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# SOIL CHEMICAL VARIABILITY IN SANDY USTALFS IN SEMIARID NIGER, WEST AFRICA[1]

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**Extreme variability in millet stands over very short distances (2 to 20 m) poses a major constraint to grain production in Niger and other Sahelian countries. This study was undertaken to examine the chemical properties of associated productive and unproductive soils. Soil samples (0 to 15 cm) were taken at 26 sites along a 15-m transect between a productive and an unproductive region in a field of the Labucheri soil series (sandy, siliceous, isohyperthermic Psammentic Paleustalf). Chemical properties of soil profiles at three locations along the transect were also examined. Unproductive soils were 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 and appear to account for the variability that exists in millet stands. All soils become acidic at depths ≤30 cm. We propose a scheme for the genesis of these highly variable, acidic soils in this semiarid region.**

One of the most striking features in millet [*Pennisetum americanum* (L.) K. Schum] fields in the poorly buffered sandy soils of the semiarid Sahelian environment of Niger is the extreme variability in plant growth over very short distances. Millet growth often diminishes from very productive regions to completely barren areas over distances varying from 2 to 20 m. This extreme variability has been noted extensively in the Ustalf, Ustult, Psamment, and Tropept soil orders (Daniels and Wilding 1983). The zones between these irregularly distributed productive and unproductive regions are characterized by gradually declining millet growth, as defined by smaller plants, delayed maturity, shorter and more poorly filled grain heads, and diminished yields. Millet germinates uniformly in all regions of the fields, and growth appears to be essentially uniform until 1 to 2 wk after plant emergence. Differences in growth become apparent at this time. The plants in the most unproductive regions eventually die, leaving places in fields completely devoid of vegetation. Completely barren regions tend to be larger in years of marginal rainfall. Poor stands also appear to be associated, though not consistently, with microlow regions in the field topography. Although potential millet yield lost to this problem has not yet been quantified, variability in millet stands is apparent in many if not most of the millet and sorghum fields throughout Niger and other parts of the Sahel. Data collected by one of the authors from a field of the Labucheri soil series (sandy, siliceous, isohyperthermic Psammentic Paleustalf) exhibiting an extreme degree of variability indicated that up to 75% of the potential yield was not being realized.[3] Extreme variability not only severely reduces yields, but also poses a major obstacle to field research efforts. Differences between treatments are difficult to detect because of large variation between replications within a given treatment.

Data collected from a mechanically planted field of the Labucheri soil series on the ICRISAT (International Crops Research Institute for the Semiarid Tropics) Sahelian Center 40 km south of Niamey, Niger, indicated that areas of poor growth within this field do not vary extensively in their location from year to year. Soil data indicated that KCl-extractable Al and soil pH in 1 *M* KCl were the only two soil chemical properties that correlated with plant height throughout the growing season. Low soil pH and high exchangeable Al indicate excessive soil acidity.

Reduced productivity on acid soils may result from any of a number of soil chemical and

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biological processes. Lanyon et al. (1977) found that increasing the pH from 5.1 to 5.6 improved millet forage production of two highly weathered soils, a Rhodic Paleudult and a Typic Haplorthox, by reducing Mn uptake. 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%. Woodruff and Kamprath (1965) found that fertilizer P required for optimum millet growth was reduced by 50% when the exchangeable Al was first neutralized with lime. Adams and Hathcock (1984) found subsoil Ca deficiency associated with Al toxicity in two coastal plains soil series of Alabama. Molybdenum is generally less available in acid soils (Barshad 1951). Lee (1971) reported that excess Al decreased root absorption of Ca, Mg, and Zn by potato roots.

The objective of this study was to determine the relationship between soil chemical properties and variability in millet stands.

## MATERIALS AND METHODS

A 15-m transect was selected in a field at the ICRISAT Sahelian Center near Niamey, Niger, West Africa (13° 15′ N latitude, 2° 18′ E longitude), where millet growth declined continuously from an excellent millet stand to a completely barren region. The soils belonged to the Labucheri series. The surface 15 cm of soil was collected at approximately 60-cm intervals along the transect for a total of 26 sampling sites. All soils were analyzed for pH (1:1 in $H_2O$), and exchangeable acidity and Al by the KCl extraction method of Thomas (1982). Exchangeable cations (Ca, Mg, K, Na, and Mn) were extracted by the ammonium acetate procedure described by Thomas (1982). Calcium, Mg, Na, and Mn were determined by atomic absorption spectrophotometry and K by atomic emission spectrophotometry. The effective cation exchange capacity (ECEC) was determined by the summation of cations.

