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Variability in Pearl Millet (*Pennisetum americanum*) Fields in Semiarid West Africa

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Abstract *Extreme variability in pearl millet [*Pennisetum americanum *(L.) K. Schum] growth over very short (2–20 m) distances in the poorly buffered sandy soils of the semiarid West African Sahel poses major limitations to millet production and to field research efforts. A pot study using soils taken at 26 sites along a 15-m transect from an unproductive to a productive region in a research field was conducted to determine the causes of variability in millet growth. Plant analyses showed that millet-shoot weight 37 days after planting correlated best with shoot Al concentration (R^2 = 0.81 for the 22 most unproductive sites). The critical concentration for Al toxicity in millet shoots was approximately 600 μg g^{-1}. Millet growth also correlated well with shoot K concentration (R^2 = 0.53). Poorly growing plants had deficient concentrations of P and K and potentially toxic levels of Mn. Low concentrations of plant P may be related to P fixation by soil Al.*

Keywords spatial variability, pearl millet, Al toxicity, Mn toxicity, P fixation.

Introduction

Extreme variability in pearl millet [*Pennisetum americanum* (L.) K. Schum] growth over very short distances is a major limitation to millet production in semiarid Sahelian West Africa, a region frequently plagued by food shortages. Millet growth can diminish from a highly productive region to a completely barren area over distances as short as 2 m. While millet production lost to this problem has not yet been quantified over large agri-

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cultural regions, variability in crop stands is evident in many if not most millet fields in Niger and other Sahelian countries and also affects sorghum (*Sorghum bicolor*) and cowpea (*Vigna unguiculata*) production. These crops are the food staples in most Sahelian countries. Causes of variability have been shown to be more limiting to crop production than water when rainfall is as little as 240 mm yr^{-1} (Chase unpublished data).

Studies by the authors (Scott-Wendt *et al.* 1988) indicate that unproductive soils of the Labucheri soil series (sandy, siliceous, isohyperthermic Psammentic Paleustalf) on the ICRISAT (International Crops Research Institute for the Semiarid Tropics) Sahelian Center 40 km south of Niamey, Niger, are associated with low (<4.5) pH, high Al+H saturation of the cation exchange sites, and decreased amounts of exchangeable K, Ca, and Mg when compared with productive sites. These chemical properties may result in Al or Mn toxicity or deficiencies of K, Ca, Mg, and P.

Dey *et al.* (1980) determined that the critical N concentration for pearl millet was 32 g kg^{-1} in whorl-cut plants at the knee-high stage and 25 g kg^{-1} in third and fourth leaf at ear-emergence stage. Gregory (1979) showed that N concentrations in millet fell rapidly from 60 g kg^{-1} at emergence to less than 20 g kg^{-1} at flowering. Ajakaiye (1979) found that maximum millet growth 24 days after planting in Hoagland's solution was achieved

Table 1

Selected chemical properties of soils taken along a transect from an unproductive to a productive region

Extreme	Site No.	Position m	pH	Exchangeable cation Ca	Mg	K	Al + H (KCl-extr.)	ECEC cmol(+) kg^{-1}	Al + H Sat'n %
				cmol(+) kg^{-1}					
Unproductive soil	1	0.0	4.39	.43	.04	.08	.66	1.21	55
	2	0.6	4.45	.52	.05	.08	.61	1.26	48
	3	1.2	4.57	.45	.06	.08	.64	1.22	52
	4	1.8	4.54	.56	.07	.09	.56	1.27	44
	5	2.4	4.50	.41	.05	.08	.61	1.15	53
	6	3.0	4.51	.42	.05	.07	.62	1.16	53
	7	3.7	4.65	.47	.05	.07	.60	1.19	51
	8	4.3	4.68	.42	.05	.08	.59	1.14	52
	9	4.9	4.95	.46	.06	.08	.50	1.10	46
	10	5.5	5.02	.62	.10	.07	43	1.22	35
	11	6.1	5.03	.56	.07	.08	.41	1.12	37
	12	6.7	5.07	.56	.08	.08	.42	1.14	37
	13	7.3	5.24	.53	.08	.09	.42	1.12	38
	14	7.9	5.60	.66	.09	.10	.24	1.08	22
	15	8.5	5.94	.68	.13	.11	.23	1.14	20
	16	9.1	5.97	.81	.11	.12	.18	1.23	15
	17	9.8	6.22	.75	.11	.12	.13	1.11	12
	18	10.4	6.02	.94	.12	.09	.15	1.30	12
	19	11.0	5.94	.64	.11	.12	.16	1.03	16
	20	11.6	6.29	.74	.13	.17	.12	1.16	10
	21	12.2	6.50	.86	.14	.44	.11	1.54	7
	22	12.8	6.33	.90	.14	.23	.11	1.38	8
	23	13.4	6.46	.89	.15	.16	.14	1.34	10
	24	14.0	5.98	.85	.14	.16	.11	1.26	9
Productive soil	25[a]	14.6	7.64	1.66	.17	.20	.05	2.08	2
	26[a]	15.2	7.70	4.82	.29	.23	.00	5.34	0

