Causes and Effects of Acidity in Sahelian Soils

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Abstract

Extensive areas of the Sahel are covered with sandy acid soils with low buffering capacities and low activity clay systems. This is in marked contrast to most soils of North America, developed in semi-arid conditions. Acidity in these soils is believed to be a consequence of parent sands derived from acid continental terminal deposits, strong paleoclimate and contemporaneous leaching, and base-cycling processes. Acidity in these soils negatively affects land use, soil physical and chemical properties, and plant and crop diversification, and disturbs the balance of pastoral and agrarian agriculture of the region. Finally, it makes agronomic research difficult because random variability within plot treatments often exceeds systematic variability due to treatments. This is a significant problem worthy of continued efforts to determine the scale, magnitude, and extent of spatial soil variability directly or indirectly due to soil acidity.

Résumé

Causes et effets de l'acidité des sols sahéliens : *De vastes zones sahéliennes sont caractérisées par des sols sableux acides ayant de faibles pouvoirs tampon et des systèmes argileux d'activité réduite. Cette situation est en contraste avec celle de la plupart des sois soumis aux mêmes conditions de semi-aridité en Amérique du Nord. Dans le cas du Sahel, on pense généralement que l'acidité est l'une des multiples conséquences de sables d'origine déposés par le continental terminal, de paléoclimats plus humides et plus lessivants et de processus contemporains de lessivage et d'échange des bases. Elle a un effet négatif sur l'utilisation et les propriétés physico-chimiques des sols, la diversification des plantes et des cultures et les rendements. De plus, l'acidité est préjudiciable à l'équilibre existant entre les systèmes pastoraux et agricoles de la région. Enfin, elle gêne la recherche agronomique du fait que la variabilitité aléatoire entre traitements appliqués sur les parcelles est souvent plus grande que la variabilité systématique due aux traitements eux-mêmes. C'est là un problème important dont l'étude mérite d'être poursuivie en vue de déterminer l'échelle, l'ordre de grandeur et la mesure dans laquelle la variabilité spatiale des sols est due, directement ou indirectement, à l'acidité de ces sols.*

Introduction

Extensive areas of the Sahelian region in West Africa comprise red, sandy, strongly leached, acid soil resources utilized for pearl millet/cowpea production (Fig. 1). The soils vary greatly in thickness, associated geologic deposits, and geomorphic landforms, and reflect both semi-arid tropical environments and the more pluvial paleoclimate. Most of the soils are Ustalfs, Ustults, Tropepts, and Psamments, indicative of their diversity in soil texture, acidity, and subsoil clay enrichment (Daniel and Wilding 1983, West et al. 1984 and 1987, Wendt 1986, Bui 1986). Chemically and mineralogically,

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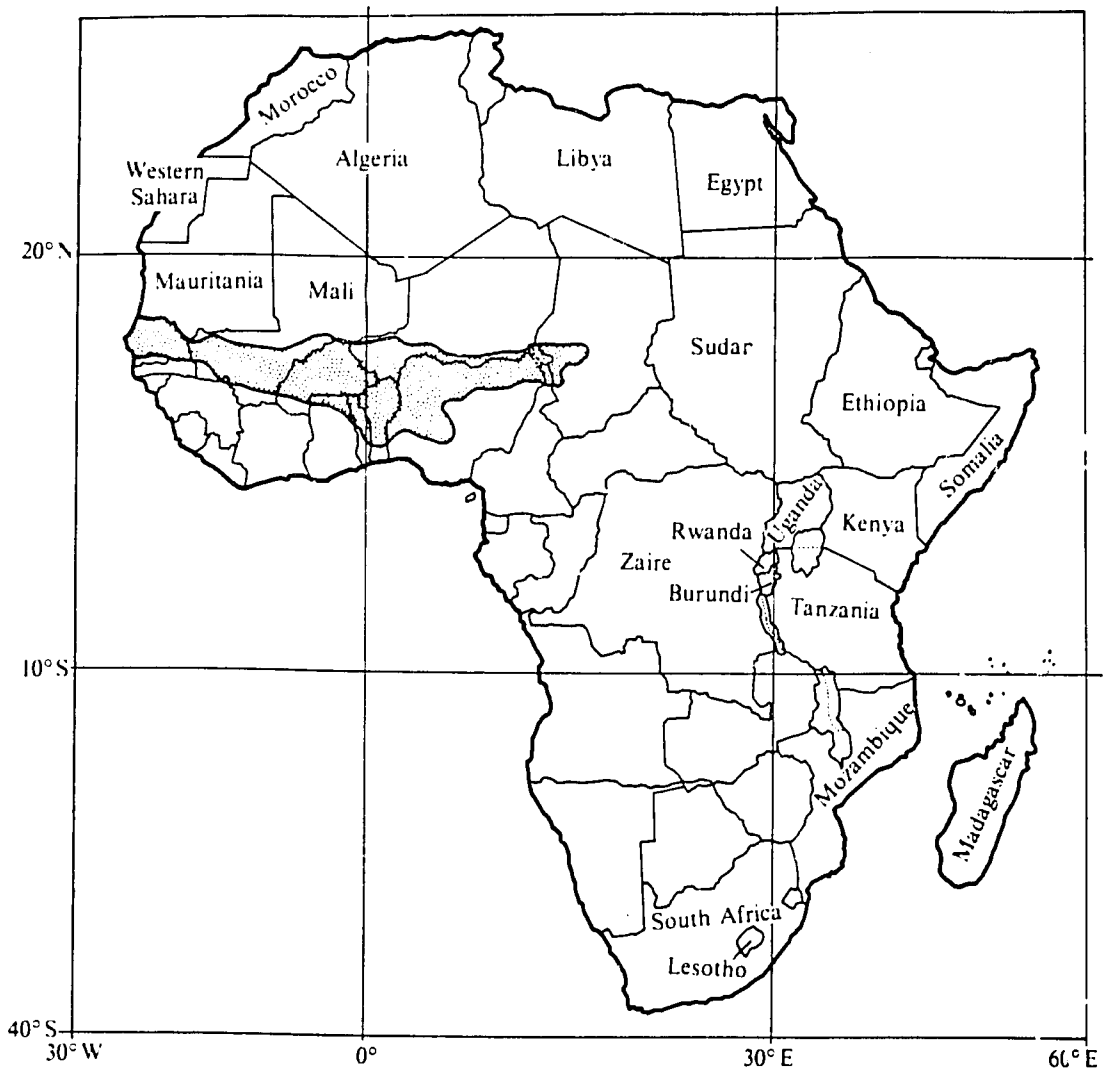