Soil profiles were examined by taking samples at 0- to 2-, 2- to 5-, 5- to 10-, 10- to 15- 15- to 20-, 20- to 25-, 25- to 30-, 30- to 40-, 40- to 50-, 50- to 60-, and 60- to 70-cm depth increments at the productive and unproductive extremes of the transect and at a site at the center of the transect. A sample of blowing sand was also collected at the soil surface. All these samples were subjected to the analyses described previously.

## RESULTS

### *Transect soils (surface 15 cm)*

Soil samples taken from the surface 15 cm across the transect showed that pH values decreased and exchangeable acidity and Al levels increased as the unproductive site was approached (Fig. 1). Increases in Al + H levels corresponded to decreasing levels of exchangeable Ca, Mg, and K (Table 1). The cation exchange capacity of the soils remained relatively constant across the transect. Charcoal and ash residue in the soil at sites 25 and 26 indicate that some woody material had been burned there in the past, which probably explains the surprisingly high pH and levels of Ca and Mg at these sites.

A correlation matrix (Table 2) shows that pH; percentage of Al + H saturation; and exchangeable Ca, Mg, Al, and Al + H all correlated very strongly with position on transect. Correlation

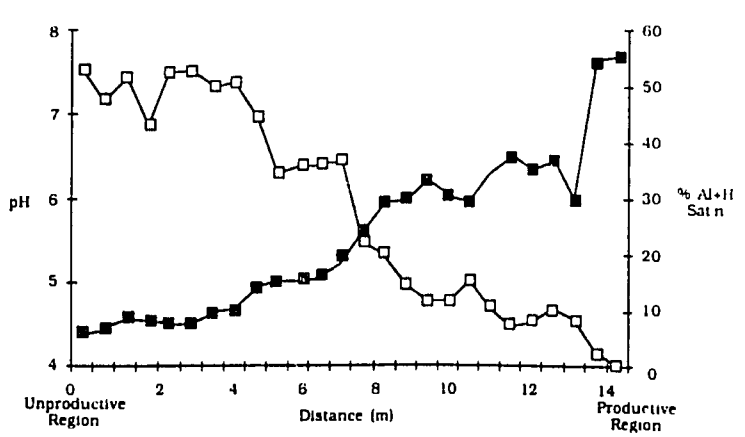


FIG. 1. Percentage Al + H saturation and pH of the surface 15 cm of soil along a transect from an unproductive to a productive region. ■—■ pH; □—□ Al + H saturation.

TABLE 1

*Selected chemical properties of soils taken from the surface 15 cm of soil taken along a transect from an unproductive to a productive region*

