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The alkali soils of the middle Niger valley: Origins, formation and present evolution

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Abstract

In Niger Republic, the regional development of irrigation along the river Niger is confronted with a large extent of alkali soils. For a sound management of the irrigated area, it appears necessary to understand the present evolution of these alkali soils. The study of one of these areas, located on the Liptako bedrock, reveals a concentric soil distribution: within a zone of brown soil with abrupt textural change and alkaline in depth (stagnic Solonetz), appears a ring of brown steppe soils (cambic Calcisol), around zones of alkali soils (Solonetz). These alkali soils are not saline but their soil solution is more concentrated than in brown steppe soils. The abrupt boundary between the brown steppe soils and the alkali soils is related with morphological and geochemical changes, resulting from calcite and fluorite precipitation in the soil solution. The detailed study of this contact demonstrates the current transformation of alkali soils into brown steppe soils. Therefore, it appears that soil alkalization is no longer in process on the terraces of the river Niger. The formation of brown steppe soils and alkali soils may be explained by the juxtaposition of two contrasted hydrological regimes in a former pond. This hypothesis is supported by aerial pictures and microscopic observations. It is also consistent with a recent study of the hydrology of Sahelian ponds and with considerations on the chemical quality of the runoff. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: non-saline alkali soils/sodic soils; soil genesis; de-alkalization; Sahel; Niger

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1. Introduction

In the semi arid area of the middle Niger valley (Niger Republic, Fig. 1), irrigation techniques have been developed to respond to aridity and increasing population. Initially, the agricultural practices most suitable for the region have been tested on a few trial areas. Often, on these areas, the main threat to sustainable agriculture is the reduced fertility associated with alkali soils existing prior to irrigation. Bozza and Boyer (1988) observed that up to 70% of the area of some irrigated perimeters were covered by non-saline alkali soils.

These alkali soils apparently always develop in contact with the non-alkaline brown steppe soils (Barbiéro and Berrier, 1994). The contact between the two soil types is always so abrupt that in all the West-Africa surveys, those two units were represented as an associated soil unit (Gavaud, 1977; Maignien, 1965).

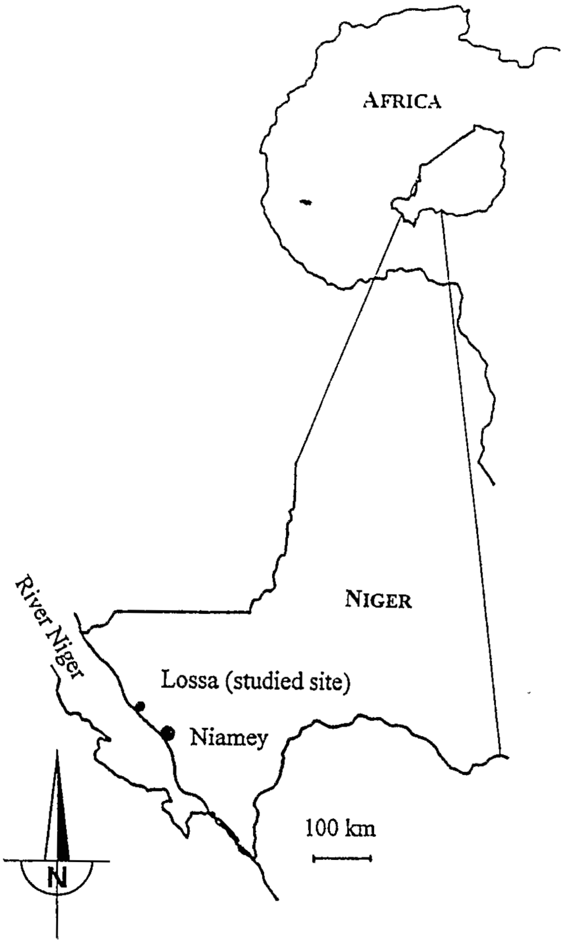


Fig. 1. Location of the study site.

Such soil distribution has been observed along the river Falémé in Sénégal (Chauvel, 1966) and also in semi-arid Pakistan (Choudhri, 1972). However, this pattern differs clearly from what exists in Mali, upstream in the Niger valley, where a shallow water table is responsible for present alkalization (N'Diaye, 1987; Valles et al., 1989a; Bertrand et al., 1993, 1994).

This specific distribution of soil units observed in the Niger valley, in Niger, raises the question of their origin, which is the first objective of this paper. The main difference between the two soil types (alkali soil and brown steppe soil) is that the soil solution is more concentrated in the alkali soils, although they are non-saline. Therefore, two hypotheses are proposed to explain the genesis of these soils: (i) soil alkalization is induced by the concentration by evaporation of accumulated dilute solutions; (ii) the absence of soil alkalization where brown steppe soils are observed result from localised percolation of fresh water.

The second objective of this paper is to explain the present evolution of alkali soils, i.e., does the alkalization corresponding to such distribution of soil units, progress or regress, which is essential for a sound management of irrigation in these areas using local waters.

2. Materials and methods

The study is located at 'Lossa'–Niger (13°54'N 1°35'E) in a 90 ha domain under irrigation (Fig. 1). This irrigated area lies at the bottom of a 10 km^2-catchment on the east side of the river Niger. The northern part of the domain (15 ha) was surveyed in detail (Fig. 2).

The climate belongs to the type III semi-arid of the African zonation (Griffiths, 1972), with a short rainy season from June to September (400 mm rainfall). The annual potential evapotranspiration is 2400 mm. During the 8 months of the dry season, dry winds are blowing from the Northeast. The mean annual temperature is about 33°C with maximum around 47°C recorded. The water table located at 30 to 40 m deep is not subject to evaporation, and therefore not responsible for present alkalization.