Figure 1. Location of sandy acid soils in the semi-arid tropics of West Africa.

these sandy soils are uniquely different from their fertile base-rich, neutral-to-alkaline North American counterparts (Nettleton and Peterson 1983, Allen and Fanning 1983). The Sahelian soils are generally strongly acid, infertile, weakly buffered, kaolinitic systems with few weatherable mineral reserves. This fact is not well appreciated by many soil scientists and agronomists.

Hence, the purpose of this paper is to propose: (1) multiple working hypotheses for the observed acidity in sandy soils of the Sahel, and (2) effects of such acidity to their use and management. Recent research conducted on sandy soils in Niger, which are representative of many soils in the Sahel, serves as the basis for this report.

Stratigraphy, Geomorphology, and Soils

Stratigraphy

Surface deposits are a sequence of sandy materials that cover ironstone caps, which in turn cover

loamy Miocene (possibly as young as Eocene) deposits (Continental Terminal). These units control the soils, geomorphology, and hydrology of the area. The Continental Terminal sediments that are about 25 million years old are deeply weathered and exposed only in road cuts, seldom at the surface (Sombroek and Zonneveld 1971, Gavaud 1966, Greigert 1966). Ironstone caps the Continental Terminal in most parts of the landscape and is exposed at escarpments or breakaways along multilevel pleateaus and ledges within the Miocene sediments. The ironstone cap is a prominent pedogenic landscape feature formed during the late Pliocene or Early Quatenary periods (about 2 million years ago), presumably under wetter paleoclimates. It can be between 20 cm and 1 m or more thick, either as a continuous unit, as sesquioxide blocks, or as cemented ironstone gravels. The ironstone serves as an effective base for the modern soils and as a root-and-water restrictive layer. When on a sloping gradient, it is the interface along which interflow occurs. The sandy cover materials are between 2 and 8 cm or more in thickness, over an almost universal ironstone cap. The texture of this sandy cover is fine sand, fine loamy sand, and rarely, fine sandy loam. In the uplands, it is mostly of eolian origin while on low terraces, floodplains, and in the dallols, it may be a combination of fluvial and eolian processes. The age of these deposits range from a few thousand years in dallols to about 40 000 years in more stable uplands.

Geomorphology

The area can be divided into four geomorphic elements (Daniels and Wilding 1983). The landscape is dominated by broad, gently-sloping plateaus with discontinuous sand cover, sandy valley systems that slope gently from the ironstone-capped plateau toward a dry stream bed, broad (terrace-like) sand plains, and dallols (dry fossil valleys).

Major plateaus, several kilometers across, are recognized at 220-, 240-, and 260-m elevations along the Niger River. They generally have thin sand covers with or without low dune forms. The valley systems start just below the ironstone cap of the plateaus, have thick sand near the escarpment breakaway with discontinuous paleosols in the lower sand unit, and slope smoothly to the valley floor. The sandy surfaces are apparently a combination of fluvial and eolian processes.

The sand plains consist of thick (2-6 m) eolian sands over "stepped" surfaces or levels of laterite gravels that slope gently toward adjacent river or stream systems. The sand has a well-expressed dune relief and some deflation depressions occur. The sand cover on all "stepped" levels only differs in color, texture, and pH. It abruptly overlies a cemented laterite gravel contact that probably represents a constructional floor of fluvial gravels. The sands were emplaced on these surfaces probably about 20 000 to 40 000 years ago; thus, the soils are more strongly developed than their dallol counterparts (Sombroek and Zonneveld 1971).

The dallols are unique, sand-plugged fossil stream valleys. Construction of these nearly level landforms was apparently by both fluvial and eolian processes. Surfaces express marked dunal relief and activity; these sandy deposits are probably less than 1000 years old, and commonly have shallow water tables between 1 and 5 m below the surface in southern Niger (Bui 1986).

Soils

Soils on the ICRISAT Sahelian Center (West et al. 1984) are representative of extensive areas of major pearl millet/cowpea production centers in the vicinity of Niamey, including the sand plains and upper reaches of valley sand systems. The Center is located on a sand plain. These areas comprised deep, red, sandy soils with weakly developed subsoils (Psammentic Paleustalfs, Psammentic Haplustalfs, and Ustoxic Quartzipsamments). The Labucheri and Dayobu are extensive series in this area (Tables 1 and 2) and are deep arid soils on the sand plains. Dallols are also extensively used for pearl millet/cowpea production but the soils are coarser-textured, less red, and less acid than their upland counterparts (Bui 1986). Soils on nearly level, broad, laterite-capped plateaus are very acid, thin, and variable in texture and thickness of subsoils over laterite or laterite gravels. Most of these soils are Ustoxic Dystropepts and Petroferric subgroups of Haplustults, Haplustalfs, and Dystropepts (Daniels and Wilding 1983, Hagen et al. 1986). The Gagani is a representative soil on plateaus (Table 3). They are generally loamy in texture rather than sandy. These areas are not extensively used for pearl millet/cowpea production but are important forest and pastoral grazing lands.

