soils

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Abstract

Marked spatial variability in crop growth over short distances in sandy Sahelian soils (psammentic Palenstalf, sandy siliceous, isohyperthermic) causes yield reductions within a farmer's field and complicates analysis of results from field experiments. Planting pearl millet in a field for two consecutive years indicated that the location of the areas of poor soil does not change perceptibly between years, and that crops are more affected in bad years than in good years.

Relating plant height to soil physical and chemical properties at 101 points on two transects showed high correlations with soil acidity and other properties. Data taken from an area 20 km from Sadoré supported this finding. Analysis of surface soil samples and profiles taken along a transect between areas of healthy and poor crop growth show that acidity decreases and alkalinity increases as the healthy area is approached, and that healthy areas have soils with low acidity (<50% Al + H saturation) down to 35-cm depths, while poor soils are acidic on the surface (<5 cm).

Pot studies and subsequent plant analyses of 4-6 week-old seedlings showed high Al (>1400 mg kg⁻¹) and Mn (>1600 mg kg⁻¹) levels in plants grown in poor soils. Al tissue contents of >600 mg kg⁻¹ were consistently associated with poor plant growth. Liming poor soils two weeks before planting reduced Mn tissue but did not reduce Al tissue or improve plant growth. In sum, plants grown in good soils respond far more strongly to fertilizer applications than plants grown on poor soils.

Résumé

Variabilité spatiale des cultures des sols sahéliens : *Une forte variabilité spatiale de la croissance des cultures sur de petites distances dans les régions sahéliennes de sols sableux (psammentic Palenstalf, sables, silices, isohyperthermique) diminue les rendements des cultures et complique l'analyse des résultats découlant des expériences menées par les chercheurs. Des semis de mil pendant deux années consécutives dans un même champ ont indiqué : l'absence d'un déplacement perceptible des poches de sols médiocres d'une année à l'autre, et l'aggravation du préjudice porté aux cultures pendant les mauvaises années par rapport aux bonnes années.*

La mise en relation de la hauteur des plantes et des propriétés physico-chimiques du sol le long de deux transects a montré une forte corrélation entre l'acidité du sol et les propriétés y afférentes. Les données recueillies dans un rayon de 20 km ont corroboré cette constatation. L'analyse des échantillons et des profils des sols en surface suivant une ligne transversale séparant les zones de bonne et médiocre croissance montre : une diminution de l'acidité et une augmentation des bases à mesure que l'on se rapproche de la zone où la croissance est bonne, et

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une faible acidité des bons sols (50% Al + saturation H) jusqu'à une profondeur de 35 cm tandis que les sols pauvres sont acides en surface (5 cm).

Des études en pot et l'analyse des plantules âgées de quatre à six semaines ont montré que les plantes cultivées sur sols médiocres étaient caractérisées par des teneurs élevées en Al (1400 ppm) et en Mn (1600 ppm). Les plantes ayant une teneur en Al 600 ppm étaient toujours associées à une faible croissance. D'une façon générale, la réponse des plantes aux engrais est de loin supérieure en sols riches qu'en sols pauvres. On a mis en évidence un effet positif de la chaux sur la diminution en Mn, mais non en Al.

Introduction

In many areas of the Sahel, crops grown on sandy soils display a marked degree of spatial variability in crop establishment, growth, and yield within a single field. In some cases, the variability in crop growth is because of the physical and biological properties of the coarse, poorly buffered soil system. While crop variability may frequently be attributed to the existence of termite mounds, proximity to trees, previous human activity (Chase 1984, Moorman and Kang 1978), soilborne pests (Germani and Reversat 1982), or various pedogenic processes (Wilding and Drees 1978, Van Wambeke and Dudal 1978), a particularly pronounced variability exists, which has a different cause. In such cases, patches of poor pearl millet growth, 6–30 m in diameter virtually next to highly productive stands cause yield losses and confound treatment effects in researchers' field experiments (Moorman and Kang 1978).

The objectives of the studies reported here were to determine the causes of variability, and to seek methods to eliminate the sources of this variability.

Symptoms

In the agricultural fields near Niamey, Niger, patches of poor pearl millet (*Pennisetum americanum*) growth are often observed in farmers' fields and on research station plots. They are frequently associated with slightly depressed areas in the fields, and often have darker surface soil than that in adjacent productive regions, and a weak, porous crust. Productive regions, in constrast, are often associated with slightly elevated regions and loose, very sandy soils. Symptoms of poor growth begin to appear in pearl millet 1–2 weeks after emergence. The seedlings exhibit stunted growth and the leaves curl longitudinally, often turning yellow, purple, or brown. If soil-moisture remains high, less-affected plants may continue to grow and may eventually produce a small head. The more-affected plants die if deprived of water even for a short period. Cowpea crops (*Vigna unguiculata*) when affected become yellow and grow more slowly but usually do not die.