[a] These sites had free calcium salts and therefore the amount of calcium extracted is not representative of, and gives elevated values for, the exchangeable calcium and ECEC.

when millet P concentrations were between 4.9 and 5.7 g kg^{-1}. Critical nutrient concentrations vary depending on the growth stage of the plant. Phosphorus and K concentrations fell from 4.0 to 1.0 g kg^{-1} and from 37 to 10 g kg^{-1}, respectively, between 20 days after planting and flowering stage (47 days after planting). Gupta *et al.* (1981), employing 26 surface soils from India, concluded that the critical Zn concentration for millet tissue was 17 $\mu g\ g^{-1}$. Lanyon *et al.* (1977) reported that raising the pH from 5.1 to 5.6 improved millet yields on two soils, an Alcoa silt (Rhodic Paleudult, clayey, oxidic, thermic) and a Delicias clay (Typic Haplorthox, clayey, oxidic, isohyperthermic). Yield increases responded to decreases in Mn concentrations from 1050 to 933 $\mu g\ g^{-1}$ and from 344 to 143 $\mu g\ g^{-1}$ in plants grown on the respective soils. The authors indicated that Al concentrations were not toxic in these experiments.

Data on critical Ca or Al concentrations for pearl millet plants could not be found in the literature. Walker *et al.* (1975) found that liming a Greenville sandy clay loam soil from pH 4.8 to pH 7.1 (1:1 H_2O) decreased Al concentrations in millet forage from 536 to 321 $\mu g\ g^{-1}$, but did not improve forage yield. Kamprath (1970) reported that corn, which is considered to be very tolerant of high soil acidity, was affected by Al when Al saturation of the cation exchange sites reached 44%.

Critical Mg and K concentrations for pearl millet appear to be related to one another. Cummins and Perkins (1974) found that the critical Mg concentration for millet grown in sand and fertilized with Hoagland's solution was 1.3 g kg^{-1}, the concentration representing the average Mg concentrations of the plants at 54 and 81 days after planting. Potassium concentrations averaged 49 g kg^{-1} at this critical Mg level. However, when a similar greenhouse study was conducted using a magnolia sandy loam soil (Rhodic Paleudult, clayey, kaolinitic thermic), the critical Mg concentration was 4.5 g kg^{-1}, with a corresponding K concentration of 22.5 g kg^{-1}. The authors concluded that critical Mg requirement varied according to environmental conditions and K availability to the plants.

The objective of this study was to determine the chemical causes that result in variability in millet stands.

Materials and Methods

A 15-m transect was selected in a field where millet growth declined continuously from an excellent millet stand to a completely barren region. The surface 15 cm of soil was collected at approximately 60-cm intervals along the transect for a total of 26 sampling sites. Analysis of the soils has been previously reported (Scott-Wendt *et al.* 1987). Selected chemical properties are summarized in Table 1. Soil from each site was thoroughly mixed by hand in a large basin before placing it into four pots. Each pot contained 7250 g of air-dried soil with no chemical amendments.

Pearl millet (*Pennisetum americanum*, var. CIVT) was planted at a depth of 2 cm. Pots were watered to above field capacity every 2 to 3 days with well water. Analysis of the well water confirmed that it was similar in composition to rainwater falling in the region. Since no greenhouse was available, the pots were placed outside unprotected from the dry, hot wind and in a relatively uncontrolled environment. The experiment took place in March and April during the dry season so that insect damage and rainfall effects were eliminated. Pots were pressed into loose sand to allow them to drain freely. The pots were rotated twice during each experiment by exchanging the pots most exposed to the wind with the pots in the downwind positions. Seedlings were thinned to four plants

14 days after planting. Millet was harvested 37 days after planting. The plant material was washed, and shoots were separated from roots. Both shoots and roots were dried for 72 hours at 60°C and weighed.