Textures of soils in uplands are dominated by

Table 1. Selected soil physical and chemical properties of the Labucheri soils in Niger (Psammentic Paleustalf; sandy, siliceous, isohyperthermic), sampled at the ICRISAT Sahelian Center, Sadoré, Niger, Africa.

Depth (cm)	Horizons	Particle size distribution (mm) Sand (%)	Silt (%)	Clay (%)	Organic C (%)	pH (H_2O) 1:1	pH (0.1 N KCl)	NH_4OAC extractable bases Ca (meg (100g)$^{-1}$)	Mg	Na	K	KCL extractable Al	NH_4OAC CEC	ECEC	Base saturation (%)	Extr. Fe (%)
0-9	A1	90.7	6.2	3.2	0.31	4.9	3.7	0.3	0.1	0.0	0.1	0.3	1.6	0.8	30	0.4
9-30	A2	90.6	5.6	3.8	0.18	4.9	3.8	0.1	0.1	0.0	0.1	0.4	1.1	0.7	28	0.4
30-58	Bt1	88.3	5.7	6.1	0.13	4.9	3.9	0.2	0.1	0.0	0.1	0.3	1.2	0.8	36	0.5
58-78	Bt2	88.7	5.5	5.9	0.11	5.0	4.2	0.4	0.2	0.0	0.1	1.1	0.1	0.8	60	0.4
78-98	Bt2	88.0	5.3	6.8	0.10	5.1	4.2	0.3	0.2	0.0	0.1	0.1	1.1	0.7	55	0.6
98-122	Bt3	88.7	5.0	6.4	0.09	5.6	4.5	0.3	0.3	0.0	0.0	0.0	1.1	0.7	63	0.5
122-146	Bt3	88.6	3.5	8.0	0.07	5.5	4.6	0.3	0.3	0.0	0.0	0.1	1.1	0.7	61	0.5
146-173	Bt4	89.1	4.2	6.8	0.10	5.5	4.5	0.3	0.3	0.0	0.0	0.1	0.9	0.6	66	0.5
173-200	Bt4	89.0	4.1	7.0	0.07	5.8	4.6	0.3	0.3	0.0	0.0	0.1	0.9	0.7	68-0.6	
430-460	C	90.0	7.3	5.1	0.04	5.1	4.2	0.3	0.2	0.0	0.1	1.1	1.2	0.6	39	0.5

Table 2. Selected soil physical and chemical properties of the Dayobu soils in Niger (Ustoxic Quartzipsamment, isohyperthermic, coated), sampled at the ICRISAT Sahelian Center, Niamey, Niger, Africa.

Depth (cm)	Horizons	Particle size distribution (mm) Sand (%)	Silt (%)	Clay (%)	Organic C (%)	pH (H_2O) 1:1	pH (0.1 N KCl)	NH_4OAC extractable bases Ca (meg (100g)$^{-1}$)	Mg	Na	K	KCL extractable Al	NH_4OAC CEC	ECEC	Base saturation (%)	Extr. Fe (%)
0-15	A1	92.5	3.0	4.5	0.25	5.1	4.0	0.2	0.1	0.0	0.1	0.6	1.5	0.9	22	0.3
15-27	A2	91.7	3.2	5.1	0.15	4.9	3.9	0.1	0.0	0.0	0.1	0.7	1.5	0.9	10	0.3
27-44	Bt1	92.1	3.2	4.7	0.11	4.8	3.9	0.1	0.0	0.0	0.0	0.7	1.3	0.9	11	0.2
44-62	Bt2	92.7	3.0	4.3	0.08	4.8	3.9	0.0	0.0	0.0	0.0	0.6	1.1	0.7	11	0.3
62-80	Bt3	93.0	2.5	4.5	0.08	4.8	4.0	0.1	0.0	0.0	0.0	0.6	1.0	0.7	12	0.3
80-103	BW	92.5	3.2	4.3	0.07	4.8	4.0	0.1	0.0	0.0	0.0	0.6	1.0	0.7	13	0.3
103-126	BW	93.4	2.5	4.1	0.09	4.9	4.0	0.1	0.0	0.0	0.0	0.5	0.9	0.7	20	0.3
126-150	BC	94.5	1.9	3.6	0.06	4.8	4.0	0.1	0.0	0.0	0.0	0.5	0.8	0.7	23	0.3
150-173	BC	95.0	2.0	3.0	0.05	4.5	4.0	0.1	0.1	0.0	0.1	0.4	0.7	0.7	39	0.3
173-200	C	94.6	2.9	2.5	0.04	4.9	4.1	0.1	0.0	0.0	0.0	1.4	0.7	0.6	24	0.3
200+	Laterite contact															

Table 3. Selected soil physical and chemical properties of the Gagani soils in Niger (Petroferric Haplustult; loamy, siliceous isohyperthermic, shallow), sampled at the ICRISAT Sahelian Center, Niger, Niamey, Africa.

Depth (cm)	Horizons	Particle size distribution (mm) Sand	Silt	Clay	Organic C	pH (H_2O) 1:1	pH (0.1 N KCl)	NH_4OAC extractable bases Ca	Mg	Na	K	KCl. extractable Al	NH_4OAC CEC	ECEC	Base saturation	Extr. Fe
		(%)			(%)			meg (100g)$^{-1}$					meg (100g)$^{-1}$		(%)	
0-9	Al	81.1	10.9	8.0	0.37	4.9	3.8	0.3	0.2	0.0	0.1	0.8	2.6	1.4	22	1.0
9-24	Bt	79.6	9.5	10.9	0.31	4.4	3.8	0.2	0.1	0.0	0.0	1.3	3.2	1.6	9-1.0	
24-34	2Bt[1]	78.6	8.4	13.0	0.26	4.6	3.9	0.3	0.2	0.0	0.0	1.0	2.9	1.5	18	1.1
34-35	2Bsm	Laterite contact.														