Materials and Methods

The Site

Preliminary studies were conducted at the ICRISAT Sahelian Center (ISC), located approximately 40 km southeast of Niamey, Niger, West Africa (13° 15'N latitude 2° 18'E longitude), at an altitude of 240 m. The site is located on a sand plain with 2–8 m thick eolian sands covering one of a series of stepped surfaces comprised of cemented laterite gravels (West et al. 1984). The soil is sandy, siliceous, isohyperthermic Psammentic Paleustalf, comprised of approximately 90% sand. The surface horizon (25–30 cm thick) is a yellowish red sand uderlain by a thick (>1 m) red loamy sand or red sand horizon.

Rainfall is highly irregular both in distribution and total amount during the short (approximately 4 mo) rainy season. Long-term mean annual rainfall for the Kolo research station, about 20 km from the ISC, is 574 mm, with a 90% probability of receiving more than 380 mm (Sivakumar et al. 1979). Annual rainfall at the ISC during the studies described here was between 240–680 mm.

The site had been used for a traditional pearl millet-fallow rotation before being donated to the ISC. Two years of fertilized crops had been grown on the 2-ha experimental field before the present studies were begun. Previous experiments there could not be interpreted due to the extreme variability in crop growth. Soils at the ISC are representative of the large surrounding pearl millet-growing areas. To extend the applicability of this on-station study, three additional sets of soil samples (per field) were taken from similar soils from three off-station fields within 20 km of the ISC site, where variability in crop growth had been observed.

Soil Sampling and Analysis

To determine causes of crop variability, two 50 m × 50 m transects that intersected perpendicularly at their midpoint were established. They extended over both productive and unproductive crop growth areas. Soil samples (0–15 cm depth) were taken at 1-m intervals along each transect. They were analyzed by the Institut national de recherches agronomiques du Niger (INRAN) for organic matter, P (Bray I), particle-size distribution, cation exchange capacity (CEC), bases (K, Ca, Mg, and Na), and effective CEC. Soil pH (1:2.5 in both H_2O and KCl), exchangeable acidity and Al, soil bulk density, soil surface elevation, and plant height were determined. All soil parameters were regressed against plant height of pearl millet grown in pockets adjacent to each sampling site.

In another study, 26 soil samples (0–15 cm depth) were collected at regular intervals along a 15-m transect where pearl millet development declined somewhat regularly (i.e., from superior growth to plant death). In addition, soil samples were collected in increments to a depth of 70 cm at each end and at an intermediate location on the transect. All soils were analyzed for bases, pH, and exchangeable Al and Al+H. The bulk of the 26 samples taken along the transect were then used in pot studies.

ISC Field Studies

Field studies were conducted at the ISC from 1984 through 1985 to estimate the extent and severity of variability in crop growth. In 1984, pearl millet (var. CIVT) was machine-planted at a 1.0 × 0.75-m grid spacing in a 2-ha field. Simple superphosphate (SSP) was machine-banded at the time of seeding at a rate of 150 kg ha^{-1} (15 kg P ha^{-1}). Urea (100 kg ha^{-1}) was applied by hand adjacent to each hill, half at planting and half at first weeding [about 15 days after planting (DAP)]. Approximately 30 DAP, plants were measured in the 50 × 50-m square defined by the intersecting transects described above. Head number, length, and weight were recorded for each hill at harvest.

In 1985, the field was planted and fertilized at the same rates and times as in 1984. Hand planting permitted hills to be placed at the recommended 1 × 1-m spacing. Plant heights and yield parameters were recorded in the 50 × 50-m subplot as in 1984. Soil samples were collected on a 4 × 4-m grid and analyzed for pH (H_2O and KCl), exchangeable acidity, and Al.

Pot Studies

Four pot studies were conducted during the 1984-1985 dry season. Their objectives were:

- Study 1: To determine the effect of soils taken along a transect between productive and unproductive field regions on pearl millet seedling root and shoot growth, and shoot mineral composition.
- Study 2: To determine the effects of lime and Ca applied to productive and unproductive soils on pearl millet seedling root and shoot growth, and shoot mineral composition.
- Study 3: To determine the effect of nutrient applications, both individually and in selected combinations, on pearl millet seedling root and shoot growth, and shoot mineral composition.
- Study 4: To repeat the third study using different combinations and a soil-sterilization treatment to test for biotic factors.

For the first study, the 26 soil samples collected along the transect between productive and unproductive field regions, discussed above, were mixed individually. Four replications from each of the 26 soil sites, using 7.5 kg of air-dried soil per pot, were employed. Without further treatment, pearl millet was grown for 37 days, and then harvested. Plant shoots and roots were dried and weighed, and shoots digested and analyzed for mineral composition.

Studies 2, 3, and 4 were carried out using soils from extremely productive and unproductive areas of the experimental field. Each of the two types of soils was mixed and 10 kg of soil used in each pot. Amendments (Wendt 1986, Table 1) were added 2 weeks before pearl millet was planted. Five replications of each treatment were employed. Plants were thinned to four per pot after the first week, and were allowed to grow for 28 days before harvesting. Harvested plants were treated as in the first

Table 1. Pearl millet shoot growth in liming trial (Wendt 1986).