Under the sandy superficial horizon, the soils have a sandy clay texture. They have developed from an alkaline gneiss with biotite. This parental material, locally called 'Liptako bedrock', is part of the regional Birrimian substratum. The regolith (i.e., weathered parent material, isalterite) of this crystalline bedrock appears between 1 and 1.2 m deep. Preliminary studies of the whole catchment show three major differentiations in the sandy clay soil properties (Barbiéro, 1995):

1. a non-saline alkali soil ($pH_s = 8.5$ to 9.8 (s = on saturated paste), $EC_s = 2.2$ to 3.2 dS m^{-1}, SAR = 12 to 28 $(\text{mmol l}^{-1})^{1/2}$, E.S.P. = 5 to 40%);
2. a non-alkaline brown steppe soil ($pH_s < 8.4$, $EC_s = 0.7$ to 2.2 dS m^{-1}, E.S.P. = 0.5 to 2%), which is much more fertile;

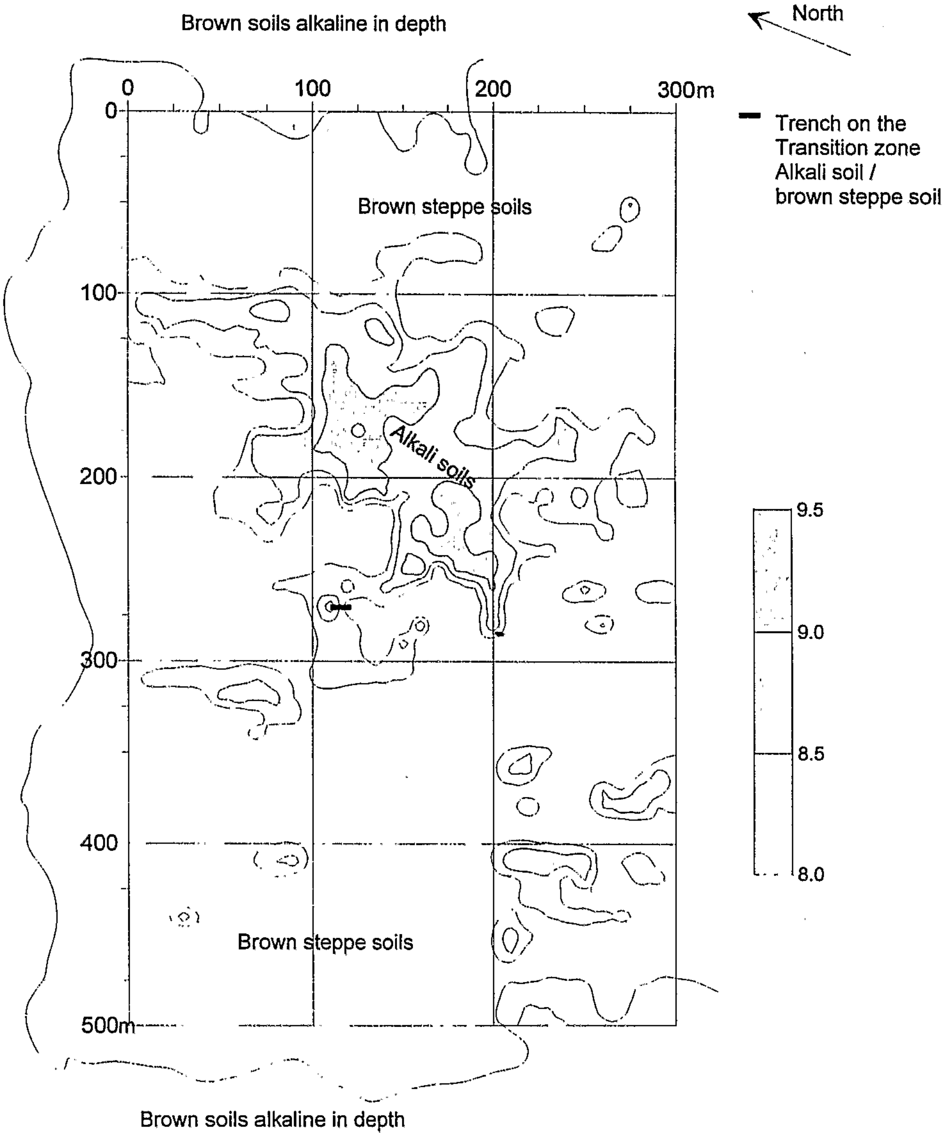


Fig. 2. pH survey of the 15 ha and concentric distribution of the soils in the studied zone.

3. a brown soil with abrupt textural change alkaline in depth (in depth: $pH_s = 9.1$ to 9.3, $EC_s = 1.5$ to 2.5 dS m^{-1})

2.1. Soil survey

The distribution of alkali soils/brown steppe soil does not appear straightaway. Therefore, a detailed soil pH survey of the 15 ha north of the irrigated domain was run along a 10 m squared grid. Barbiéro (1995) showed that the pH distribution according to this grid was relevant for a precise delineation of the soil units. Soil was collected with an auger at a depth of 40 cm, under the superficial sandy horizon. The pH was measured in the laboratory on saturated pastes. Soil morphology was observed and described in 18 pits inside and outside the irrigated area (Fig. 2). The pH data combined with morphological observations were used to delimit the soil units. Two soil types were observed in the 15 ha irrigated area: the non-saline alkali soil and the non-alkaline brown steppe soil. Evidence of brown soil with abrupt textural change alkaline in depth was found at the limit of the area. Therefore, the survey was extended outside the irrigated area to cover all the catchment bottom and to understand the soil distribution.

An aerial picture of the catchment was used to complete the observations (I.G.N., 1975, Plate 4).

2.2. *Morphology and geochemistry*

A detailed study had been conducted along a 7 m long and 1.2 m deep trench excavated through an abrupt boundary between brown steppe soils and alkali soils (Fig. 2) which has been located by the soil survey. The trench has been shown to be chemically and morphologically representative of the two soils. The pedological horizons were identified, described and sampled for laboratory characterisation and geochemistry (Fig. 3). Air dry soil blocks were impregnated with a polyester resin and vertical thin sections (70 × 110 mm) were made and described according to Brewer (1976). Precipitation forms of the calcite in calcareous concretions were observed using a SEM (XL 20 Philips at 15 kV) with a LINK Analytical eXL energy dispersive X-ray system.

Over one face of the trench, the pH values were measured in situ (on saturated paste) along a regular grid (0.1 m deep × 0.2 m wide) to locate accurately the variation of geochemical characteristics. To define and measure the general geochemical soil characteristics along the trench, 72 soil samples were also taken according to a coarser regular grid (0.1 m deep × 0.95 m wide, Fig. 3). Saturated paste extracts were analysed by ion chromatography (Dionex).

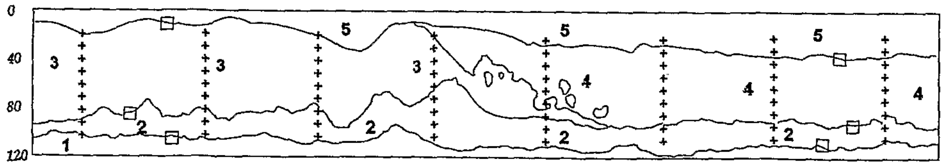


Fig. 3. Distribution of the horizons close to the contact zone: alkali soils/brown steppe soils. (1) Weathered layer with parent-rock structure, (2) calcareous weathered horizon, (3) grey sandy clay loam horizon, (4) brown sandy clay loam horizon, (5) superficial sandy horizon, (+) chemical analysis sampling points, ([]) thin sections.