1. Gravel content is 57% by weight.

sands and loamy sands, but shallow soils associated with plateaus are gravelly and finer textured (loamy sands and sandy loams, Table 3). Most, but not all of the upland soils on stable landforms have weakly expressed argilic horizons that slow the rate of saturated flow, increase the rate of unsaturated flow, and increase the sorptive capacity (West et al. 1984 and 1987). Water retention is low and plant-available water ranges from 0.05 to 0.1 cm cm^{-1}. Infiltration and permeability are rapid but upon high intensity, short-duration storm events runoff has been observed even on these sandy soils.

Mineralogically, these soils are residual systems dominated by quartz/kaolinite/Fe-oxide (geothite) systems (West et al. 1984). Quartz comprises most of the skeleton grains interlinked together into a weakly cohesive soil matrix by kaolinite/Fe-oxide grain coatings. This matrix provides for large macropore conduits through which rapid water and solute transport occurs. The buffering capacity is low because of the low-activity clay system and low clay contents. Hence, soluble and readily-exchangeable components are rapidly transferred vertically to subsoils or restrictive layers via the wetting front. The low water retention characteristics of these soils favor this process.

Chemically, these soils have several properties in common; they are acidic, low in cation exchange capacity (CEC), mineral reserves, and organic matter, and have low buffering capacity. The pHs are acidic to strongly acidic and base saturations are generally less than 35% in the upper 50 cm (Tables 1 to 3, and Figs. 2 to 4). Extractable Al (1N KCl and Al percentages are correspondingly highest in superficial and upper subsoil zones (Figs. 2 to 4). Base saturations increase with depth in deep sandy soils with argilic horizons (Labucheri, Table 2 and Fig. 2) to more than 50% in lower Bt horizons. Exchangeable Al percentage is greatest between 9 and 30 cm. Parent sandy C horizons, when observed at 4-4.5 m below the surface, remain very strongly acidic and contain small quantities of exchangeable Al. Deep sandy soils without argilic horizons (Dayobu, Table 2 and Fig. 3) also increase in base saturation with depth but never more than 40%; exchangeable Al percentage in this soil is greater than 75% between 15 and 100 cm. The C horizons in these soils also remain extremely acidic with base saturation of about 25% and exchangeable Al percentage of about 65%. Shallow soils, representative of plateau surfaces (Gangani, Table

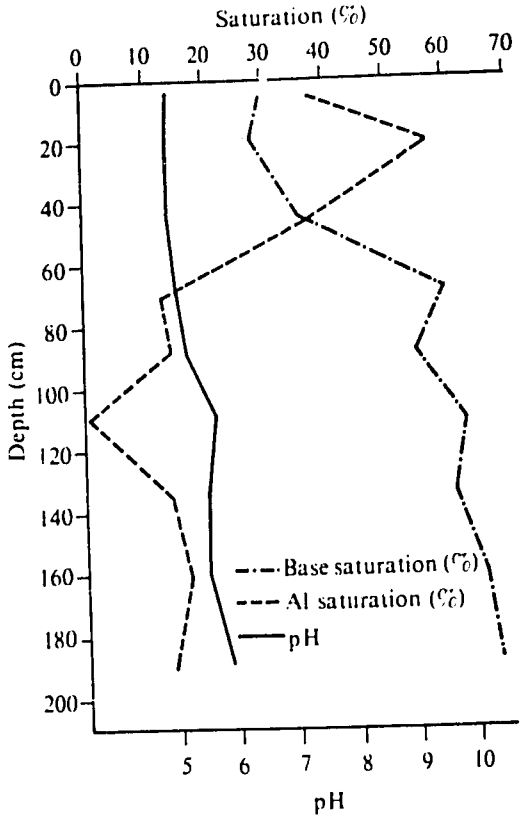

Figure 2. Depth distribution of pH, base saturation percentage, and aluminum saturation percentage in the Labucheri soils.

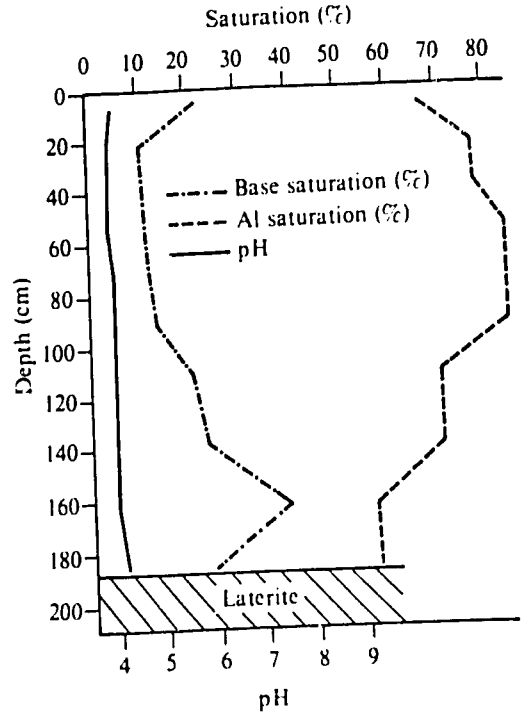

Figure 3. Depth distribution of pH, base saturation percentage, and aluminum saturation percentage in the Dayobu soils.

3 and Fig. 4), are extremely acidic in both A and Bt horizons of the sand mantle and in the 2Bt gravelly sandy loam horizons just above the laterite contact. These gravelly subsoils reflect the weathering profile into the Continental Terminal sandstones from which the laterite was also formed. The base saturations are commonly <25% with corresponding exchangeable-Al percentage values between 60 and 80%.