Amendment	Rate (kg ha^{-1})	Lime factor	Shoot wt. (g pot^{-1})	pH
Productive soil site				
(Control)	0	0	0.831efg[2]	5.42
$Ca(OH)_2$+MgO	27	1	0.999fgh	5.69
$Ca(OH)_2$+MgO	54	2	0.795ef	5.69
$Ca(OH)_2$+MgO	108	4	0.882efgh	6.28
$Ca(OH)_2$+MgO	216	8	0.686de	6.96
$Ca(OH)_2$+MgO	540	20	0.848efg	8.18
$Ca(OH)_2$	35	1	0.876efgh	6.02
$Ca(OH)_2$	70	2	0.799ef	5.86
$Ca(OH)_2$	140	4	0.677de	6.32
$Ca(OH)_2$	280	8	0.786ef	7.18
$Ca(OH)_2$	700	20	0.489cd	8.33
$CaCl_2.2H_20$	69	1	1.115h	5.97
$CaCl_2.2H_20$	139	2	1.082gh	5.72
$CaCl_2.2H_20$	278	4	0.648de	5.42
$CaCl_2.2H_20$	556	8	1.105fgh	5.94
Unproductive soil site				
(Control)	0	0	0.236b	4.59
$Ca(OH)_2$+MgO	244	1	0.250bc	5.98
$Ca(OH)_2$+MgO	489	2	0.194ab	7.10
$Ca(OH)_2$+MgO	978	4	0.148ab	8.39
$Ca(OH)_2$+MgO	1955	8	0.057ab	9.25
$Ca(OH)_2$	316	1	0.233b	6.02
$Ca(OH)_2$	630	2	0.141ab	7.08
$Ca(OH)_2$	1260	4	0.121ab	8.91
$Ca(OH)_2$	2520	8	0.078ab	9.28
$CaCl_2.2H_20$	627	1	0.067ab	5.13
$CaCl_2.2H_20$	1254	2	0.035ab	5.09
$CaCl_2.2H_20$	2507	4	0.000a	5.15
$CaCl_2.2H_20$	5016	8	0.000a	4.88

1. Denotes the multiple of equivalents of exchangeable acidity in the soil that the applied lime can neutralize. For the $CaCl_2.2H2O$ treatments, it refers to the calcium equivalents relative to the limed soils.
2. Means not followed by the same letter are significantly at $P = 0.05$ by Duncan's multiple range test.

pot study. In all four pot studies, pots were watered regularly with well water from ISC whose properties are nearly equivalent to rainwater.

Results and Discussion

Analysis of Soils

Chemical and physical parameters from the 101 soil samples collected from the intersecting 50-m transects were statiscally compared to pearl millet plant heights 35 DAP. The highest correlations were obtained between plant height and percentage of silt (r = -0.35**), exchangeable Al+H (r = 0.33**), exchangeable Al (r = -0.36**), and soil pH (r = 0.22**). Exchangeable bases and CEC, both related to pH in these acid soils, were also highly correlated with plant height.

To determine if soil acidity was related to poor crop growth in other areas as well, three paired samples from adjacent productive and unproductive regions were taken from similar soils in three farmers' fields within 20 km of the ISC. In all three cases, the relationship between soil acidity parameters and plant growth was highly significant (Table 2). The same relationship was observed in the experiment using soils taken along the transect described above. Analyses of the surface 15-cm of soil showed that pH increased and exchangeable acidity (Al+H) decreased along the transect leading to the productive site (Fig. 1). Exchangeable Ca, Mg, and K also increased (Wendt 1986). Al saturation ($r = -0.95$), exchangeable Ca ($r = 0.88$), Mg ($r = 0.94$), Al ($r = -0.95$), Al+H ($r = -0.96$), and pH ($r = 0.96$) correlated strongly with the position on the transect.

Soil-profile samples at the two extremes and at the midpoint of the transect were analyzed. The chemical analyses indicated a very low effective CEC (<1.3 cmol kg^{-1}) and highly variable amounts of exchangeable cations. Of particular interest is the variation in the exchangeable Al+H saturation, i.e., the percentage of exchangeable Al+H vs the sum of the exchangeable Ca, K, Mg, Na, and Al+H (Fig. 2). All soils had a low Al+H saturation at the surface, however the Al+H saturation of the unproductive extreme of the transect increased to 45% at a depth of only 3.5 cm. The Al+H saturation at the productive extreme increased more gradually,

Table 2. Soil chemical parameters in farmers' fields as a function of crop growth (n = 3).

Area	pH (H_2O)	pH (KCl)	Exchangeable Al+H (cmol kg^{-1})	Exchangeable Al (cmol kg^{-1})
Area with poor pearl millet yield	5.06	3.99	0.42	0.17
Area with good pearl millet yield	5.86	4.74	0.15	0.00
SE	±0.19	±0.18	±0.06	±0.04
CV (%)	8.50	10.30	50.80	-