The quantified ions were: Na^+, K^+, Ca^{2+}, Mg^{2+}, $NH4^+$, Cl^-, $SO4^{2-}$, F^-, $NO3^-$, $NO2^-$, $PO4^{3-}$, acetates, formates and oxalates. To distinguish and quantify fluoride from small organic anions (acetates and formates) a second analysis was performed using the sodium tetraborate as eluant. Although, sample volumes were too small for titration of the carbonate alkalinity (i.e., $(HCO_3^-) + (CO_3^{2-})$), which forms the major anionic compound, its value was derived from the ionic balance of the solution. An acid titration (method of Gran, 1952) was performed on three samples giving similar results as the estimation by the ion balance. Silica was quantified by colorimetry (Na-molybdate method at pH 1.6 Charlot, 1961). Equilibrium computations were performed using the 'Aqua' software package (Valles and De Cockeborne, 1992), derived from the 'Gypsol' model (Valles and Bourgeat, 1988).

Using the same procedure, an analysis of the geochemical content of surface runoff water was undergone. Runoff water was collected on the upslope of the studied area after rain in four different puddles. The chemical quality of the runoff water, regarding the risk of alkalization, was estimated using the concept developed by Valles et al. (1991).

3. Results

3.1. Soil distribution in the landscape

Fig. 2 shows the extent of the three soil units in the studied area. Three 'concentric domains' may be defined: (A) in the centre of the area, delimited by a pH jump (8.5), a 3 ha zone corresponds to grey–brown alkali soils with high pH values. Because of their prismatic structure and natric horizon, they are classified as Solonetz (FAO et al., 1994). Smaller alkaline spots also exist outside of this main area. (B) These alkaline zones are surrounded by a broader leached area defined by non alkaline brown steppe soils (cambic Calcisol) with lower pH (7 to 7.5). (C) In the outermost part of this area, are mapped brown soil with abrupt textural change, alkaline at depth, with gradual centrifugal pH rise (7.5 to 8.5). This third soil unit is classified as stagnic Solonetz.

3.2. Soil morphology

Fig. 3 presents the soil profile along the 7 m trench in the transition zone (Fig. 2). The alkali soil is located on the left end of the trench and the brown steppe soil in the right end. The alkali soil shows a shallow, grey (10YR6/1 (dry)) sandy and coherent superficial horizon (about 0.05 m) overlying a grey (10YR5/2) sandy clay and hardly coherent material (about 70 cm in depth) with a large prismatic structure (from 0.5 to 1.2 m wide) and a massive substructure (Fig. 4). The weathered bedrock below this prismatic layer exhibits various lime

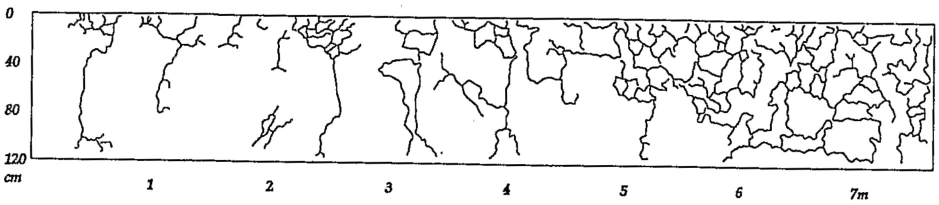


Fig. 4. Distribution of the macro structure (main cracks) close to the contact zone: alkali soils/brown steppe soils.

($CaCO_3$) patterns: nodules, soft powdery volumes of 0.05 to 0.10 m, and pseudo-mycelia. The calcareous nodules have a white consolidated cortex and a grey compact centre (Fig. 5a). These nodules are solid and impossible to break under finger pressure. The calcite crystals in the nodules do not exhibit any

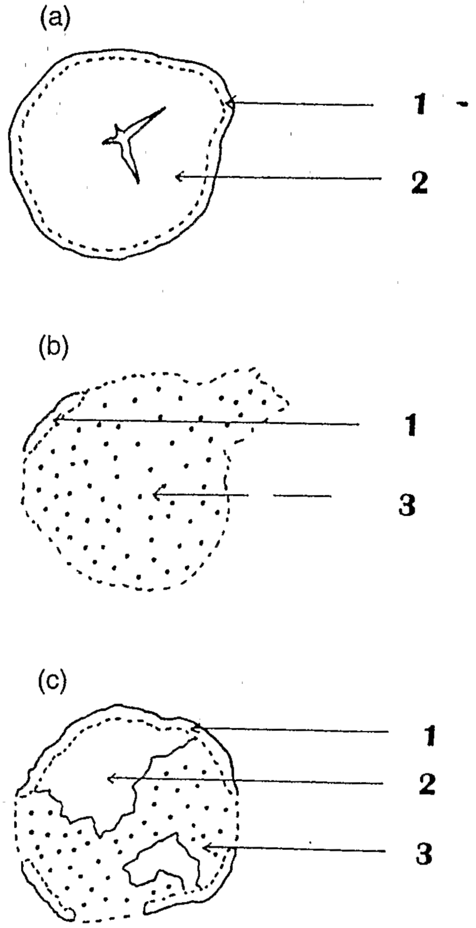


Fig. 5. Morphology of the calcareous nodules: (a) Alkali soil, (b) brown steppe soil, (c) transition zone (1 white indurated cortex, 2 grey calcareous (with Quartz) matrix, 3 soft calcareous powder).

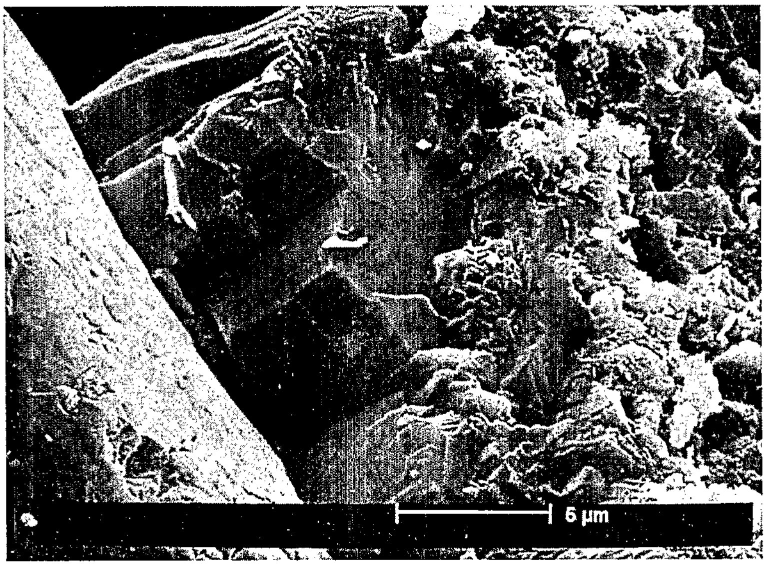


Plate 1. Precipitation forms of calcite in the nodules of alkali soils.

corrosion patterns (Plate 1). The weathered bedrock with undisturbed petrographic structure appears near 1 m deep.