| Extreme | Site no. | Position, m | pH | Exchangeable cation | | | | | ECEC cmol(+)/kg | Al+H Sat'n, % |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Ca | Mg | K | Na | Al+H | | |
| | | | | cmol(+)/kg | | | | | | |
| Unproductive soil | 1 | 0.0 | 4.4 | .43 | .04 | .08 | .04 | .66 | 1.25 | 53 |
| | 2 | 0.6 | 4.5 | .52 | .05 | .08 | .03 | .61 | 1.29 | 47 |
| | 3 | 1.2 | 4.6 | .45 | .06 | .08 | .02 | .64 | 1.24 | 52 |
| | 4 | 1.8 | 4.5 | .56 | .07 | .09 | .03 | .56 | 1.30 | 43 |
| | 5 | 2.4 | 4.5 | .41 | .05 | .08 | .02 | .61 | 1.16 | 53 |
| | 6 | 3.0 | 4.5 | .42 | .05 | .07 | .01 | .62 | 1.17 | 53 |
| | 7 | 3.7 | 4.7 | .47 | .05 | .07 | .02 | .60 | 1.20 | 50 |
| | 8 | 4.3 | 4.7 | .42 | .05 | .08 | .02 | .59 | 1.16 | 51 |
| | 9 | 4.9 | 5.0 | .46 | .06 | .08 | .02 | .50 | 1.12 | 45 |
| | 10 | 5.5 | 5.0 | .62 | .10 | .07 | .03 | .43 | 1.24 | 35 |
| | 11 | 6.1 | 5.0 | .56 | .07 | .08 | .02 | .41 | 1.14 | 36 |
| | 12 | 6.7 | 5.1 | .56 | .08 | .08 | .02 | .42 | 1.16 | [illegible] |
| | 13 | 7.3 | 5.2 | .53 | .08 | .09 | .02 | .42 | 1.14 | 37 |
| | 14 | 7.9 | 5.6 | .66 | .09 | .10 | .01 | .24 | 1.09 | 22 |
| | 15 | 8.5 | 5.9 | .68 | .13 | .11 | .05 | .23 | 1.19 | 19 |
| | 16 | 9.1 | 6.0 | .81 | .11 | .12 | .02 | .18 | 1.25 | 14 |
| | 17 | 9.8 | 6.2 | .75 | .11 | .12 | .02 | .13 | 1.12 | 12 |
| | 18 | 10.4 | 6.0 | .94 | .12 | .09 | .03 | .15 | 1.33 | 11 |
| | 19 | 11.0 | 5.9 | .64 | .11 | .12 | .01 | .16 | 1.04 | 15 |
| | 20 | 11.6 | 6.3 | .74 | .13 | .17 | .01 | .12 | 1.17 | 10 |
| | 21 | 12.2 | 6.5 | .86 | .14 | .44 | .01 | .11 | 1.55 | 7 |
| | 22 | 12.8 | 6.3 | .90 | .1[illegible] | .23 | .01 | .11 | 1.39 | 8 |
| | 23 | 13.4 | 6.5 | .89 | .15 | .16 | .02 | .14 | 1.35 | 10 |
| | 24 | 14.0 | 6.0 | .85 | .14 | .16 | .02 | .11 | 1.28 | 9 |
| Productive soil | 25[a] | 14.6 | 7.6 | 1.66 | .17 | .20 | .01 | .05 | 2.09 | 2 |
| | 26[a] | 15.2 | 7.7 | 4.82 | .29 | .23 | .02 | .00 | 5.36 | 0 |
| Blowing sand | – | – | 6.5 | .76 | .11 | .12 | .03 | .09 | 1.11 | 8 |

[a] These soils 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.

TABLE 2

*Correlation matrix of soil chemical properties of soils along a transect from productive to unproductive regions*[a]

| Variable | Shoot wt. | pH | Exch. Ca | Exch. Mg | Exch. K | Exch. Na | Exch. Al | Exch. Al+H | ECEC | % Al sat'n |
|---|---|---|---|---|---|---|---|---|---|---|
| Shoot wt. | – | .67**[b] | .72** | .66** | .72** | −.24 | −.63** | −.69** | .55** | −.72** |
| pH | .67** | – | .91** | .95** | .65** | −.27** | −.95** | .98** | .33 | −.98** |
| Exch. Ca | .72** | .91** | – | .93** | .60** | −.14 | −.88** | −.92** | .55** | −.95** |
| Exch. Mg | .66** | .95** | .93** | – | .63** | −.15 | −.91** | −.95** | .44* | −.96** |
| Exch. K | .72** | .65** | .60** | .63** | – | −.37 | −.52** | −.59** | .72** | −.61** |
| Exch. Na | −.24 | −.27 | −.14 | −.15 | −.37 | – | .22 | .27 | .04 | .23 |
| Exch. Al | −.63** | −.95** | −.88** | −.91** | −.52** | .22 | – | .97** | −.19 | .96** |
| Exch. Al+H | −.69** | −.98** | −.92** | −.95** | −.59** | .27 | .97** | – | .27 | .99** |
| ECEC | .55** | .33 | .55** | .44* | .72** | .04 | −.19 | .27 | – | −.35 |
| % Al sat'n | .72** | .98** | .95** | −.96** | −.61** | .23 | .96** | .99** | −.35 | – |

[a] The final two sites (25 and 26) were excluded from the analysis because of the presence of free salts in the soil.