Plant shoots were ground using a Wiley mill and passed through a 20 mesh sieve, then digested in a Technicon block digester using the sulfuric acid-hydrogen peroxide procedure of Nelson and Sommers (1973). Nitrogen and P were determined on an autoanalyzer using the indophenol blue method (Keeney and Nelson 1982) and molybdate blue method (Olsen and Sommers 1982), respectively. Calcium, Mg, Al, Fe, and Mn were determined using atomic absorption spectrophotometry and K by atomic emission spectrophotometry.

Multiple regression techniques were used to examine relationships between soil nutrients, plant growth, and plant elemental concentrations.

Results and Discussion

Plant biomass and nutrient parameters for the transect pot experiment are presented in Table 2. Poorly growing plants commonly had necrotic, poorly branched, and restricted root systems, a primary symptom of Al toxicity.

Table 2

Shoot growth and elemental concentrations for plants grown in soils taken along the transect

Site No.	Shoot Wt. g per 4 pots	Plant elemental concentration N	P	K	Ca	Mg	Al	Mn
		g kg^{-1}						
12	0.92	32.0	1.3	19.4	16.3	4.5	1439	461
13	1.07	16.6	1.7	23.0	11.5	3.5	1104	306
6	1.25	22.4	1.2	14.1	7.6	2.5	1047	736
8	1.25	22.8	1.1	18.9	9.0	3.6	858	459
7	1.27	33.9	1.5	15.6	9.4	3.2	1095	648
9	1.31	34.7	1.3	18.6	9.8	3.4	950	538
1	1.37	41.3	1.3	16.8	8.5	2.3	1167	1677
4	1.79	33.4	1.1	20.6	8.4	2.9	851	718
3	1.95	21.4	1.1	19.8	8.2	3.3	728	676
26	2.07	20.4	1.0	31.0	11.6	4.1	648	58
11	2.27	19.9	1.9	24.6	11.1	4.1	629	357
5	2.30	32.1	1.0	14.3	5.2	1.4	1037	1047
20	2.33	26.0	1.8	34.6	8.0	4.3	762	123
15	2.34	23.3	1.9	30.1	9.6	5.2	713	163
10	2.44	20.8	2.3	22.6	9.4	4.2	652	425
2	2.61	37.5	1.3	17.3	7.1	2.1	682	1149
23	2.73	21.4	2.0	39.8	7.6	4.5	550	106
18	2.74	19.1	2.6	28.0	8.1	4.3	452	133
19	2.99	18.4	2.0	30.6	7.3	4.1	538	146
14	3.06	22.4	1.3	22.5	7.8	4.3	507	250
22	3.30	22.2	2.4	35.2	7.9	4.3	528	118
17	3.35	17.5	2.7	31.5	8.3	4.0	526	147
25	4.64	22.8	2.0	39.0	11.7	3.9	551	86
24	4.67	16.9	2.8	44.6	7.6	3.4	563	142
16	5.41	23.1	2.3	29.8	8.7	4.6	569	142
21	6.14	28.0	2.0	38.7	7.6	3.7	511	93
S.E.	±0.432	±3.47	±0.16	±1.84	±0.86	±0.26	±128	±54
C.V. %	33.2	26.6	19.0	14.1	18.9	13.9	32.0	25.2

Table 3

Correlation matrix of plant elemental concentrations for the transect experiment

Variable	Shoot weight	Site location	Soil pH	N	P	K	Ca	Mg	Mn	Al
Shoot wt.	—	.59***	.59**	−.29	.61**	.73**	−.29	.25	−.48*	−.72**
Site location	.59**	—	.94**	−.61**	.61**	.91**	.13	.65**	−.86**	−.59**
Soil pH	**	.94**	—	−.50*	.48*	.84**	.16	.61**	−.78**	−.60**
N	−.29	−.61**	−.50*	—	−.56**	−.53**	−.02	.55**	.76**	.56**
P	.61**	−.61**	.48*	−.56**	—	.71**	−.10	.52**	−.59**	−.60**
K	.73**	.91**	.84**	−.53**	.71**	—	−.04	.56**	−.75**	−.68**
Ca	.29	.13	.16	−.02	−.10	−.04	—	.42*	−.19	.41*
Mg	.25	.65**	.61**	−.55**	.52**	.56**	.42*	—	−.81**	−.43*
Mn	−.48*	−.86**	−.78**	.76**	−.59**	−.75**	−.19	−.81**	—	.60**
Al	−.72**	−.59**	−.60**	.56**	−.60**	−.68**	.41*	−.43*	.60**	—

,,** Significant at $p = 0.05$ and 0.01, respectively.