Although the brown steppe soils has a similar soil texture as the alkali soil, large differences in the soil structure are observed. The superficial sandy horizon is generally thicker. It overlies a brown (10YR5/5) sandy clay horizon with coarse prismatic structure (0.1 m) and medium cubic substructure (angular blocky 0.01 to 0.02 m, not represented in Fig. 3). The weathered bedrock has less calcareous precipitates than the alkali soil. They include friable nodules, soft powdery volumes (from 0.02 to 0.05 m) and pseudomycelium discrete coating. These calcareous nodules are very fragile (Fig. 5b). A relict cortex is observed and the centre of the nodule is generally composed of soft powdery calcite. The calcite precipitates as irregular sphaerules (Plate 2), sometimes rhomboedric as those observed by Bouzigue et al. (1992) in a vertisol of Cuba. The weathered bedrock with undisturbed petrographic structure also appears about 1 m deep, as in the alkali soil.

In the brown soil with abrupt textural change, alkaline in depth, the superficial sandy horizon is 0.25 m thick. Its colour is 10YR6/2 and locally bleached (10YR7/1) in the lower part of the horizon. An abrupt horizontal and regular limit leads to a brown (10YR5/4 to 5/5) sandy clay horizon, 0.3 to 0.4 m thick with subangular blocky structure. Near 0.6 m depth, a significant change is observed in the colour (10YR5/2), in the structure (massive) and in the cohesion (extremely firm). The weathered bedrock appears at 0.9 m depth, including lime: nodules and pseudomycelium coating. The weathered bedrock with conserved petrographic structure (isalterite) appears near 1.1 m deep.

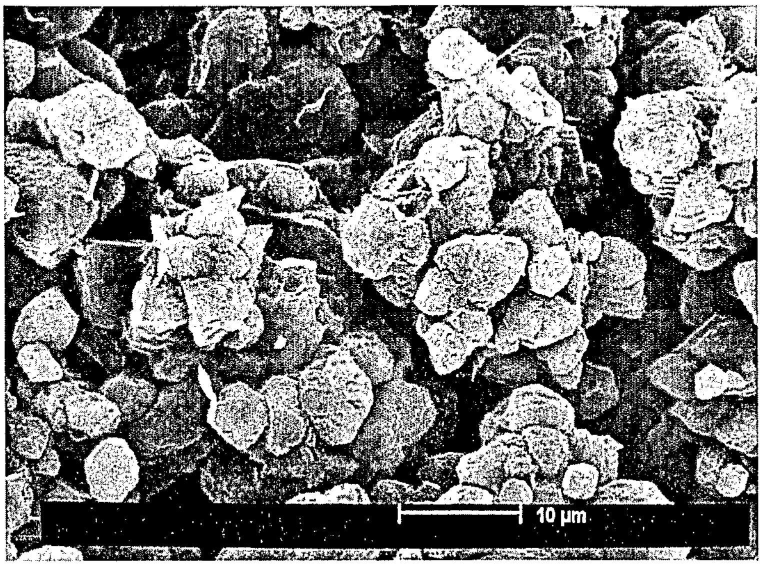


Plate 2. Precipitation forms of calcite in the nodules of brown steppe soils.

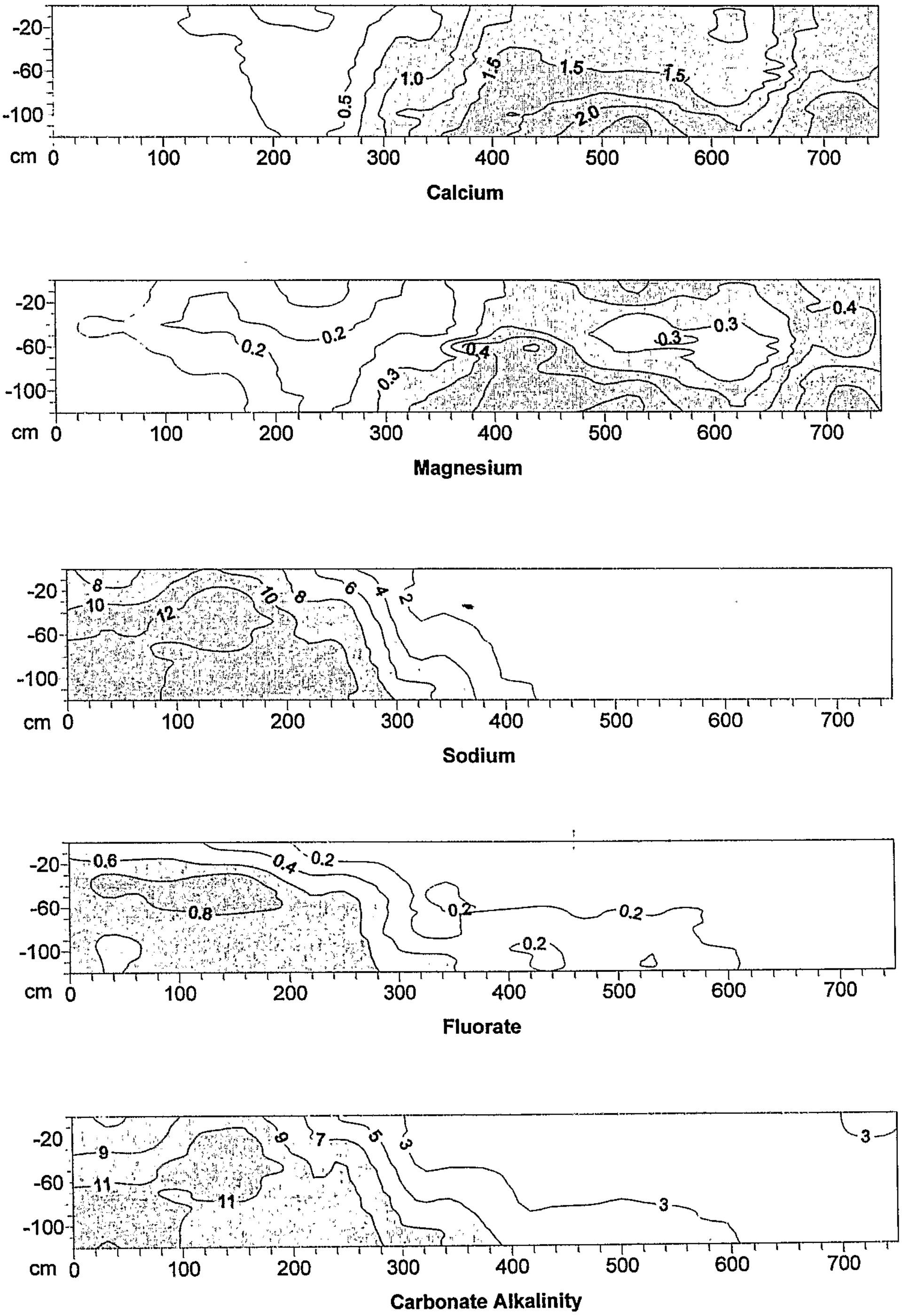
Thin section observations under an optic microscope of the alkali soils and brown steppe soils reveal many microscopic feature associated with a pond environment: i.e. sponges spiculae, diatoms, cyanophyceae. These features were not found in the brown soils with abrupt textural change, alkaline at depth.