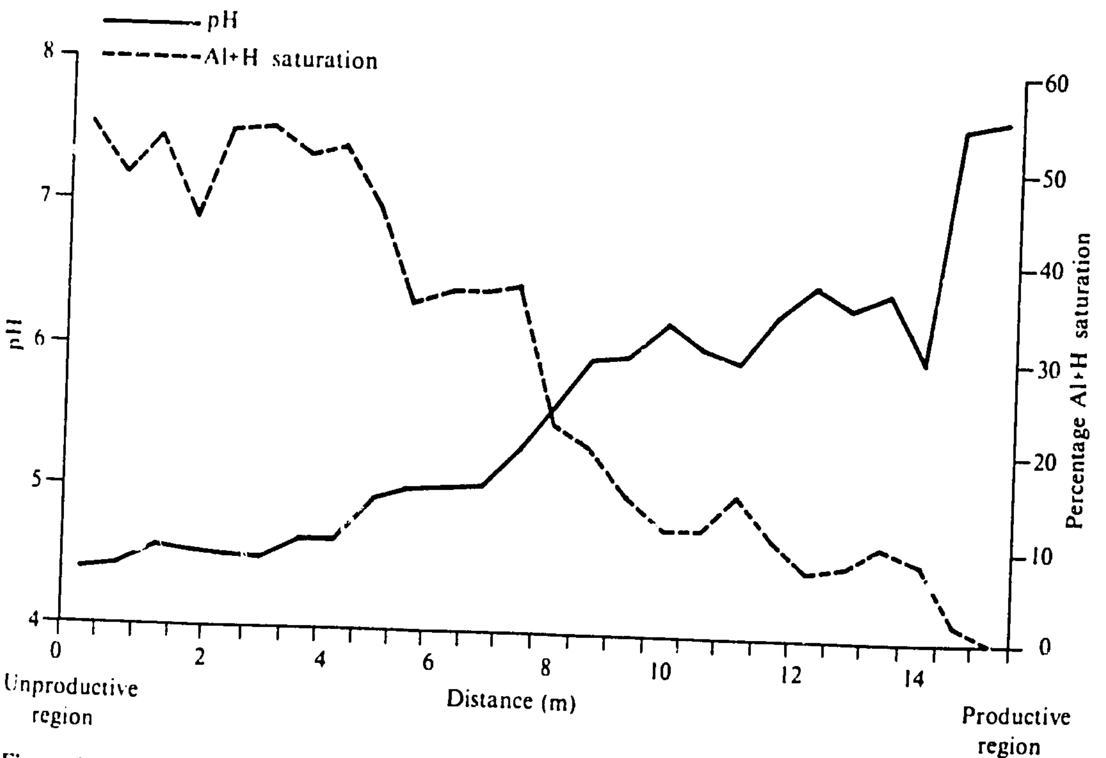

Figure 1. Percentage Al+H saturation and pH of the surface 15-cm of soil along a transect from an unproductive to a productive region (Wendt 1986).

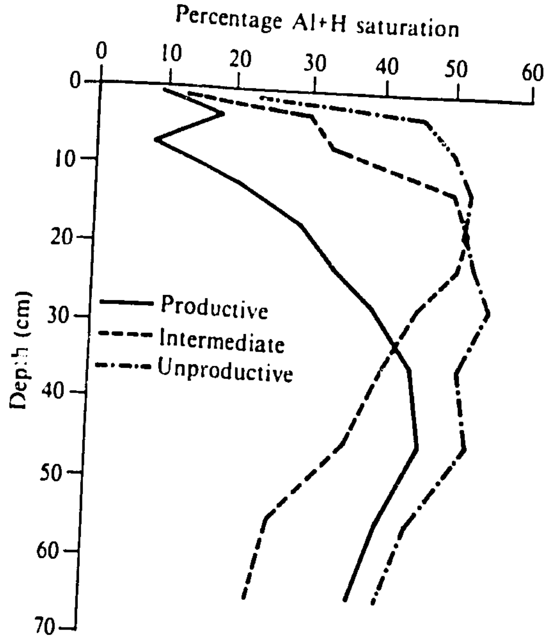

Figure 2. Percentage Al+H saturation with depth along a transect from an unproductive to a productive region (Wendt 1986).

reaching 45% saturation at a depth of 35-cm. The soil at the midpoint of the transect was saturated with 45% Al+H at about 12-cm. All soils had potentially toxic levels of exchangeable Al within 35-cm of the surface. Increases in exchangeable Al+H were accompanied by decreases in exchangeable Ca and K in all profiles (Wendt 1986).

Field Studies

In 1984, 4.7% of the 2-ha research field used at ISC was found to be totally barren, while 9% was found to produce exceptional pearl millet stands. To show the dramatic effect of short-distance changes in crop growth, two adjacent subplots were harvested and compared (Table 3). The better of the two plots yielded over eight times the grain harvested from the poor plot. Analysis of all sites in the 50 × 50 m area showed that if the entire area yielded at levels observed in the upper 10% of the sites, grain production for the field would quadruple. This suggests that far more than the 4.7% completely barren area is being affected and may respond to soil amendments.

A comparison of the growth patterns in 1984 and 1985 within the 50 × 50-m area made it apparent that given locations remained unproductive over the 2 years. However, the crop was less affected during the wetter 1985 season than in the droughty 1984 season. This difference is believed by the authors to be due to the death of marginal plants in the drier 1984 that would have survived under more humid conditions.

