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FERTILITY STATUS OF SELECTED MILLET PRODUCING SOILS OF WEST AFRICA WITH EMPHASIS ON PHOSPHORUS

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Major millet (*Pennisetum glaucum* (L.) R.Br.) producing soils of West Africa are mainly found in the Sudano-Sahelian agroecological zone. These soils are generally sandy in texture, have poor buffering capacity, and are low in native fertility. For successful management of these soils for sustainable production, fertility factors influencing nutrient availability need to be evaluated. Soils were sampled at selected locations throughout the agroecological zone. The nutrient status of these soils was determined and related to P dynamics. Soils were generally neutral to acid in reaction, but few had any measurable amounts of exchangeable Al. Total P, Bray 1 extractable P, and P adsorption maxima were low which reflected their low levels of clay and organic matter. Phosphorus sorption characteristics were controlled by the poorly crystalline Al and Fe phases and the soil clay fraction. The poorly crystalline Al and Fe phases were highly correlated with the clay fraction ($r = 0.99^{***}$). The P external requirement ranged from 11 to 40 mg P kg^{-1} soil. Given the low levels of total and labile P in these soils, P amendments will be necessary for sustained productivity. However, moderate amounts of P amendments would be necessary as a result of the relatively low fixation capacity of these soils.

West Africa produces 74% of the total millet (*Pennisetum glaucum* (L.) R.Br.) grown in Africa and 28% worldwide, making it an important millet producing area (FAO 1986). The majority of this production occurs in the Sahelian and Sudanian ecological zones where annual rainfall averages between 200 and 1200 mm/year, and potential evapotranspiration can range from 1200 to 2200 mm/year (Dancette and Hall 1979).

Parent materials of the soils of the subregion are generally composed of granitic rock or acid sands (continental terminal) which give rise to sandy, slightly acid soil systems. Parent materials for soils of the semiarid to arid regions are often reworked sands of eolian origin (Wilding and Hossner 1987). The most extensively utilized soils for millet production are classified as either Ustalfs (south) or Psamments (north) in the U.S. Soil Taxonomy.

A strong yield response is generally obtained from the use of fertilizers or organic amendments in these soils. Phosphorus is one of the most limiting nutrients to millet growth in the Sahel (Pieri 1985). Response to N fertilization is generally nonexistent until the P requirement is met (Bationo et al. 1989).

The objectives of this study were to survey the status of P and other nutrients of selected millet producing soils of the subregion and to examine the factors which influence P sorption and availability.

MATERIALS AND METHODS

Site selection

Twenty-four soils (sites) were sampled from six countries in West Africa which represented a range of soils commonly used for the production of millet (Fig. 1). Four of these sites were sampled from 2 to 4 times making a total of 31 samples.

Soil analysis

Soils were air dried and ground to pass through a 2-mm sieve. Soil pH was measured in H_2O and N KCl using a 2:1 solution:soil ratio. Exchangeable Al and total acidity were measured as described by McLean (1982). Exchangeable bases were displaced with N NH_4OAc and cations determined by atomic absorption spectrophotometry (Ca and Mg) or flame photometry (K and Na). Organic carbon was determined by the method of Walkley and Black (1934). Total N was determined by the Kjeldahl procedure as described by Bremner and Mulvaney (1982).

Total P was determined by wet digestion with perchloric acid. Available P was extracted by the

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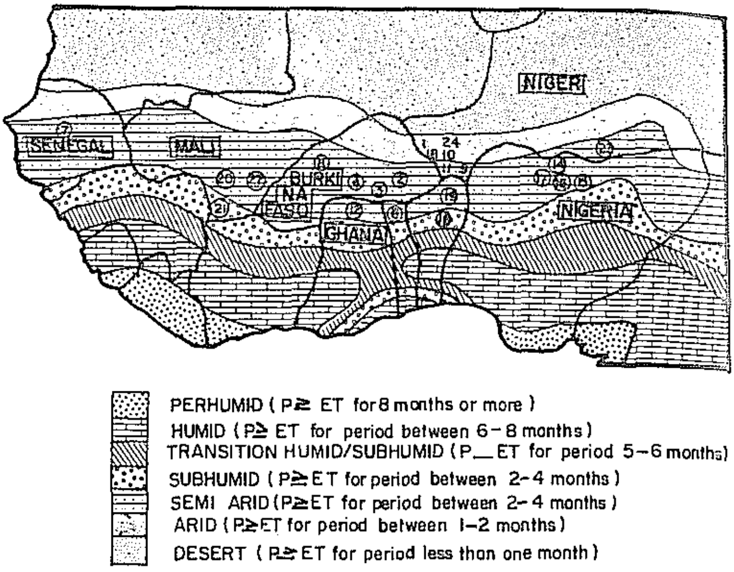

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FIG. 1. Generalized agroclimatic map of West Africa with selected locations where soils were sampled.