A correlation matrix of plant nutrient and plant biomass parameters from the pot study (Table 3) shows that shoot weight correlated with plant K and Al concentrations. Both K and Mn concentrations in the shoots correlated well with position on the transect. Since all of these parameters are highly correlated with one another, multiple regression procedures were employed to determine which factors best correlated with millet growth in the pots.

Initial linear regressions indicated that K and Al uptake were the controlling factors in millet growth, with 53% of the variability in millet shoot weight being accounted for by plant K concentrations. Aluminum concentration accounted for 51% of the variability when regressed linearly against millet shoot weight. In combination, Al and K accounted for 62% of the variability. Including other plant concentration variables in the regression model did not significantly improve the R^2 value.

An examination of the individual graphs of shoot weight vs. Al concentration suggests a nonlinear response. A graph of shoot weight vs. Al concentration (Figure 1) shows that two distinct graphical regions exist. Plants having Al concentrations > 600 $\mu g\ g^{-1}$ showed decreasing growth as Al concentration increased. This portion of the graph can be modelled by a linear equation relating shoot weight to Al concentration ($r^2 = 0.64$). The remaining plants were apparently not affected by Al levels. Variation in growth at these soil sites could not be accounted for by other plant elemental concentrations. Recorrelation after elimination of the four most productive treatments, all of which had low plant Al concentrations (<600 $\mu g\ g^{-1}$), resulted in an improvement of the correlation coefficient (r^2) for shoot weight vs. plant Al concentration to 0.81. Exceptional growth at the non-Al-limited sites cannot be accounted for with the plant elemental data collected.

Eliminating these four data points is not clearly justified. Variation in growth may be due to differences in B, Mo, or S levels, which were not measured. Zinc concentrations were not presented because of contamination of several samples in the digestion procedure, but were adequate in the uncontaminated samples when compared with the critical concentration for millet of 17 $\mu g\ g^{-1}$ as determined by Gupta *et al.* (1981). Several plants grown in soils from along the transect had weak, necrotic root systems, the primary symptom of Al toxicity. Plant Al concentration therefore appears to be the controlling factor in plant growth up until a point where plant Al is reduced to a nontoxic level. Beyond this point, other factors appear to be limiting plant growth along the transect.

One interesting note is that the plant nutrients that correlated best with position on the transect were Mn and K. Shoot Mn concentration also regressed very well against soil pH (Figure 2; $r^2 = 0.97$). However, including shoot Mn in the multiple regression procedure vs. shoot weight did not result in a significant improvement in the correlation coefficient.

Plant P concentration correlated somewhat with shoot weight ($r^2 = 0.37$). However, this may be due to a reduction of plant P concentrations by Al. When plant P and Al concentrations were regressed simultaneously against shoot weight, P concentration proved to be an insignificant factor in accounting for variability in plant growth.

A very poor correlation between location on the transect and shoot weight ($r^2 = 0.37$) was observed (Table 3). This surprising lack of agreement between millet growth in the pots and observed millet growth along the transect in the field (which was not quantified) could be the result of a combination of the following factors:

(1) Soil mixing. Since the chemical nature of the soil profile changes considerably in the surface 15 cm (Scott-Wendt *et al.* 1988), mixing could have caused a substantial variation from the natural horizonation that exists in the field. The pH