While degrees of soil acidity are associated with mappable differences in morphological properties of soils in the Sahel, remarkable spatial variability in acidity also occurs at lateral intervals too small to be delineated by conventional semi-detailed soil surveys. Detailed research on these poorly-responsive pearl millet areas are reported in this volume (Chase et al. 1989). Possible hypotheses to explain the origin of acidity in these semi-arid tropical environments are proposed in the following.

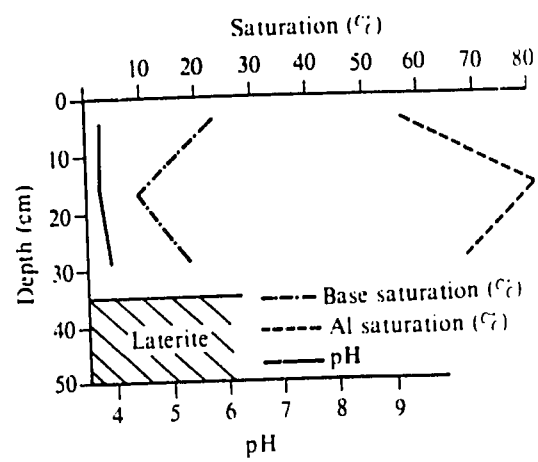

Figure 4. Depth distribution of pH, base saturation percentage, and aluminum saturation percentage in the Gagani soils.

Origin of Soil Acidity

Acidity in soils of the Sahel may be attributed to the (1) indigenous acidity of the parent sands, (2) the development of acidity in soils weathered in wetter paleoclimates, (3) leaching of bases from shallow soil systems in contemporaneous climates with concomitant development of acidity, and (4) vector dynamics between base renewal at surface horizons and base loss at lower subsoils by leaching under contemporaneous climates. It is probable, however, that soil acidity in these soils reflects multiple causes and counterbalancing base renewal vectors.

Effect of Parent Material

The parent sandy and fluvial sediments from which most of these acid soils developed, were apparently locally derived from polycycled and preweathered Continental Terminal sandstone bedrocks (Sombroek and Zonneveld 1971). Valley incision and dissection into the Continental Terminal provided an ample source of skeletal sand grains of the size, shape, and mineralogy as found in valleys and uplands of the surrounding soil landscapes. These parent sands are acidic, contain small quantities of exchangeable Al, and have kaolinitic/Fe-oxide grain coatings as found in sandy soils of the region; the coatings impart the color and acidity of these sediments. However, during the fluvial and eolian transport process, a large component of the easily detachable clay would be lost from the coatings about skeleton grains. The sands would then become less red, less clayey and less acidic; this condition more closely approximates observed sandy parent materials (C horizons) of soils in the valley sand system, sand plains, and dallols. In summary, evidence for soil acidity being an inherited property includes (1) the present semi-arid conditions, (2) the strongly acidic nature of soils and geologic material associated with the Continental Terminal deposits, and (3) the acidity of parent eolian and fluvial sandy C horizons of the soils in question.

From field morphology and laboratory analysis (Table 1 to 3), only part of the present clay, Fe-oxides, and acidity of these soils could be explained by inheritance. Pedogenesis of preweathered parent materials must also be taken into consideration to explain local regional patterns of soil. Following are several mechanisms by which this could occur.

Effect of Paleoclimate

There is a wealth of reviews of paleogeographic studies in Africa that have been published (Fairbridge 1976, Williams and Faure 1980, Maley 1981). Reconstruction of the climatic history has been attempted on the basis of: (1) stratigraphic studies of stream terraces in northern Niger (Rognon and Williams 1977, Morel 1983, Durand et al. 1983); (2) correlations with lake-level fluctuations and paleoecologic (pollen and diatoms) indices in the Chad basin (Servant and Servant-Vildary 1980, Durant and Mathieu 1980, and Maley 1981); archeological sites (Hervieu 1977); geomorphic, sedimentologic, and pedologic correlations (Sombroek and Zonneveld 1971, Gavaud 1977).

The major cycles that are important to soil acidity in sandy soils of the Sahel are summarized in Table 4. Arid periods correspond to alluviation/fluvial aggradation and eolian activity, while more humid periods correspond to vegetative stabilization of the land surface, intense soil leaching, and weathering regimes. More humid climates would also reflect major periods of downcutting and the formation of multilevel plateaus in adjustment to stream-base levels.

In summary, the formation of laterite-capped multilevel plateaus (Sombroek and Zonneveld 1971), the deep weathering into Continental Terminal sandstone, the very thick acid argillic horizons in deep sandy upland soils (West et al. 1984), the presence of buried paleosols in thick eolian sandy deposits of the valley sand and sand plain systems (Daniels and Wilding 1983, West et al. 1984), and the evidence for climatic fluctuations from paleontological records are all indicative of at least a part of the soil acidity of these soils being a consequence of paleoclimatic leaching under more pluvial (wetter) conditions.

Effect of Contemporaneous Climate on Acidity

Shallow Soils

Contemporaneous losses of bases from the solum are probable (Figs. 5 and 6) on plateau surfaces, upper segments of valley sand systems, and on the sand plains where shallow sandy soils overlay root and water restrictive layers (laterite, ironstone cemented gravels, and plinthic horizons). Restric-

Table 4. Summary of climatic history of West Africa (Bui 1985).