Bray 1 extractant, and P in solution was analyzed by the molybdate blue method as described by Olsen and Sommers (1982). Phosphorus sorption characteristics were determined using the method of Fox and Kamprath (1970).

Poorly crystalline and free Fe and Al oxides were determined by oxalate extraction (Schwertmann 1973) and citrate-dithionite extraction (Jackson 1958), respectively. Iron was measured by atomic absorption spectrophotometry. Aluminum was determined by titration to the phenolphthalein endpoint as outlined in McLean (1982).

RESULTS AND DISCUSSION

Fertility parameters

All soils were sandy to sandy loam in texture. Clay contents ranged from 0.7 to 11.7% with an average of 3.5% (Table 1). These soils exhibited a wide range of pH values from slightly acid (pH 5.2) to mildly alkaline (pH 7.6); however, only one soil had a pH higher than 7.2. While Al saturation ranged up to 15%, only 13% of the soils contained measurable amounts of exchangeable Al. These results indicate that soil acidity, especially Al toxicity, is not a problem of regional concern but instead should be a focus of localized research and control.

Levels of organic carbon, total N, and effective cation exchange capacity (ECEC) were low. The interrelationships between these fertility-related variables are listed in Table 2. Native levels of organic C were highly correlated with total N ($r = 0.97^{***}$) which indicated that crop production within these systems, where N fertilizers are not used to any great extent, could be dependent on the maintenance of soil organic matter. Organic C was also highly correlated with ECEC ($r = 0.87^{***}$) which indicated that soil organic matter might be a more dominant influence on soil cation exchange capacity (CEC) than the soil clay fraction.

Native phosphorus status

The amount of total P in these soils ranged from 25 to 349 $mg \cdot kg^{-1}$ and a mean of 109 $mg \cdot kg^{-1}$. Available P was also generally low, ranging from 1 to 30 $mg \cdot kg^{-1}$ with an average of 6 $mg \cdot kg^{-1}$. However, 77% of these soils had available P values of less than 8 $mg \cdot kg^{-1}$ which has been determined to be the critical P level required to obtain 90% of the maximum millet yield in the sandy soils of Niger (Bationo et al. 1989). None of these soils had a recent history of phosphorus fertilization, so the available P parameter represents a background level for agricultural soils of this region.

The low contents of the above P parameters may be related to several factors, including;

1) Parent materials, which are mainly composed of eolian sands; these materials con-