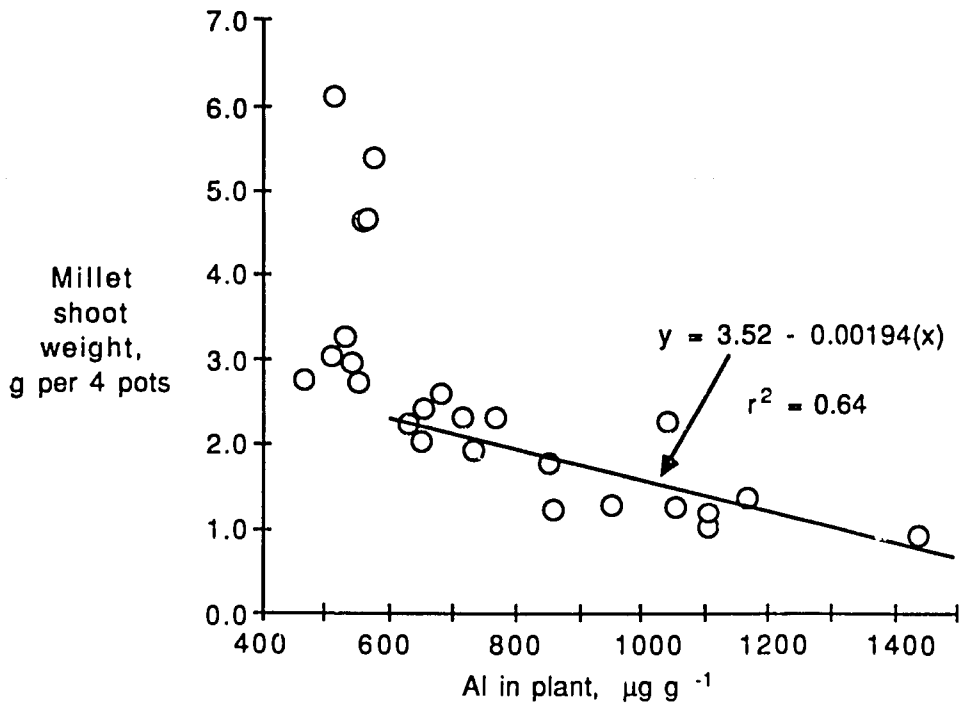

Figure 1. Shoot weight vs. Al concentration for plants grown in the surface 15 cm of soil taken along a transect from an unproductive to a productive region.

changes brought by the mixing of horizons could have very definite effects on soil chemical equilibrium as well. Aluminum species in particular may be slow in reaching an equilibrium state if pH changes occur due to mixing. Equilibrium between Al monomers and polymers is not rapid (Hsu 1968).

(2) Sampling depth. Soils in the field all have increased levels of acidity with depth (Scott-Wendt *et al.* 1987). Therefore, the surface 15 cm may not be representative of the soil environment experienced by the millet roots in the field.

(3) Lack of moisture stress in the pots. Moisture was maintained at sufficient levels in the pots so that drought stress would not limit growth. This improved moisture situation may have permitted water and nutrient uptake by damaged roots that would not have ordinarily taken place in the field.

(4) Variations in soil temperature and moisture in the pots. Since the pots were not in a protective greenhouse, it was impossible to maintain all of the pots at a consistent temperature. Moisture levels may have been affected as well.

A comparison of nutrient concentrations of plants grown along the transect critical values for millet in the literature indicates that poorly growing plants had high levels of Al and Mn. Millet grown along the transect had Al concentrations as high as 1440 $\mu g\ g^{-1}$ and Mn concentrations as high as 1680 $\mu g\ g^{-1}$. All plants had deficient P concentrations. Potassium appears to be deficient in many plants. Magnesium concentrations appeared to be sufficient in most plants. Nitrogen concentrations are in the normal range in several of the unhealthy plants, yet are below the critical N concentration of 32 g kg^{-1} determined by Dey *et al.* (1980) in the better treatments.