3.3. Chemistry of alkali soils and brown steppe soils

The soil solutions show distinct chemical facies, from a calcic bicarbonate type in the brown steppe soil to a sodic bicarbonate type in alkali soil. The changes in the chemical facies along the 7 m length trench are presented in Figs. 6 and 8. A similar distribution of sodium, fluoride, carbonate, alkalinity and TDS is observed, towards the alkali soil, whereas calcium and magnesium concentrates are towards the brown steppe soil. Fluoride concentrations are particularly high and were found to be a major component (Fig. 6d).

The chemical analysis data were sorted according to their sodium amount and presented in concentration diagrams (Fig. 7). In these diagrams, the concentration factor is defined as $CF = [Na]/[Na]_0$ where [ ] denote molality and $[Na]_0$ refers to the lowest Na molality measured in the samples.

Soil solutions are more concentrated in alkali soils than in brown steppe soil. Referring to CF, fluoride content and carbonate alkalinity increase consistently but less rapidly than sodium concentration; calcium, magnesium and potassium amount decrease. An initial approximately constant silica molality is followed by an increase at elevated concentration factors. The pH value of soil solution



Calcium

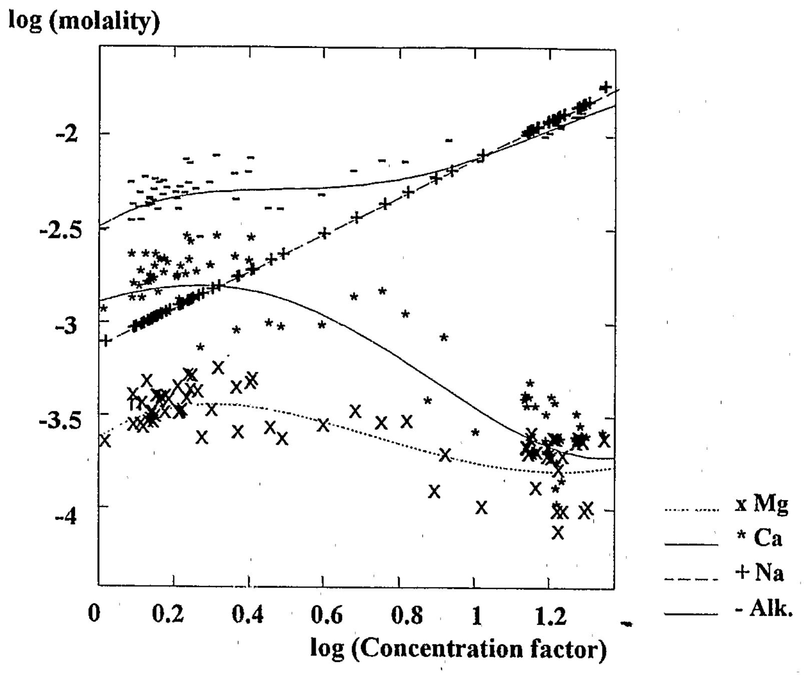
Magnesium

Sodium

Fluorate

Carbonate Alkalinity

Fig. 6. Spatial distribution of the chemistry close to the contact zone: alkali soils/brown steppe soils (meq l^{-1} on the saturated paste extract).



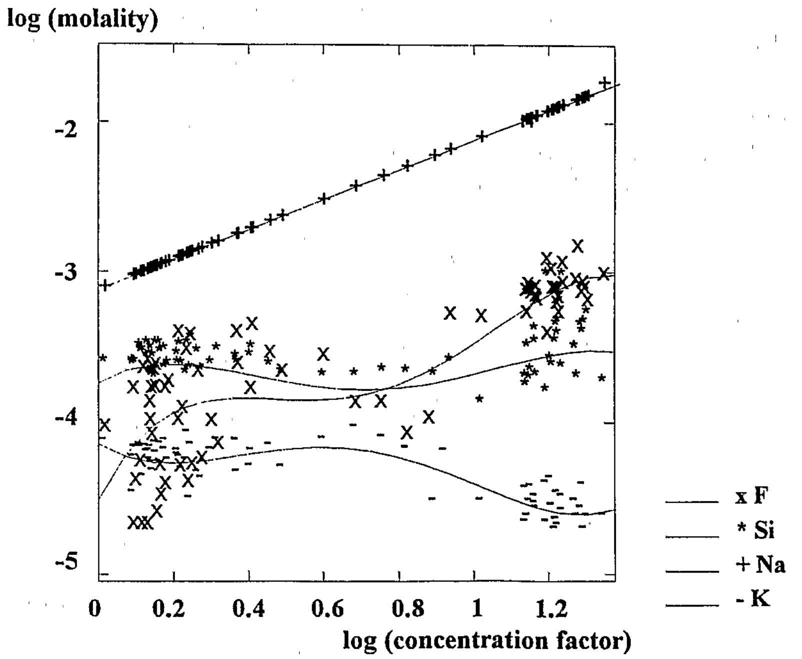


Fig. 7. Concentration diagrams.