Years B.P.	Climate	Evidence
0-4000	Arid	Pollen and dictom assemblages; Lake Chad fluctuations
4000-12000 maximum 7000	Humid	Lake Chad high
12000-20000	Arid	Lake Chad minimum; maximum 17000 deposition of Erg 2
20000-29000 maximum 22000	Humid	Lake Chad maximum
29000-38000	Arid	Fluvio-lacustrine and interdunal evaporitic deposits in Lake Chad area
38000-40000	Humid	Southern margin of Lake Chad high
40000-50000	Arid	Deposition of Erg 1

tive layers that form a graded surface serve as the interface along which water and mobile solutes are transferred beyond the limits of biocycling by plants in the immediate proximity (Fig 5A).

During periods of moisture deficit and high surface soil temperatures, water is lost by vapor transfer and thus any bases remaining in contact with the laterite are not moved back to the surface (Fig. 5B). Likewise, biocycling is not an effective mechanism of base recharge to the surface because of the paucity of bases left in the system. The only effective means of base renewal in these soils is dust inputs. However, because of the sparse vegetation, crusted soil surface, and extreme desertification on these shallow acid sandy soils, little dust can be entrapped; most will not be deposited, or if deposited, are readily removed by wind deflation and water erosion.

Where shallow sandy soils directly overlie the Continental Terminal sandstone or a plinthic horizon (iron-pan) at the interface, the soils are generally gravelly and strongly acidic. In this case, the impediment to vertical root-water movement is the plinthite horizon or the underlying sandstone. When these restrictive layers form a graded surface, losses of bases by interflow above the restrictive layers is the same as when laterite is the impediment. Acidity in these soils is a combination of strongly-weathered residual soil material coupled with contemporaneous base loss by leaching and lateral interflow.

Deep Sandy Soils

Development of soil acidity in deep sandy soils is shown in Figure 6. During the rainy season (Fig 6A), bases and nutrients progressively move to deeper soil depths or to restrictive impermeable layers with the wetting front of successive rains. Marked soil acidity and Al saturation occurs at depths in the soil corresponding to those zones in which the greatest number and most frequent wetting fronts have occurred. Because these soils are so coarse-textured and poorly buffered, development of acidity may be closely correlated with leaching events and dynamically change seasonally with depth along the leaching front. Hydrological measurements at the ICRISAT Sahelian Center, Niger, indicate that during the rainy season, wetting fronts up to 2 m or more are possible. Hence, during these periods, bases would be transferred progressively downward depending upon the frequency and intensity of seasonal rainfall events. Where the laterite contact or other restrictive layer (Dayobu, Fig. 6A) is present within the wetting front, bases would be transferred laterally along the slope gradient as interflow similar to the process described for shallow soils. The Dayobu as an interdunal depression may also receive more intense leaching because of runon water received from adjacent dunal crests.

Conversely, during periods of moisture stress between rainfall events of the wet season and during the long dry season, base movement is upwards