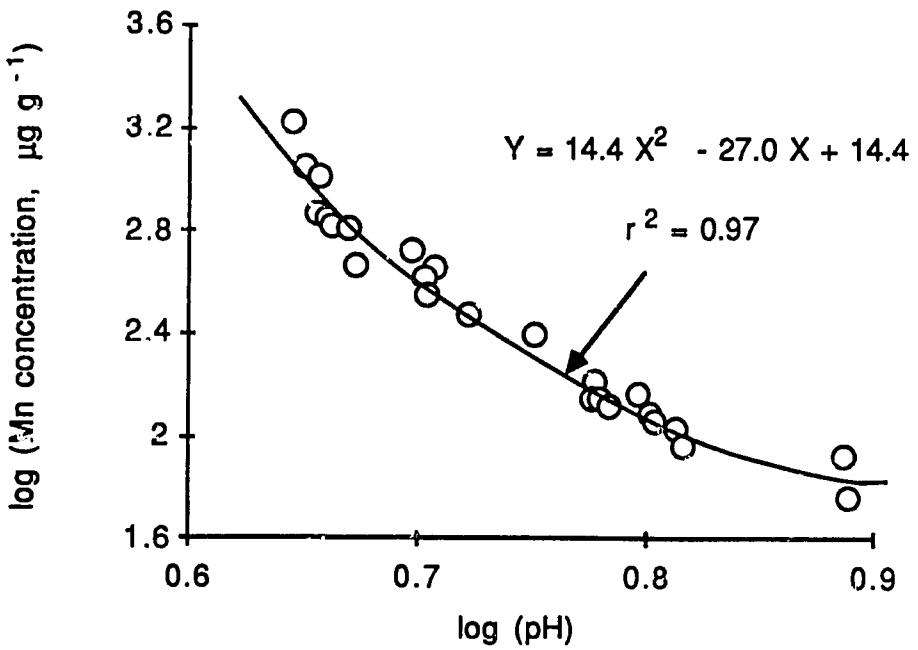

Figure 2. Log (Mn concentration) vs. log (pH) for millet shoots grown in soils taken along a transect from an unproductive to a productive region.

Conclusions

Elemental Toxicities and Deficiencies

The transect experiment indicated that Al was the primary element limiting plant growth, the critical plant Al concentration being about 600 $\mu g\ g^{-1}$ in millet plant tops. Aluminum concentrations in millet shoots correlated very well with shoot biomass in the transect experiment for the 22 most unproductive sites along the 26-site transect ($r^2 = 0.81$). The other four sites exhibited normal growth and low levels of Al, indicating that after Al toxicity has been eliminated, other fertility factors begin to affect yields.

Potassium deficiencies may also be contributing to variability. Shoot biomass correlated very well with plant K concentrations ($r^2 = 0.53$). Potassium concentrations were deficient at most soil sites when compared with critical K concentrations in millet grown by Cummins and Perkins (1974). Kamprath and Foy (1971) caution that liming may induce K deficiency through ion competition effects.

Phosphorus deficiencies are indicated at all soil sites when compared with P concentrations reported by Ajakaiye (1979). Phosphorus availability can be depressed in low pH soils by the formation of Al phosphate compounds (Birch 1951). Mineralization of organic P is depressed at low pH values as well (Thompson *et al.* 1954). Plant P concentration did not correlate well with shoot weight, however, and was insignificant in a multiple regression analysis relating plant Al and P concentrations with shoot weight, indicating that P deficiency is not the major source of variability. The primary response to P fertilization observed at the ICRISAT Center in Niger where these experiments were performed may be due to immobilization of Al by P. Woodruff and Kamprath (1965) observed that the P requirement for optimal millet growth was reduced by 50% when the exchangeable soil Al was first neutralized by liming.

Manganese is clearly not the principal cause of poor plant growth in the soils studied, but may be a contributing factor. Lanyon *et al.* (1977) found that increasing the pH from 5.1 to 5.6 improved millet forage production of two highly weathered soils by reducing Mn uptake.

Nitrogen is clearly deficient when compared to plant N concentrations reported by Dey *et al.* (1980). The low levels of N were particularly apparent in soils not having excessive Al concentrations. Plant N concentration did not correlate well with plant growth, however. It is likely that these soils would respond to N applications once other nutrient toxicities/deficiencies have been corrected.

Magnesium levels to not appear to be deficient when compared with Mg concentrations in millet reported by Cummins and Perkins (1974).

Soil Amendment Strategies

Eliminating causes of variability in both farmers' fields and research plots in the semiarid region of West Africa could result in dramatic yield increases and diminish variation in researchers' plots. Several possible approaches exist for eliminating variability.

Liming unproductive soils may be the best way to eliminate Al and Mn toxicity. Since the soils in this region have a very low CEC, lime requirements for the field studied would probably not exceed 500 kg ha^{-1} if only unproductive sites were limed. Caution must be exercised in lime application. Liming soils beyond an optimal pH of 5.5 to 6.0 may render other plant nutrients such as Fe, Mn, Cu, and Zn unavailable (Price and Moschler 1970). Ion competition effects due to the increased levels of Ca could also aggravate existing K and Mg deficiencies. Lime applications should be supplemented with K and Mg. Phosphorus additions will probably be necessary as well.

Calcium sulfate additions may also relieve soil acidity problems. Calcium sulfate acts by displacing Al from the cation exchange sites and rendering it more leachable. This amendment strategy would also require additions of K, Mg, and P.

Once nutrient deficiencies are corrected, water may become more important as a limiting factor to plant growth. In years of marginal rainfall, adequate plant nutrition and elimination of elemental toxicities may determine the success or failure of a crop stand. A healthy soil environment is therefore crucial in the Sahel, where years of marginal rainfall are common to the dryland farmers. These factors make clear the need for additional soil fertility research in the Sahel.

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