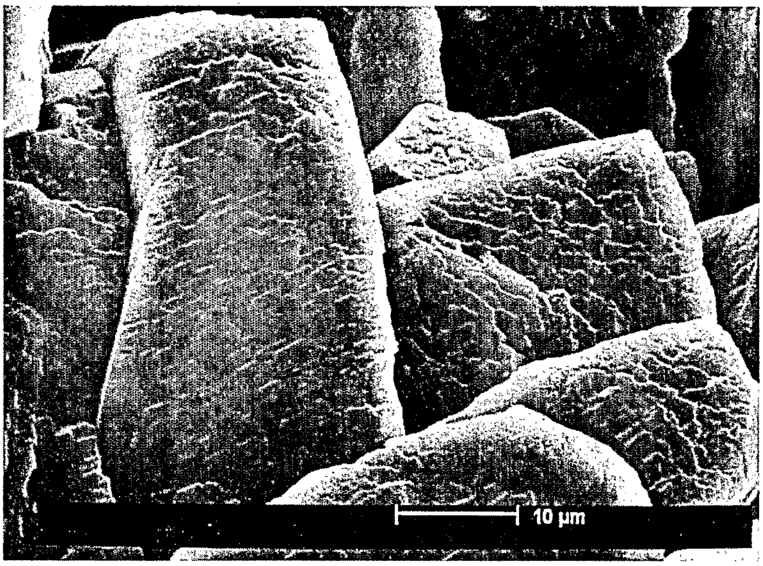


Plate 3. Precipitation forms of calcite in the nodules close to the contact zone.

increases with sodium concentration. Chloride and sulfate vary similarly. However, their amounts are low, their relation with sodium is more scattered and they do not exhibit a particular distribution along the large pit.

3.4. *Morphological and geochemical transition between alkali soils and brown steppe soils*

The bedrock does not show any lateral variations of facies in the 7 m long trench. The morphological transition between the alkali soil and the brown steppe soil is highlighted by a lateral change in the grey (10YR5/2) sandy clayey matrix of the alkali soil. Nuciform volumes of the brown (10YR5/5) matrix appear progressively in the grey (10YR5/2) matrix and become predominant at $x = 4$ m in Fig. 3. This change in the colour of the soil defines the

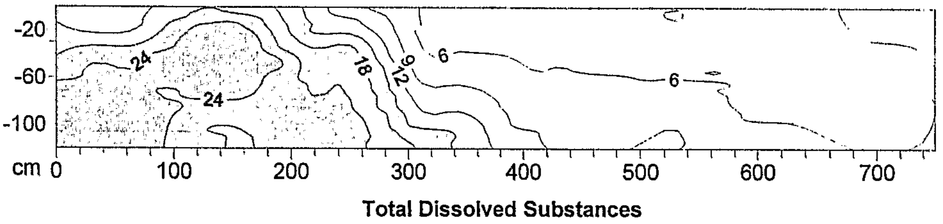


Fig. 8. Distribution of the Total Dissolved Substances (TDS) values close to the contact zone: alkali soils/brown steppe soils (meq l^{-1} on the saturated paste extract).

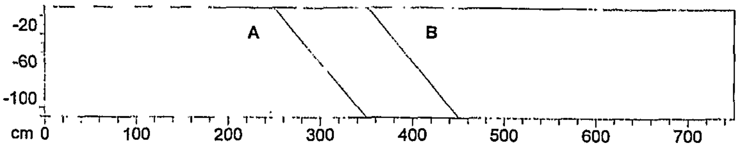


Fig. 9. The gap of 1 m between the (A) morphological and (B) geochemical transition.

morphological transition between the two soil types. The changes from a coarse prismatic to massive structure to a finer prismatic cubic angular blocky structure indicate a transition in the same place.

Close to this transition, the strength of the calcareous nodules is intermediate between the two former descriptions (Fig. 5c). They can be crushed on a knife blade. Two types of calcite precipitates are observed in these nodules. Crystals of calcite similar to those described in the alkali soil are observed, though with many dissolution patterns (Plate 3). Such dissolution pits of the calcite in basic solutions were described by Delmas et al. (1987). Calcite similar to the sphaerules observed in the brown steppe soils are also found in the same nodules.

The geochemical transition can be located using the distribution of Total Dissolved Substances (TDS) of the saturated paste extracts (Fig. 8). This geochemical transition is offset of 1 m to the left, compared to the morphological transition (Fig. 9).

3.5. Quality of the runoff waters

The chemical analysis of the runoff waters are reported in Table 1. The runoff waters are very diluted (TDS ranges from 1.2 to 4.8 meq l^{-1}) but present a positive Calcite Residual Alkalinity ($RA_{calcite}$ = Alkalinity − Ca in eq l^{-1}) ranges from +0.4 to +1.1 meq l^{-1} (Van Beek and Van Breemen, 1973) and therefore belong to the carbonate alkaline family (Valles et al., 1991). Such water evolves in a carbonate alkaline way by concentration.

Table 1
Chemistry of the runoff waters

Sample (mmol l^{-1})	Na	K	Ca	Mg	Cl	SO_4	F	NO_3	Alkali
1	0.060	1.987	0.026	0.016	0.092	0.036	0.171	0.319	1.145
2	0.098	0.448	0.029	0.015	0.061	0.021	0.026	0.021	0.420
3	0.266	0.330	0.174	0.108	0.092	0.052	0.029	0.079	0.883
4	0.273	1.403	0.273	0.108	0.307	0.072	0.045	0.257	1.660

4. Discussion

The geochemical data suggest that carbonated alkalinity and fluoride are controlled by a geochemical process. Calcium and magnesium are also clearly controlled. Calcite precipitate are observed in alkali soil and brown steppe soil and the equilibrium with respect to calcite is reached. Moreover, Fig. 10 shows that the soil solutions are also in equilibrium with respect to fluorite (CaF_2) in the alkali soil. The precipitation of fluorite in the alkali soil is probably concomitant with the precipitation of calcite, although the presence of fluorite could not be verified by X-ray diffraction (XRD) due to its low contents. Calcite and fluorite precipitation explains the major change in the chemical facies between brown steppe soils and alkali soils. Calcite precipitation is a usual mechanism in alkalization processes. However, fluorite precipitation, well known in saline alkali soils or alkaline brines (Darragi et al., 1983; Gueddari, 1984; Chernet and Travi, 1993) and suspected by Jacks and Sharma (1995) in south India, has never been reported in non-saline alkali soils (Barbiéro et al., 1995). It amplifies the geochemical control of calcium which is initiated by the calcite formation. Microanalysis conducted on the calcareous precipitates indicate a Mg^{2+} content of 2% in the calcite. This process cannot explain the control of