Pot Studies

Soil Collected Along a Transect

Plant biomass and pearl millet shoot mineral concentration as a function of position along the transect between unproductive and productive field regions were closely correlated with mineral concentration in the soil (Wendt 1986). Extremely high concentrations of Al (>1400 μg g^{-1}) and Mn (>1[illegible]0 μg g^{-1}) suggest that both of these elements may have reached toxic levels in some plants. Pearl millet shoot weight correlated extremely well (r = -0.89) with plant Al concentration (Fig. 3). The critical Al concentration for pearl millet growth appears to be <600 μg g^{-1}. Plant Mn concentration correlated strongly with soil pH (Fig. 4). However, it did not correlate well with pearl millet shoot weight, and proved to be an insignificant factor in

Table 3. Pearl millet yields measured in two 7 m × 5.25 m plots separated uniformly by one meter in a research field and fertilized at the ICRISAT Sahelian Center in 1984.

Total hills	Surviving hills	Number of heads	Head weight	Grain weight	Stalk weight
			(kg ha^{-1})		
49	11	27	158	124	470
49	44	157	1302	1030	2340

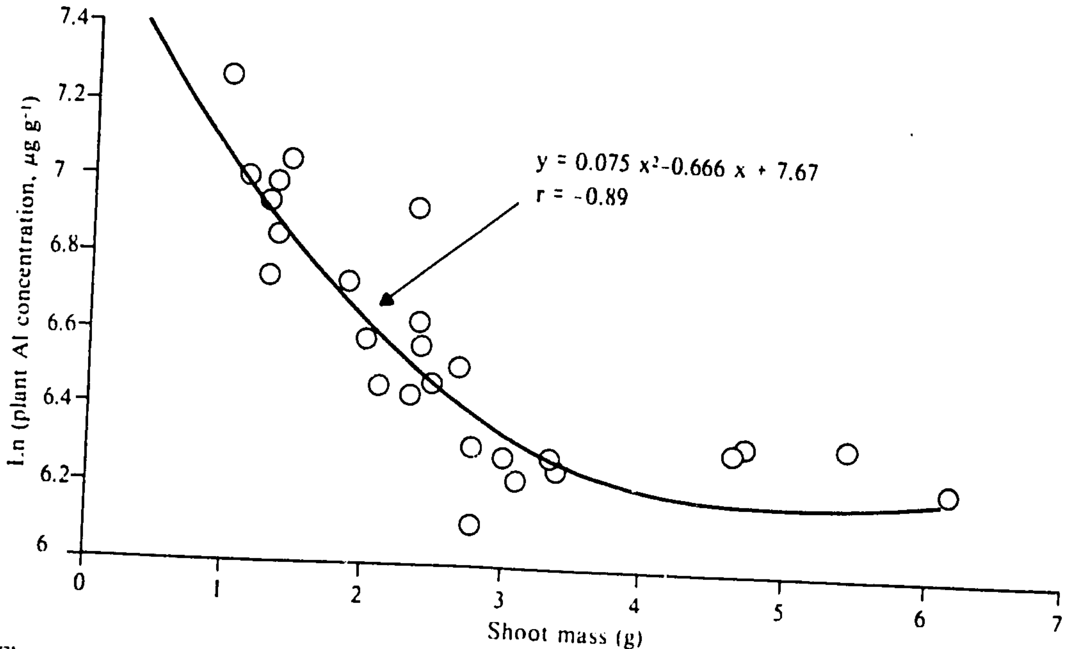

Figure 3. Ln (Al concentration) vs shoot mass for plants grown in the surface 15-cm of soil taken along a transect from an unproductive to a productive region (Wendt 1986).