TABLE 1

Chemical and physical properties of soils

Location	pH		Total			Exchangeable						BS[b]	Al$_{sat}$[c]	Dithionite		Oxalate		Bray total		b	P$_{ext}$[e]
	H$_2$O	KCl	OC[a]	N	Clay	Ca	Mg	K	Na	Acidity	ECEC			Al	Fe	Fe	Al	P	P		
			%	ppm	%			cmol·kg^{-1}				%	%			mg·kg^{-1}					
Makalondi	6.8	5.5	0.36	177	1.2	0.60	0.33	0.25	0.02	0.07	1.26	94.84	0.00	312	4500	247	171	3.7	51	46.08	12.3
Fada	7.1	6.3	2.94	1160	7.3	9.14	2.16	1.13	0.04	0.11	12.57	99.16	0.00	1455	14400	1025	663	15.8	237	141.32	22.8
Bittou	6.8	6.1	0.72	181	2.7	2.25	0.88	0.60	0.03	0.09	6.82	98.08	0.00	312	3400	539	202	6.9	71	77.32	19.9
Tenkodogo	6.0	4.8	0.72	192	3.0	1.55	0.73	0.15	0.06	0.08	2.57	96.88	0.00	581	5900	695	184	5.6	64	82.34	23.1
Pya	6.5	5.0	0.72	226	5.1	1.53	0.83	0.07	0.04	0.07	2.54	97.23	0.00	2509	25100	1500	337	1.0	87	94.91	28.2
Dapaong	6.4	5.8	0.51	219	1.7	0.90	0.43	0.12	0.04	0.20	1.68	87.88	1.12	738	9300	423	229	4.1	82	52.04	14.4
Bambey	6.4	4.5	0.23	87	1.3	0.59	0.36	0.03	0.03	0.13	1.14	88.59	0.00	289	2100	256	192	3.1	89	52.78	17.2
Bambey	6.6	5.2	0.26	93	1.0	0.89	0.57	0.04	0.03	0.05	1.58	96.82	0.00	289	2100	236	233	4.1	77	48.10	28.2
Sinkou[g]	6.0	4.7	0.75	333	9.0	1.58	0.72	0.29	0.06	0.10	2.75	96.36	0.00	1971	18600			9.1	180	130.68	33.8
Sinkou[f]	6.5	5.5	0.95	336	5.5	2.42	0.87	0.22	0.04	0.06	3.60	98.33	0.00	1657	18900	669	430	6.7	135	123.72	15.6
Gaya[g]	5.8	4.3	0.52	226	3.9	1.15	0.42	0.06	0.04	0.20	1.87	89.11	1.00	670	8400	445	257	3.2	96	101.00	20.8
Gaya[g]	5.7	4.2	0.56	235	4.0	1.03	0.38	0.06	0.05	0.22	1.73	87.53	0.00	626	6800			4.3	109	91.12	23.3
Gaya[f]	5.9	4.7	0.84	298	4.7	1.98	0.63	0.12	0.04	0.08	2.85	97.19	0.00	693	8200	616	450	1.7	114	104.88	25.9
Gaya[f]	6.3	5.4	0.69	189	2.9	1.14	0.30	0.16	0.02	0.07	1.69	95.84	0.00	1141	19200	694	247	5.9	191	101.00	30.7
Gobery	5.7	4.2	0.32	103	1.5	0.23	0.12	0.05	0.03	0.21	0.64	61.71	10.99	513	7500	214	157	2.0	73	61.37	25.0
Tara	5.6	4.1	0.45	197	3.1	0.47	0.27	0.10	0.02	0.39	1.20	58.06	10.04	850	14100	550	481	3.3	129	129.20	27.7
Navrongo	6.2	5.1	0.94	225	1.3	1.84	0.63	0.09	0.03	0.07	2.66	97.55	0.00	648	7300	500	184	4.5	73	66.69	14.9
Sadore[f]	5.7	4.3	0.42	123	1.3	0.37	0.23	0.08	0.02	0.22	0.91	76.24	2.20	469	6000	225	148	2.8	68	55.31	15.8
Sadore[g]	6.0	4.8	0.34	163	1.8	0.44	0.33	0.16	0.02	0.07	1.01	93.06	0.00	312	5600	297	275	8.5	85	51.51	12.4
Sadore[g]	5.2	4.1	0.22	74	1.0	0.15	0.08	0.06	0.02	0.23	0.54	57.00	9.34	357	6300	198	112	6.0	68	51.67	15.9
Daoura	6.1	5.4	0.39	128	1.1	0.83	0.50	0.06	0.02	0.07	1.48	95.25	0.00	132	1500	323	130	4.0	41	28.76	10.5
Samaru	6.0	4.9	0.96	299	5.3	1.77	0.94	0.33	0.02	0.10	3.14	96.94	0.00	1007	7500	878	502	9.0	132	130.43	26.1
Bakura	5.6	4.3	0.80	243	11.7	3.32	1.41	0.15	0.04	0.23	5.15	95.52	0.00	1253	10200	2225	761	1.4	112	192.61	56.8
Funtua	7.6	6.8	2.76	1180	4.4	16.45	2.07	0.41	0.05	0.23	19.20	98.80	0.00	1007	8600	1116	654	30.3	349	253.08	11.6
Bembereke	7.0	6.4	2.17	701	4.4	4.13	0.32	0.05	0.06	0.14	4.70	97.10	0.00	1388	14600	1138	595	7.9	160	155.35	38.6
Kandi	6.6	5.8	1.10	251	3.7	2.67	0.13	0.16	0.04	0.08	3.08	97.39	0.00	693	7000	385	295	3.2	101	78.11	20.5
Sotuba	6.2	4.9	0.48	142	3.0	1.49	0.13	0.16	0.05	0.06	1.89	36.82	0.00	670	7800	321	336	1.7	87	93.06	23.2
Bamako	5.6	4.3	0.64	194	6.0	1.86	0.09	0.15	0.09	0.19	2.36	92.14	0.42	895	8800	822	502	12.3	149	137.39	33.6
Cinzana	5.3	4.0	0.41	178	3.2	0.93	0.67	0.09	0.06	0.45	1.59	71.92	14.51	895	8800	507	502	11.1	124	133.77	39.2
Zinder	6.7	5.3	0.08	31	0.7	0.53	0.02	0.06	0.05	0.06	0.71	92.25	0.00	155	2900	111	49	1.9	43	27.80	11.0
Yeda	6.7	5.5	0.15	69	1.0	0.98	.0.08	0.07	0.06	0.05	1.23	95.93	0.00	110	1700	214	147	2.1	25	30.15	11.8
Mean	6.2	5.0	0.75	266	3.5	2.10	0.55	0.18	0.04	0.14	3.10	88.33	1.60	793	8810	599	325	6.1	109	94.30	22.9