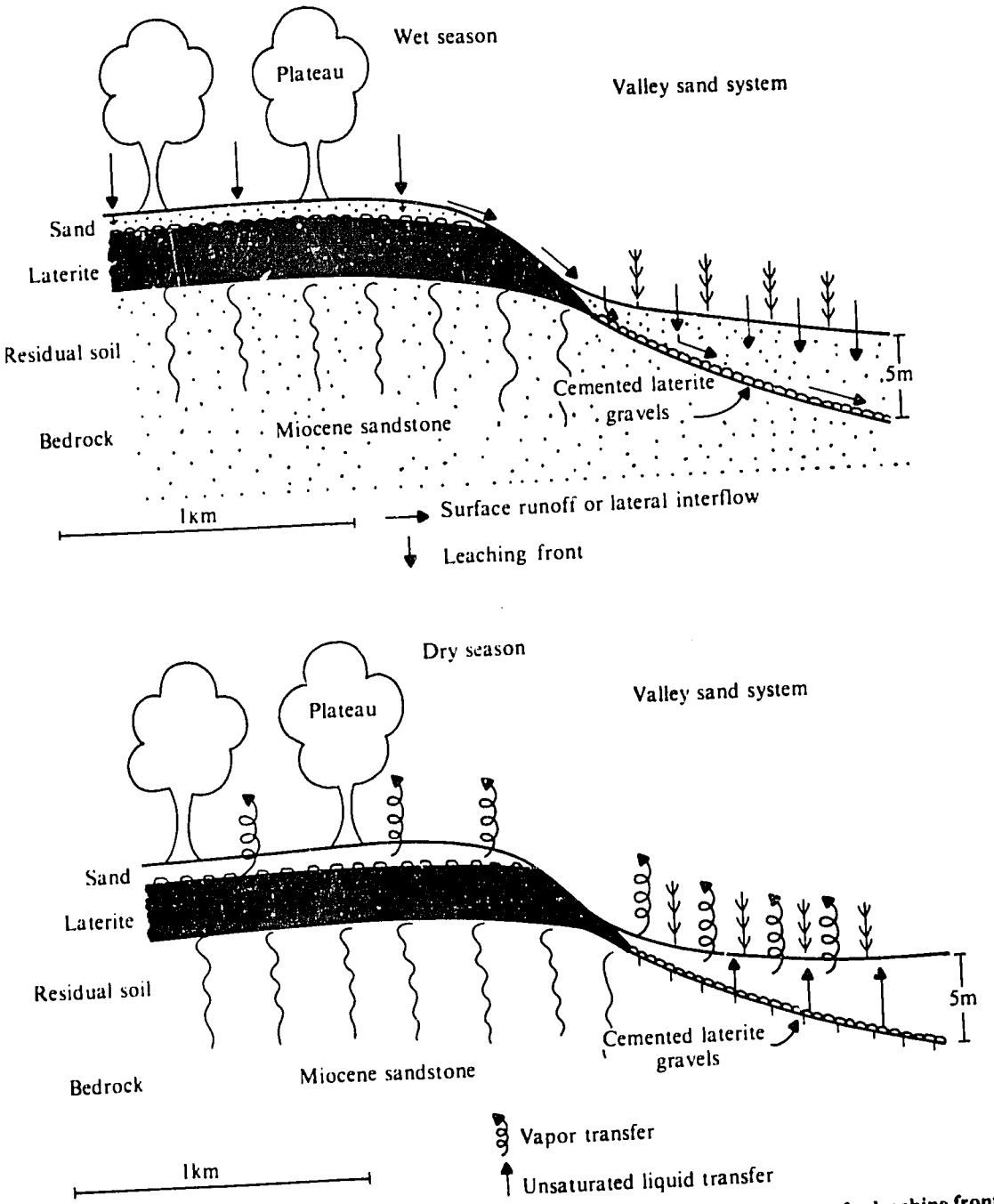

Figure 5. Schematic illustration of plateau and associated valley sand systems. a. Vectors for leaching fronts and runoff during wet season, and b. vapor and unsaturated liquid transfer during the dry season.

towards the soil surface via unsaturated liquid flow (evaporative or capillary pumping, (Fig. 6B). However, capillary rise is limited by the coarse-textured nature of these soils and by the depth at which most water loss can be attributed to vapor transport (Fig. 6B). Base recharge by evaporative pumping is thus not likely to reach the soil surface. The depth at which vapor loss of water is the primary mechanism is not known, but based on surface soil temperatures known to reach 60° C and higher dur-

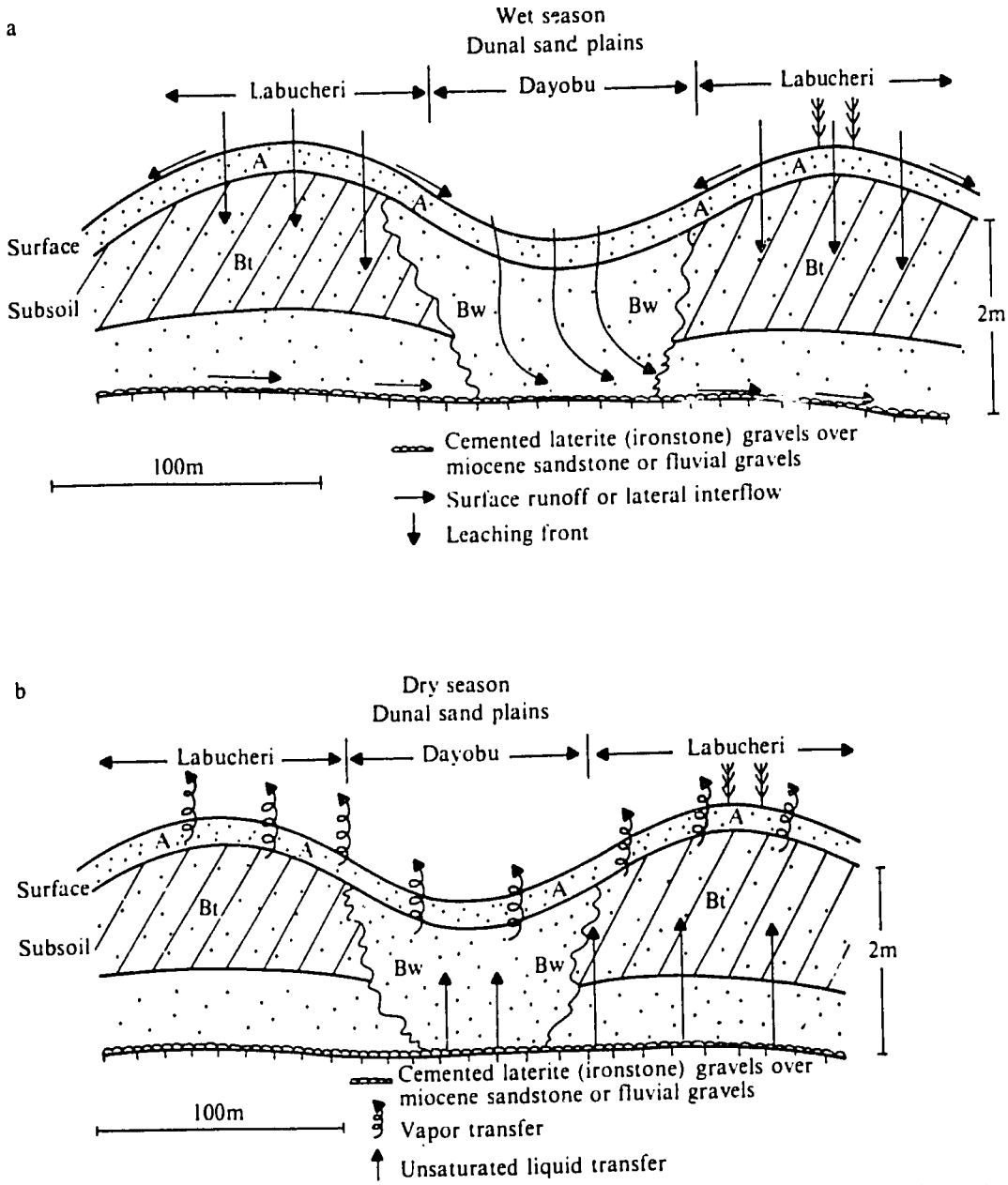

Figure 6. Schematic illustration of dunal sand plains. a. Vectors for soil runoff and leaching fronts during the wet season, and b. vapor and unsaturated liquid transfer during the dry season.

ing the dry season, the thermal gradient sustaining this process may be effective up to depths of 50–75 cm. Upward movement of bases that had been leached to lower depths can then be expected to rise to upper layers. At the soil surface base, renewal occurs in the form of biocycling by plants and animals (especially termites) and by dust inputs via harmattan winds from the Sahara Desert.