[b] *, **, significant at $P = 0.05$ and 0.01, respectively.

coefficients exceeded 0.93 ($r^2 > 0.88$) for all these statistics. Increases in Al + H are related to decreased concentrations of Ca, K, and Mg.

### *Soil profiles*

Soil profile samples at the most productive and unproductive ends of the transect reveal that soils at these locations have very different properties throughout the 70 cm of profile sampled (Table 3). The profile at the midpoint of the transect has intermediate properties. Though all three soils have ECECs below 1.3, the cations occupying the exchange sites vary markedly in each profile. Of particular interest is the variation in the Al + H saturation of the exchange sites. These were calculated as the sum of the exchangeable Al + H divided by the sum of exchangeable Ca, K, Mg, Na, Al, and H times 100. All soil profiles had a low Al + H saturation at the surface. However, the Al + H saturation of the unproductive soil increased to 46% at a depth of only 3.5 cm (Fig. 2; Table 3). The Al +

TABLE 3

*Selected chemical properties of soil profile samples at three sites along a transect from productive to unproductive regions*

| Depth, cm | Exchangeable cation | | | | | | | ECEC, | pH | Al + H Sat'n, |
|---|---|---|---|---|---|---|---|---|---|---|
| | Ca | K | Mg | Na | Mn | Al | H | | | |
| | cmol(+)/kg | | | | | | | cmol(+)/kg | (1:1) | % |
| *Unproductive soil* | | | | | | | | | | |
| 1.0 | 0.46 | 0.05 | 0.07 | 0.04 | 0.03 | 0.14 | 0.10 | 0.89 | 5.67 | 23 |
| 3.5 | 0.29 | 0.03 | 0.03 | 0.02 | 0.02 | 0.37 | 0.15 | 0.91 | 5.00 | 46 |
| 7.5 | 0.27 | 0.03 | 0.03 | 0.01 | 0.02 | 0.45 | 0.14 | 0.96 | 4.82 | 50 |
| 12.5 | 0.26 | 0.04 | 0.04 | 0.04 | 0.02 | 0.51 | 0.16 | 1.07 | 4.78 | 52 |
| 17.5 | 0.24 | 0.04 | 0.04 | 0.09 | 0.02 | 0.53 | 0.16 | 1.11 | 4.77 | 52 |
| 22.5 | 0.31 | 0.04 | 0.07 | 0.02 | 0.02 | 0.54 | 0.19 | 1.18 | 4.81 | 53 |
| 27.5 | 0.22 | 0.04 | 0.10 | 0.02 | 0.02 | 0.50 | 0.18 | 1.09 | 4.92 | 55 |
| 35.0 | 0.27 | 0.05 | 0.12 | 0.02 | 0.02 | 0.48 | 0.16 | 1.10 | 4.96 | 51 |