[a] OC = organic carbon.
[b] BS = base saturation.
[c] Al$_{sat}$ = Al saturation.
[d] b = P sorption maximum.
[e] P$_{ext}$ = P external requirement (mg P kg^{-1}).
[f] *Fallow in year preceding sampling.*
[g] Cultivated in year preceding sampling.

tain low mineral reserves and lack primary weatherable minerals necessary for nutrient recharge.

2) A high proportion of total P in these soils is often in occluded form and is not available to plants (Charreau 1974).
3) Low levels of organic matter and the removal of crop residues from fields; organic matter has a favorable effect on P dynamics of the soil; in addition to mineralizing to release P, the competition of organic ligands for Fe and Al oxides surfaces can result in a decrease in fixation of applied and native P (Bhat and Bouyer 1968).

In the semiarid tropics, maintenance of organic matter has been a very difficult task. A greater part of the residue produced is removed from the fields to be used for animal feed or used in traditional village industries. Tremendous termite activity leads to rapid decomposition of remaining residue. High temperatures during the prolonged dry season and the humid conditions during the growing season lead to a very rapid rate of organic matter mineralization (Birch 1958). This results in very low equilibrium levels of organic matter (0.75%) in these sandy soils which is reflected in low organic P contents.

Phosphorus sorption characteristics

Uptake of P by growing crops is affected by the interaction of soil P with constituents of the soil matrix. To gain a greater appreciation of the dynamics of P within these soil systems, P sorption characteristics were determined. Sorption data were fitted to the Langmuir equation, and P sorption maxima (b) were calculated from the slope of the resulting curve. The P external requirement was also determined using the P sorption data. The P external requirement is defined as the critical level of P in the soil solution needed to obtain 95% of maximum yield. Fox and Kamprath (1970) found 0.2 μg P ml^{-1} as the P external requirement for millet when grown in pots in an Ultisol. This value was used as a reference level in this document for the calculation of the P external requirement. A large range of P sorption maxima were obtained on these soils (Table 1). Soils of this region can be considered as having relatively low P sorption capacities compared to clay rich Ultisols and Oxisols found in more humid tropical regions (Sanchez and Uehara 1980). The low P sorption capacity of these soils is also reflected in the low values of the P external requirement (Table 1).

Total P in these soils was highly correlated with organic matter and the poorly crystalline Al phase (as measured by oxalate extraction) and to a lesser extent with clay, poorly crystalline Fe, and the free Al and Fe oxide phases (citrate-dithionite extraction) (Table 3).

Phosphorus sorption maxima were most highly correlated with organic carbon, clay, and poorly crystalline Al and Fe phases. It appears that the interrelationships between clay and poorly crystalline Al and Fe phases control not only P availability but also the potential reactivity of P (as measured by the sorption maxima). These results are in concurrence with those of Fox and Searle (1978). Juo and Fox (1977) found that the clay contribution to P sorption was related to the specific surface area of Fe and Al oxides, while Ellis and Truog (1955) attributed the effect of clay on P adsorption to exposed edge site Al and Fe on clay surfaces.

The relationships between organic matter, clay, and poorly crystalline Al and Fe are presented in Table 4. The poorly crystalline Al and

TABLE 2

Simple correlations (r) between selected soil fertility parameters and average annual rainfall (n = 31)

	Ca	ECEC	Organic matter	Total N	Clay	Rainfall
pH KCl	0.62***[a]	0.64***	0.65***	0.62***	−0.02	0.25*
Ca		0.98***	0.88***	0.92***	0.36***	0.31***
ECEC			0.86***	0.91***	0.40***	0.36***
Organic matter				0.97***	0.46***	0.42***
Total N					0.44***	0.34***
Clay						0.40***

[a] * and *** indicate significance at the 0.05 and 0.0005 levels, respectively.