The vector dynamics of base loss via leaching and base renewal via biocycling, dust inputs, and evaporative pumping may help explain the base-saturation and Al-saturation depth functions observed in deep sandy soils (Figs. 2 and 3). Soils without a restrictive layer within the wetting front (Labucheri, Fig. 2) have maximum Al saturation and minimum base saturation in a zone immediately below the soil surface to a depth of about 60 cm. Soils such as Dayobu (Fig. 3) and Gagani (Fig. 4) with restrictive layers intercepting the wetting front have similar bases and Al-saturation depth functions but tend to remain more acidic throughout. This is explained by the fact that bases are seasonally lost from these systems as interflow leachates above the impediments to lower landscape positions. Evaporative pumping and biocycling of bases occur as in the Labucheri soils but there are relatively few bases in the system to be recycled except for dust inputs. Hence the soils tend to remain strongly acidic throughout, contrast to deep sandy soils without restrictive layers.

Considering the low buffering capacities of these soils and the proposed chemical dynamics, caution should be exercised in interpreting data sets collected at only one point in time. Data reported here were collected on soils sampled during the 1982 rainy season. One can only speculate on the nature of the chemical properties had these soils been sampled sequentially during the rainy season or during the dry season. This is an important agronomic question worthy of future research efforts. Such research is being planned within the SAT Tropsoils CRSP program.

Effects of Soil Acidity

Major Soil Constraint to Land Use

Spatial variability in farmers fields occurs on a broad scale in the Sahel. A significant proportion of this variability is apparently associated with soil acidity, although it is recognized that there are other factors that contribute to the observed variability, e.g. termite mounds, and previous village sites. The exact land area where crops are affected by acid soils is unknown but preliminary observations indicate that it is substantial.

The primary effects of acid soils on agriculture on the Sahel are threefold: (1) crops and cropping systems are limited by their tolerance to acid soils, (2) the full potential for soil productivity cannot be realized until soil acidity problems are diagnosed and treated, and (3) areas devoid of vegetation owing to acid soils hasten desertification in the Sahel.

Acid soils affect a number of soil chemical and biological properties. Decreasing soil pH is associated with increasing aluminum (Al) and manganese (Mn) availability. Below pH values of approximately 5, concentrations of these elements may increase to levels that are toxic to plant. Low soil pH is also associated with lower concentrations of basic cations (calcium, magnesium, and potassium, Tables 1–3) available to plants. Root growth and water-use efficiency of plants are both restricted in acid soil systems with pH values low enough to have toxic levels of Al and/or Mn.

Soil Acidity and Cropping Systems

Efficient use of native and applied nutrients and water can never be realized until soil acidity problems have been resolved. The choice of crops and, therefore, cropping systems will be limited to crops and cultivars that are acid tolerant in areas where soil acidity is extensive (Sanchez 1976, 223–253 pp.).

The presence of acid soils in the semi-arid region of the tropics is noteworthy in itself. That significant areas of the Sahel are negatively affected by soil acidity is particularly important. The introduction of higher-yielding cultivars of pearl millet, sorghum, or other crops that could be grown in the Sahel will be limited to acid-tolerant varieties.

Efficient use of water resources is limited in areas where crop growth is influenced by soil acidity. Introduction of fertilizers into the cropping system, particularly acid-forming ammonium-based materials, to the poorly buffered, sandy soils will tend to lower soil pH with time. Since the soil resource is very fragile, methods to correct acidity and chemical treatments to increase crop yields must be carefully considered.

Desertification of the Sahel

Causes of desertification in the Sahel are both natural and man made (Thatcher 1979, Thomas 1980). Surface or subsurface soil acidity that negatively affects plant growth contributes to desertification in the Sahel. Bare or partially vegetated soil surfaces are subject to wind and water erosion (tiger bush plateau uplands), both of which may expose acid subsoils. Poorly-vegetated soil promotes water runoff due to a lack of impedence of water to overland flow, and due to crusting from rainfall impact that can result in clay and silt dispersion and partial surface sealing. Crusting of the sandy surface soils is expected to be minimal in the Sahel but exposure of the acid argilic subsoils could dramatically increase water runoff. Further, because such areas respond poorly to pearl millet/cowpea production, the land is used for pastoral grazing of animals and harvesting wood for fuel and for construction. This increases animal traffic and compaction, and intensifies the desertification process.

Lack of vegetation and soil litter also enhances wind erosion and movement of surface soil. Properly vegetated lands act as a deterrent to soil movement by wind erosion.

Plant Response Variability

Fields with very acidic soils show striking plant response and spatial variability over very short distances. Pearl millet growth often decreases from very productive regions to completely barren areas over distances varying from 2 to 10 m. (Wendt 1986). The zones between these irregularly distributed productive and unproductive regions are characterized by gradually declining pearl millet growth, as defined by smaller plants, delayed maturity, shorter and more poorly filled heads, and diminished yields. Pearl millet germinates uniformly in all areas of the field and growth appears to be essentially uniform until one or two weeks after emergence. Differences in growth become apparent at this time. The plants in the most unproductive regions eventually die, leaving places in the fields devoid of vegetation. Completely barren areas appear to be larger in regions of marginal rainfall. Poor stands also appear to be associated, though not consistently, with micro-low regions in the field topography (Wendt 1986).

Potential pearl millet yield, lost owing to soil acidity problems in the Sahel have not yet been quantified. Extreme variability not only severely reduces yields, but is also a major obstacle to other field research efforts. Differences between treatments are difficult to detect because of large variation between replications within a given treatment. Hence, soil acidity is not only a soil management problem for farmers but has a significantly negative impact on agronomic research endeavors in the Sudano-Sahelian zone of Africa.

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