| 45.0 | 0.20 | 0.04 | 0.06 | 0.05 | 0.02 | 0.50 | 0.14 | 1.01 | 5.07 | 53 |
| 55.0 | 0.29 | 0.04 | 0.10 | 0.02 | 0.02 | 0.40 | 0.11 | 0.98 | 4.82 | 45 |
| 65.0 | 0.35 | 0.04 | 0.14 | 0.02 | 0.02 | 0.34 | 0.14 | 1.04 | 4.97 | 41 |
| *Intermediate soil* | | | | | | | | | | |
| 1.0 | 0.42 | 0.05 | 0.10 | 0.02 | 0.02 | 0.05 | 0.06 | 0.72 | 5.98 | 12 |
| 3.5 | 0.36 | 0.05 | 0.06 | 0.03 | 0.02 | 0.20 | 0.11 | 0.84 | 5.33 | 30 |
| 7.5 | 0.38 | 0.04 | 0.05 | 0.01 | 0.03 | 0.25 | 0.10 | 0.87 | 5.16 | 34 |
| 12.5 | 0.25 | 0.04 | 0.06 | 0.03 | 0.02 | 0.47 | 0.11 | 0.98 | 5.04 | 50 |
| 17.5 | 0.24 | 0.04 | 0.06 | 0.02 | 0.02 | 0.50 | 0.11 | 0.99 | 4.96 | 52 |
| 22.5 | 0.33 | 0.04 | 0.08 | 0.01 | 0.03 | 0.54 | 0.13 | 1.14 | 4.98 | 51 |
| 27.5 | 0.42 | 0.04 | 0.10 | 0.01 | 0.03 | 0.52 | 0.10 | 1.23 | 5.00 | 45 |
| 35.0 | 0.49 | 0.05 | 0.13 | 0.03 | 0.03 | 0.42 | 0.16 | 1.30 | 5.07 | 41 |
| 45.0 | 0.52 | 0.06 | 0.18 | 0.02 | 0.03 | 0.34 | 0.16 | 1.31 | 5.17 | 36 |
| 55.0 | 0.62 | 0.05 | 0.23 | 0.01 | 0.02 | 0.22 | 0.12 | 1.27 | 5.29 | 26 |
| 65.0 | 0.59 | 0.05 | 0.22 | 0.03 | 0.02 | 0.19 | 0.09 | 1.20 | 5.34 | 23 |
| *Productive soil* | | | | | | | | | | |
| 1.0 | 0.60 | 0.06 | 0.10 | 0.02 | 0.02 | 0.05 | 0.05 | 0.91 | 6.11 | 9 |
| 3.5 | 0.49 | 0.05 | 0.06 | 0.02 | 0.02 | 0.09 | 0.08 | 0.83 | 5.66 | 18 |
| 7.5 | 0.60 | 0.07 | 0.12 | 0.01 | 0.02 | 0.05 | 0.04 | 0.91 | 5.72 | 8 |
| 12.5 | 0.45 | 0.06 | 0.11 | 0.01 | 0.01 | 0.12 | 0.09 | 0.85 | 5.53 | 21 |
| 17.5 | 0.32 | 0.13 | 0.12 | 0.03 | 0.01 | 0.20 | 0.11 | 0.92 | 5.29 | 29 |
| 22.5 | 0.36 | 0.11 | 0.16 | 0.03 | 0.04 | 0.26 | 0.13 | 1.08 | 5.15 | 34 |
| 27.5 | 0.28 | 0.10 | 0.13 | 0.02 | 0.04 | 0.33 | 0.11 | 1.00 | 5.18 | 39 |
| 35.0 | 0.24 | 0.09 | 0.12 | 0.02 | 0.04 | 0.43 | 0.07 | 1.01 | 5.07 | 45 |
| 45.0 | 0.24 | 0.12 | 0.15 | 0.02 | 0.04 | 0.44 | 0.13 | 1.14 | 4.96 | 46 |
| 55.0 | 0.33 | 0.08 | 0.22 | 0.03 | 0.03 | 0.34 | 0.15 | 1.18 | 5.05 | 41 |
| 65.0 | 0.31 | 0.09 | 0.20 | 0.02 | 0.03 | 0.28 | 0.13 | 1.06 | 5.07 | 37 |