TABLE 3

Simple correlations (r) relating selected soil properties and P sorption and availability indices (n = 31)

	Total P	Bray 1 P	b[a]	P_{ext}[b]
Organic matter	0.81***	0.71***	0.71***	0.12
Clay	0.52***	0.24*	0.75***	0.71***
Oxalate				
Al (n = 29)	0.73***	0.51***	0.91***	0.64***
Fe (n = 29)	0.48***	0.24	0.75***	0.69***
Dithionite				
Al	0.52***	0.21	0.60***	0.50***
Fe	0.48***	0.11	0.49***	0.42***
P parameters				
Total P		0.83***	0.85***	0.24
Bray 1 P			0.66***	−0.06
b				0.55***

[a] b = P adsorption maximum.

[b] P_{ext} = P external requirement.

[c] * and *** indicate significance at the 0.05 and 0.0005 levels, respectively.

TABLE 4

Stepwise multiple regression models describing relationships between organic matter, clay, and poorly crystalline Al and Fe (n = 29)

	r^2
Poorly crystalline Al	
Al = 184 + 185 organic matter	0.45***
Al = 105 + 67 clay	0.72***
Al = 79 + 92 organic matter + 54 clay	0.80***
Poorly crystalline Fe	
Fe = 340 + 340 organic matter	0.24***
Fe = 45 + 168 clay	0.78***
Fe = 27 + 63 organic matter + 160 clay	0.80***
Poorly crystalline Al + Fe	
Al + Fe = 534 + 520 organic matter	0.33***
Al + Fe = 166 + 234 clay	0.84***
Al + Fe = 123 + 154 organic matter + 211 clay	0.86***

*** Indicates significance at the 0.0005 level.

Fe in these soils are associated with the clay fraction. The fact that organic matter and clay inhibit the formation of a strongly crystalline oxide phase has been well documented (Schwertmann 1988). Sanchez and Uehara (1980) stated that the positive correlation of organic matter contents to P sorption is most likely a result of increased "finely divided sesquioxides" in soils containing increased levels of organic matter.

Bray 1 P was highly correlated with organic matter and poorly crystalline Al. No significant correlation was obtained with the total free Al and Fe phases.

CONCLUSIONS

The results of this study indicate that selected surface soils from millet growing areas of the semiarid tropical region of West Africa can be described by the following characteristics:

1) Sandy to sandy loam textures in the surface horizon.
2) Low levels of clay and organic matter resulting in low effective CEC.
3) A small percentage of soils containing any appreciable amounts of exchangeable Al.
4) Low levels of native soil P.
5) Relatively low P sorption capacity.
6) P sorption and availability parameters controlled by Al and Fe oxides, organic matter, and clay soil fractions.

In the attempt to manage these soils it should be noted that these poorly buffered soil systems can become acidified and depleted of nutrients under continual cropping systems. Total P levels are low and P solution concentration (intensity factor) can be limiting. The quantity factor can also become an immediate concern for sustained production. Under the traditional farming system in Niger, average millet grain and stover yields are 400 and 2,200 kg·ha^{-1}, respectively (Bationo et al. 1989). The amount of P taken up in grain is 0.8 $kg \cdot ha^{-1}$ and 0.6 $kg \cdot ha^{-1}$ in stover, representing a net annual plant uptake of 1.4 $kg \cdot ha^{-1}$ of P. In this system, it is estimated that 75% of stover is removed from the field and used either as animal feed or in village industries. This represents a significant annual export of 1.25 $kg \cdot ha^{-1}$ from the already P-deficient soil. The shift from the traditional long-term fallow system to continuous cropping as a result of increased population pressure in these regions does not permit recycling of the nutrients necessary to maintain adequate nutrient levels for sustained production. A few years of continuous cropping could therefore lead to severe nutrient deficiencies.

Sustained agricultural production will therefore require management technologies that will promote nutrient availability in general. To maintain an adequate pool of labile P in these soils will require input of P from external sources. This could be in the form of inorganic P fertilizers; however, the low adsorption capacity of the soils will necessitate the use of low to medium levels of P. Phosphorus can also be supplied from organic sources, including manure and crop residue. Return of millet residue to the field at the end of the planting season will reduce the complete loss of P taken from the soil.

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