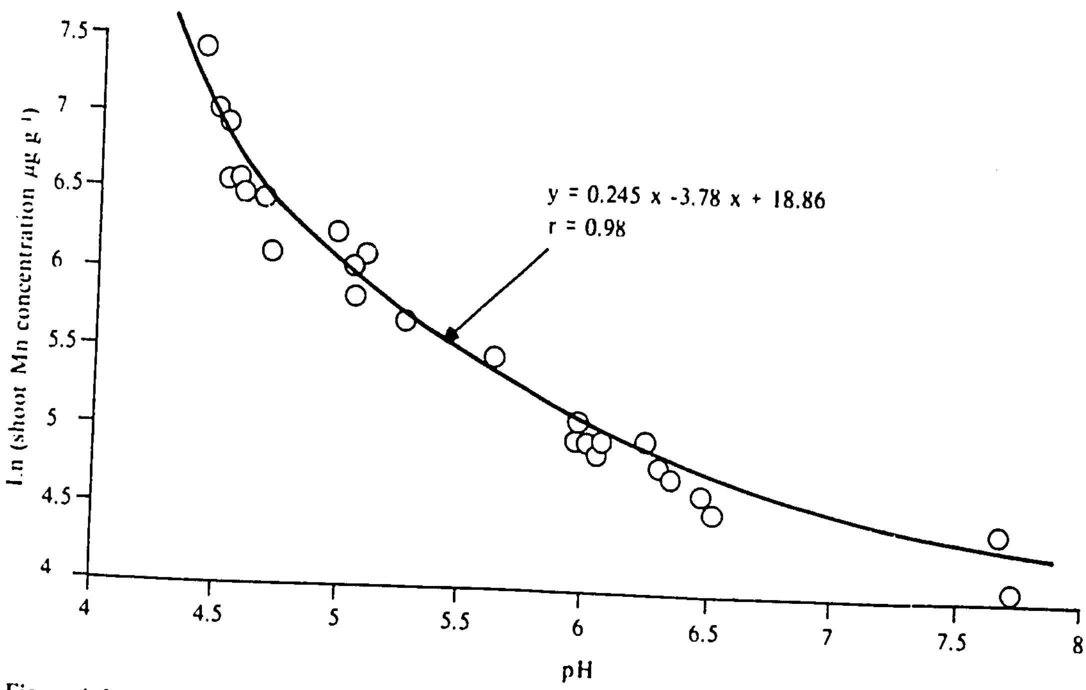

Figure 4. Ln (shoot Mn concentration) vs soil pH (1:1) for plants grown in the surface 15-cm of soil taken along a transect from an unproductive to a productive region (Wendt 1986).

estimating pearl millet shoot weight in a multiple regression analysis with plant Al concentrations. The effect of toxic levels of Mn may be obscured Al toxicity or other elemental deficiencies.

The Liming Experiment

Selected chemical properties of soils collected for the liming study are summarized in Table 4. The productive soil had higher pH, base saturation, and exchangeable Ca, Mg, and K levels, and less exchangeable Al than the unproductive soil.

Pearl millet seedling growth and soil pH of various treatments in the liming experiment are summarized in Table 1. Liming did not improve shoot weight in either soil. The productive soil produced higher shoot biomass than the unproductive soil in all treatments. In the unproductive soil, shoot biomass was further inhibited by the addition of $CaCl_2.H_2O$, which resulted in the death of the plant at the highest rates of application. However, low rates of $CaCl_2.H_2O$ actually increased Al- and Mn-uptake in the unproductive soils. These unexpected results are explained by plant-tissue analysis (Table 5). Lime applications, while dramatically reducing Mn concentrations, did not reduce plant Al uptake. Additions of Cacl, actually increased Al and Mn uptake in the unproductive soils. Other authors (Farina et al. 1982, Fox et al. 1986, Soileau et al. 1969) have reported plant uptake of Al plants limed to neutrality. Hargrove (1986) hypothesized that this phenomenon may be due to the solubilization of Al-organic matter complexes at pH values between 5 and 7. Bloom et al (1979) concluded that Al-organic matter complexes control soil solution Al concentrations in soils with low CEC, even if the soils have low organic matter contents. Farina et al. (1982) suggest that availability of Al at near-neutral pH values may be due to increased micro-

Table 4. Selected chemical properties of soils used in the liming experiment (Wendt 1986).

Parameter	Soil site	
	Unproductive	Productive
Exch.[1] Ca, cmol(+) kg⁻¹	0.47	0.68
Exch. Mg, cmol(+) kg⁻¹	0.04	0.09
Exch. K, cmol(+) kg⁻¹	0.06	0.12
Exch. Na, cmol(+) kg⁻¹	0.02	0.02
Exch. Al, cmol(+) kg⁻¹	0.36	0.03
Exch. Al+H, cmol(+) kg⁻¹	0.57	0.17
E Bases, cmol(+) kg⁻¹	0.59	0.87
ECEC, cmol(+) kg⁻¹	1.19	1.07
Al+H saturation (%)	49	16
pH, H_2O	4.58	5.67
pH, 1 M KCl	3.86	4.56

1. Exch. = Exchangeable.

Table 5. Elemental concentrations in selected treatments in the liming experiment (Wendt 1986).

Amendment	Rate factor[1]	Shoot wt.	Al	Mn
Productive soil type				
Control	0	0.831c[2]	397 A	156 A
$Ca(OH)_2$	1	0.876c	485 A	118 A
$CaCl_2.2H_2O$	1	1.115d	606 A	221 A
$CaCl_2.2H_2O$	2	1.082d	345 A	304 A
Unproductive soil type				
Control	0	0.236b	2328 CD	1373 B
$Ca(OH)_2$	1	0.233b	1397 B	237 A
$Ca(OH)_2$	2	0.141ab	1574 BC	83 A
$Ca(OH)_2$	3	0.067a	1697 BC	78 A
$CaCl_2.2H_2O$	1	0.035a	2539 D	2044 C

1. The multiple of equivalents of acidity that the applied lime is capable of neutralizing. In the case of calcium chloride, refers to the equivalents of Ca, relative to the liming treatment for that soil.
2. Means not followed by the same letter are significantly different at $P = 0.05$ by Duncan's multiple range test.

Table 6. Yield response to fertilizer treatments in the first nutrient experiment (Wendt 1986).