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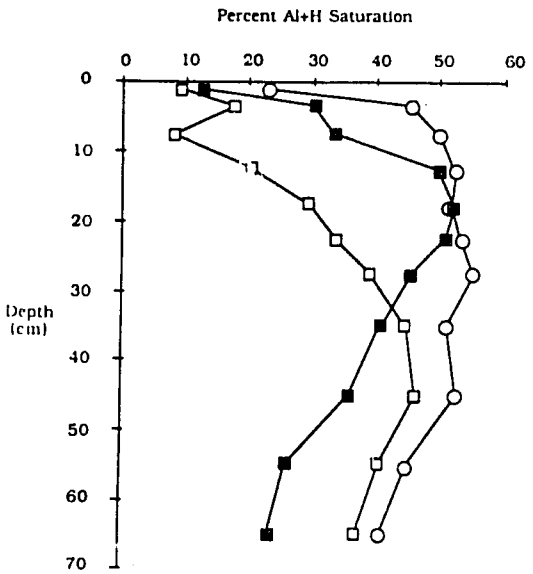


FIG. 2. Percentage of Al + H saturation with depth along a transect from an unproductive to a productive region. □—□ productive; ■—■ intermediate; ○—○ unproductive.

H saturation of the productive soil rose more slowly and gradually, reaching 45% saturation at a depth of 35 cm. The Al + H levels in the intermediate soil increase to 50% at the 12.5-cm depth. Exchangeable acidity in all soils decreased at greater depths after the initial increase. However, all soils have potentially toxic levels of Al within 35 cm of the surface for Al-sensitive crops.

### *Blowing surface sand*

Chemical properties of blowing sand taken from the soil surface are presented at the bottom of Table 1. The sand has a pH, cation exchange capacity, and base status very similar to those of productive soils. Color similarities between productive soils and blowing sand were noted as well.

## DISCUSSION

Soils at the unproductive extreme of the transect are strongly associated with low pH, high Al + H saturation, and lower levels of exchangeable Ca, Mg, and K. Under these circumstances, several nutrient deficiencies, as well as elemental toxicities, may be limiting plant growth, either individually or in combination. At the pH values below 5.5, Al toxicity is possible. Aluminum + H saturation values of up to 53% further indicate the possibility of Al toxicity. Manganese toxicity may also be a cause of poor millet growth in the unproductive soils. Twelve of the 26 sites had pH values below 5.2, the pH at which Mn generally becomes plant-available in excessive quantities.

Exchangeable soil K, Ca, and Mg all increase as the productive soil site is approached. Deficiencies of any of these elements could be inhibiting plant growth at the unproductive soil sites. Aluminum-induced P deficiencies may also be restricting yields.

Clear chemical differences between productive and unproductive soils indicate potential elemental deficiences/toxicities. Millet is in general very tolerant of infertile soil conditions. Therefore fertility trials and elemental analysis of plant tissues will be necessary to determine exactly which differences between productive and unproductive soils contribute to poor millet growth. In addition, other locations throughout the Sahelian region should be examined to determine if soil variability in other regions is due to similar chemical differences.

Soil profile analyses indicate that the difference between productive and unproductive soil sites is related to the thickness of the higher pH surface soil. Soils at the most productive site had 35 cm of surface soil with an Al + H saturation below 45%, compared with 12.5 cm in the intermediate soil and only 3.5 cm in the most unproductive soil. Below the depth of the higher pH zone, the soils are more acid and do not differ significantly. This indicates that modification of the surface soil would be sufficient to improve the productivity of the unproductive soils.

The very presence of the problem of Al toxicity in an ustic, semiarid environment is in itself noteworthy, because soils in such environments are commonly unweathered and basic. West et al. (1984) report that these soils probably formed under more pluvial paleoclimatic conditions than currently exist. Recent surface depositions of blowing sand appear to be the cause of the high base status at the soil surface. The lack of 2:1 clay minerals and high iron oxide/clay ratios further distinguish these soils from those typical of ustic environments in temperate regions.

The similarity between blowing surface sand and productive soils raises the possibility that the fertility of productive soil sites may be en-

hanced by recent accumulations of blowing sand. Large quantities of blowing soil material move through the Sahelian regions, particularly during the dry season and immediately preceding early rains in May and June. The blowing soil tends to accumulate around vegetation and plant residue.

Productive soil sites are commonly observed on microhigh locations in field topographies. Unproductive sites, by contrast, are commonly at microlow positions. Unpublished data collected by one of the authors indicate that unproductive microlow regions are wetted to greater depths after rains due to runoff accumulation. Areas with little or no plant growth are more subject to leaching of basic cations, for there is much more water moving down through the profile than being absorbed by plant roots and transpired. The greater movement of water into the soil results in more intensive leaching of bases and thus lower soil pH. Thus the unproductive soils, by increased leaching losses, may perpetuate their infertile status. Productive regions, by basic cation cycling and sand capture as a result of greater plant residue, may enhance their soil fertility. The plant residue may also serve to diminish wind deflation of the surface horizon. The low cation exchange capacity of both unproductive and productive soils results in a poor buffer capacity. This lack of capacity to resist microenvironmental variations brought about by sand deposition, vegetative cover, leaching, runoff, and water and wind erosion is the primary genetic source of variability. These considerations are important factors in developing soil management schemes to protect soil resources and to rejuvenate barren soil areas.

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