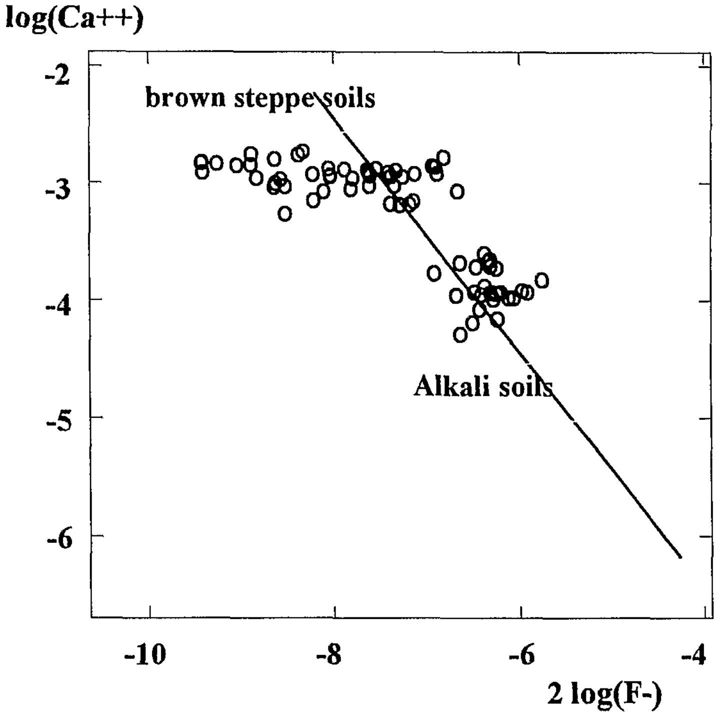


Fig. 10. Saturation with respect to fluorite of paste extracts from alkali soils and brown steppe soils.

Mg^{2+} observed in the soil solutions. Magnesian silicate formation probably occurs simultaneously (Barbiéro, 1995, Marlet et al., 1996) as observed in other Sahelian regions such as Mali (Valles et al., 1989b) and Chad (Gac et al., 1977). Alkaline dissolution of the pond biogenic opal can enhance this process. All these precipitations use up the bivalent cations and induce a significant increase in the Sodium Adsorption Ratio (SAR).

The alkaline and sodic environment induces clay dispersion, decrease in aggregate stability, fabric collapse resulting in an important decrease of soil hydraulic conductivity. The soil becomes very compact and the resistance to penetration increases drastically. A very hard crust appears at the soil surface after rainfall (Barbiéro, 1995). These physical consequences of alkalization are a well-known phenomena (Shainberg and Letey, 1984; Abu Sharar et al., 1987; Sumner, 1993).

4.1. Origin of the soil geochemistry

The main difference between the two soil types is that the soil solution is more concentrated in alkali soils. It results in the precipitation of calcite and fluorite, after the equilibria are reached. Therefore, two hypotheses are proposed to explain soil genesis: (i) soil alkalization is induced by the concentration by evaporation of accumulated solutions; (ii) the absence of soil alkalization where brown steppe soils are observed results from localised percolation of dilute water.

None of these hypotheses are exclusive; the two mechanisms can occur at the same time depending of hydrological regime zonal distribution. Indication of the former hydrological environment that will explain the soil formation was researched in the present features of the studied area.

The soil units show a concentric distribution. On the aerial picture (Plate 4), structures associated with former pond limits are observed in the valley bottom, in the presently irrigated area of 'Lossa'. The limits of the pond outlined in Plate 4, and that intersect successively, show clearly that the former pond had moved several time southwards. The formation of this pond is controlled by the recent formation of a dune ridge and the building of river lee bank from the Niger, morphological features entrapping the surface runoff toward the N and NW. Today, the river bank is discontinuous and the catchment is open to the Niger alluvial plain.

Other evidences of this former endorheism of the 'Lossa' catchment are recorded in the soil. The numerous remains of aquatic microscopic organisms, observed in alkali soils and brown steppe soils support the existence of a former temporary ponding at the top of the modified soils.

The water in the former pond originates from local runoff. The runoff water collected up slopes from the site show ambiguous chemical characteristics. Water runoff is a diluted solution, undersaturated with respect to calcite, fluorite

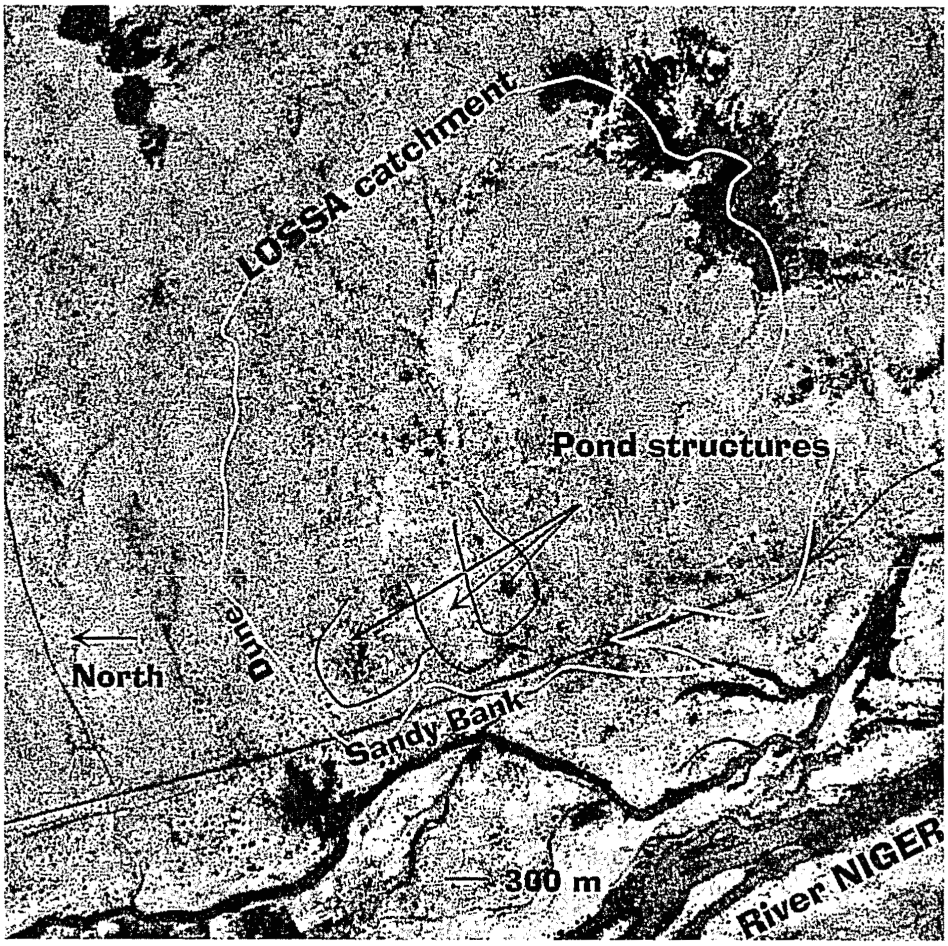


Plate 4. Aerial picture of 'Lossa' catchment and indices of a former pond in the valley bottom.

and magnesian silicate. Such water can leach soluble salts of the soil by percolation. As its alkalinity is higher than its calcium content, solution evolves to carbonated alkaline by evaporation (Van Beek and Van Breemen, 1973; Cheverry, 1974; Droubi et al., 1980, Valles et al., 1991). The fate of soil in contact with this type of solution depends on the balance between evaporation and percolation.