Treatment	Nutrients applied	Shoot wt (g pot⁻¹)	
	Unproductive type		
1	P, Ca, Zn, S, B, N, Mo, K, Mg, lime, Mn, Cu	1.09	de[2]
2	P, Ca, Zn, S, B, N, Mo, K, Mg, lime, Mn	0.59	bc
3	P, Ca, Zn, S, B, N, Mo, K, Mg, lime	1.03	de
4	P, Ca, Zn, S, B, N, Mo, K, Mg[1]	0.75	cd
5	P, Ca, Zn, S, B, N, Mo, K[1]	0.27	ab
6	P, Ca, Zn, S, B, N, Mo[1]	0.26	ab
7	P, Ca, Zn, S, B, N[1]	0.20	ab
8	P, Ca, Zn, S, B[1]	0.15	a
9	Zn, S, B[1]	0.09	a
10	Ca, B[1]	0.11	a
11	B	0.12	a
12	N, P, Zn, S	0.60	bc
13	P, Zn, S	0.26	ab
14	Zn, S	0.07	a
15	N, Mo	0.08	a
16	Mo	0.10	a
17	N	0.07	a
18	P	0.24	ab
19	K[1]	0.07	a
20	Control	0.12	a
	Productive soil type		
21	Control	1.33	e
22	P, Ca, Zn, S, B, N, Mo, K, Mg, Mn, Cu[1]	3.11	f

1. These treatments contained chloride salts.
2. Means not followed by the same letter are significantly different at $P = 0.05$ Duncan's multiple range test.

bial degradation of Al-organic matter at higher pH values and consequent release of plant-available Al-organic acid complexes.

Nutrient Experiments

Soil properties in the nutrient experiment were similar to those in other trials. Productive soils had higher pH, base saturation, and exchangeable Ca, Mg, and K levels, and lower exchangeable acidity. Plant response to nutrient applications in the unproductive soils was sufficient to increase plant growth, which never exceeded growth of plants in the productive soils with no amendments applied (Table 6). Plant growth in productive soils improved dramatically in response to nutrient application.

A significant increase in pearl millet shoot weight in the unproductive soils occured with the application of N, P, Zn, and S alone (Treatment 12). While several fertilizer combinations improved pearl millet production on the unproductive soil, all successful treatments involved P and N.

Tissue analyses (Table 7) indicate that unproductive soils did not supply adequate levels of P, K, and Mg, and were toxic to Al and Mn. Additions of P, K, and Mg increased plant growth by ameliorating apparent deficiencies of these nutrients in unproductive soils. Lime decreased plant Mn concentrations (Treatments 1, 2, and 3). Elimination of lime from treatments did not result in increased plant Al uptake. This is probably due to the presence of P in unlimed treatments. Elimination of P from the nutrient solution increased plant Al uptake (Treatment 18 vs 20) and decreased plant

Table 7. Elemental concentrations in selected treatments in the first nutrient experiment (Wendt 1986).

Treatment	Shoot wt (g pot⁻¹)	P	K	Mg	Al	Mn	Soil pH
		Plant elemental concentration					
		(g kg⁻¹)			(µg g⁻¹)		
		Unproductive soil type					
1	1.09de[1]	2.6cd	35.9de	2.4b	417a	163a	5.44gh
2	0.59bc	2.7bcd	37.5ef	2.4b	484a	217a	5.48h
3	1.03de	2.5cd	35.2de	2.4b	397a	134a	5.29fgh
4	0.75cd	3.3de	38.7ef	1.9ab	430a	818b	4.76abcd
5	0.27ab	3.0cde	40.8ef	1.4a	596a	1265bc	4.87bcde
12	0.60bc	2.8cd	27.6cd	1.9ab	268a	929b	5.22fgh
13	0.26ab	2.5bcd	17.5ab	1.7ab	660a	939b	4.54a
17	0.07a	1.4ab	11.3a	1.8ab	2237c	1561c	4.69bc
18	0.24ab	2.1bc	23.8bc	2.0ab	631a	967b	5.11efg
20	0.12a	0.8a	19.1abc	1.7ab	1248b	786b	4.64ab
		Productive soil type					
21	1.33e	2.3bcd	32.8de	4.6c	303a	122a	5.00cdef
22	3.11f	4.1e	45.4f	5.9d	332a	261a	5.09def

1. Means not followed by the same letter are significantly different at $P = 0.05$ by Duncan's multiple range test.

Table 8. Yield response to fertilizer treatments in the second nutrient experiment (Wendt 1986).

Treatment	Nutrients applied	Shoot wt g pot⁻¹
	Unproductive soil type	
1	Control	0.05a[3]
2	P	0.31ab
3	P, N	1.09bcd
4	P, N, Ca[2]	0.38ab
5	P, N, Ca, Mg, S[2]	0.43ab
6	P, N, Ca, Mg, S	1.12bcd
7	P, N, Ca, Mg, S, Zn[2]	0.31ab
8	P, N, Ca, Mg, S, Zn, K[2]	0.47ab
9	P, N, Ca, Mg, S, Zn, K, B[2]	0.56ab
10	P, N, Ca, Mg, S, Zn, K, B, Mo[2]	0.45ab
11	P, N, Ca, Mg, S, Zn, K, B, Mo, lime	1.58cde
12[1]	P, N, Ca, Mg, S, Zn, K, B, Mo, lime	1.62cde
13	P, N, Mg, S, Zn, lime	1.15bcd
	Productive type soil	
14	Control	0.70abc
15	P, N	2.00def
16	P, N, Ca, Mg, S, Zn[2]	2.81f
17	P, N, Ca, Mg, S, Zn, K, B, Mo[2]	3.85g
18[1]	P, N, Ca, Mg, S, Zn, K, B, Mo	2.22ef

1. These soils were sterilized by heating at 105°C for 24 hours.
2. These treatments contained chloride salts.
3. Means not followed by the same letter are significantly different at $P = 0.05$ by Duncan's multiple range test.

Table 9. Elemental concentrations in selected treatments from the second nutrient experiment (Wendt 1986).

Treatment	Shoot wt	Plant elemental concentration						
		N	P	K	Ca	Mg	Al	Mn
		(g kg⁻¹)						$\mu g\ g^{-1}$
1	0.05a[1]	-	0.7a	14.0a	8.7cd	1.5ab	2574e	866e
2	0.31ab	-	1.8bc	15.4a	6.8abc	1.3a	1052bcd	438bc
3	1.09bcd	-	2.3bcd	14.3a	6.8abc	2.0ab	613abc	673de
5	0.43ab	-	1.8bc	14.6a	8.2bcd	2.2b	1148cd	774de
6	1.12bcd	-	2.2bcd	14.9a	6.6ab	2.4b	519abc	609cd
10	0.45ab	-	1.5ab	32.8bc	6.5ab	1.3a	1514d	826de
11	1.58cde	-	2.7cd	42.4d	9.4de	1.7ab	317a	152a
13	1.15bcd	43.2b	2.8d	16.6a	11.0e	3.8c	420ab	222a
14	0.70abc	38.8ab	1.6b	34.3c	8.3bcd	4.9d	679abc	184a
15	2.00def	45.3b	6.6e	25.3b	6.3a	4.6cd	397ab	320ab
16	2.81f	43.5b	6.4e	29.5bc	8.7cd	6.1e	509abc	208ab
17	3.85g	37.4ab	6.4e	45.0d	7.1abc	3.6c	539abc	186a
18	2.22ef	34.9a	6.9e	44.1d	9.8de	4.4cd	638abc	174a

1. Means not followed by the same letter are significantly different at $P = 0.05$ by Duncan's multiple range test.

biomass. All treatments that had P as an amendment showed reduced plant Al concentrations, clearly showing the effect of P in reducing Al toxicity. Additions of P had no effect on plant Mn concentrations.

Yields and plant mineral compositions for the second nutrient experiment are summarized in Tables 8 and 9. This experiment generally substantiated what had been observed in the first nutrient experiment. The combination of P and N reduced Al concentrations in pearl millet shoots grown on unproductive soils and improved biomass production substantially. Further, the detrimental effect of chloride salt additions is clearly evident (Treatment 3 vs 4, 5 vs 6, Table 8). The chloride salts had the effect of increasing Al uptake and decreasing shoot biomass. When sulfate salts were substituted for chloride salts (Treatment 4, Table 8) biomass production and shoot Al concentration improved dramatically. Soil sterilization did not improve the unproductive soils (Treatment 11 vs 12, Table 8) indicating that biological factors were not the cause of poor crop performance.

Phosphorus availability from applied P was higher in productive than in the unproductive soils (Treatments 1 and 3 vs 14 and 15). The apparent increase in P-fixation in unproductive soils suggests that P is being precipitated by Al in the solution (Birch 1951). Phosphorus can also be immobilized by Al in root tissue (Wright and Donahue 1953). Phosphate "liming", i.e., the precipitation of Al with P, may be an inefficient use of P fertilizer in acid Sahelian soils. Woodruff and Kamprath (1965) observed that P fertilizer addition for optimal pearl millet growth was reduced by 50% when the exchangeable soil Al was first neutralized by liming.

Conclusion

Aluminum toxicity is the probable cause of poor pearl millet growth in the unproductive soils used in the pot studies and is probably the primary cause of variability in pearl millet stands in the fields examined. Mn toxicity may also be an important factor contributing to poor crop production, but in these studies it was at most a secondary problem.

Elemental deficiencies exist in these soils, compounding the variability problem. The unproductive soils in particular produced plants deficient in N, P, K, and Mg when compared to values given in the literature. These deficiencies may also play a role in soil variability as they are more pronounced in unproductive than in productive soils. Even soils taken from relatively productive areas in the field responded dramatically to fertilizer inputs. This indicates the need for comprehensive fertilizer research involving several nutrients and nutrient combinations.

Liming of unproductive soils with $Ca(OH)_2$ had a significant effect in increasing soil pH and reducing plant Mn uptake, but did not affect plant Al uptake or improve biomass production. The ineffectiveness of lime applications in reducing Al toxicity has been reported elsewhere and is still under investigation by the authors. The use of chloride salts increased plant Al uptake and decreased plant biomass on the unproductive soils, but did not adversely affect plant growth in productive soils. By comparison, the use of sulfate salts did not have an adverse effect on either productive or unproductive soils.

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