The juxtaposition of two hydrological regimes in contrast had been described by Desconnet (1994) in Sahelian ponds. During rainfall and afterflow, the pond fills up with runoff up to a 'high stand'. When the water supply stops, a consequent evacuation by infiltration is observed down to a 'minor stand'. From this intermediate stand, the infiltration is blocked by the presence of a clay decantation sheet at the centre of the pond, that reduces considerably vertical infiltration: the standing water can only evaporate.

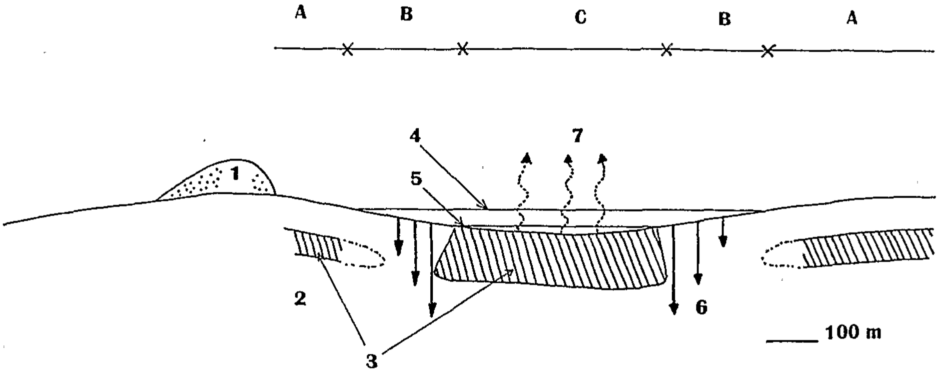


Fig. 11. Hypothetical model of alkali soil and brown steppe soil genesis under the former pond (A) Brown soil with abrupt structural change, alkaline in depth, (B) non-alkaline brown steppe soil, (C) non-saline alkaline soil; (1) dune or sandy bank, (2) crystalline bedrock, (3) alkaline horizons, (4) and (5) high and low levels of the former pond, (6) infiltration and soil leaching, (7) evaporation.

All these observations and remarks match and allow to put forth a model of soil genesis in the study area (Fig. 11). Initially the catchment bottom was probably cover by brown soil, alkaline in depth resulting from the bedrock weathering in semiarid conditions. Alkali soils and brown steppe soils proceed from two contrasted hydrological regimes in an old pond, supplied by dilute but potentially alkalinizing water. The percolation of the water between the high and the low level of the pond has probably leached the brown soil alkaline in depth into brown steppe soil. Opposite, evaporation and concentration of water below the low stand increased alkalinization and led to alkali soils in the central part of the pond.

4.2. Present evolution of the soil

The endorheism explains the soil origin by redistribution of alkalization in the valley bottom. Nowadays, since the pond has disappeared, the present dynamic of these two soil units has to be considered. The contact between brown steppe soil and alkali soil is abrupt and shows a significant inclination from the vertical (Fig. 3). Such contact between two very contrasted soil units, from a chemical and morphological point of view, appears like a lateral transformation. The inclination of the contact suggests a downwards transformation of alkali soil into brown steppe soil by pond leaching (Fritsch et al., 1992) as an upwards alkalization, under dominant evaporation, both being controlled by Holocene climate cyclicity.

Small grey volumes are observed in the brown matrix and brown volumes are observed in the grey matrix. These volumes can be interpreted as precursors or as remnants; they do not give any information about the direction of the transformation. A decisive hint is provided by the structure and aspect of calcareous nodules (Fig. 5a,b,c; Plates 1–3). The nodules are compact and stable in the alkali soil, composed of calcite and quartz. The cortex is continuous. They are weathered in the vicinity of the contact zone and vanish in the brown steppe soil. The cortex which is observed in the brown steppe soil is discrete, relictual and indicates a degradation of these nodules along the trench. The nodules form only in the alkaline environment and are destroyed in neutral steppe soils, related with increased biological mulching. The fragmentation of the nodules is confirmed by the dissolution patterns of calcite observed near the transition zone. Intact nodules being attributed to alkali soils, this dynamic of the calcite shows a regression of alkali soils.

The detailed study of the contact demonstrates a natural transformation of alkali soils into brown steppe soils. The gap of 1 m (Fig. 9) observed between morphological transition (changes in colour, structure, compactness, Figs. 3 and 4) and geochemical transition (increase in the TDS on the 'saturated paste extract', Fig. 8) shows that the alkali soil lost its geochemical properties before acquiring the morphology of brown steppe soils. This gap shows that the transformation is today in process.

The transformation generates an abrupt boundary between alkaline and brown steppe soils. It probably results from a 'funnel effect' due to the hydrodynamic properties of the soils. At each rainfall, the water runs over the surface of the alkali soil, which is hardly permeable and then overflows the boundary, percolating into the more permeable brown steppe soil (Barbiéro, 1995).

The external boundary of this palaeo-pond is more progressive resulting from reduced percolation because of irregular high stands and/or rapid emersion after the rain.

5. Conclusion

Brown steppe soil and alkali soils are twined soil units frequently observed in the West-African Sahelian zone. A similar association was studied in the middle valley of the river Niger (in Niger Republic) to understand the origins and the present evolution of alkali soils.

The soil distribution (brown steppe soils and alkali soils) probably inherited from former mesomorphology which includes a pond, arise from two hydrological regimes in contrast. From a geochemical point of view, alkalization sets on by concentration of the soil solution, which evolves in a carbonate alkaline way, with precipitation of calcite, fluorite and probably magnesian silicates. The studied area of 'Lossa' appears representative of the regional soil alkalization story. Soil unit distribution and geochemical processes similar to the 'Lossa' site were observed in other sites, even on alluvial deposits downslope (for example 'Sona' (13°58′N 1°34′E), Guero, 1987; Bozza and Boyer, 1988; Valet, 1995).

Nevertheless, soil alkalinity induced by ponding cannot be generalised to the whole Sahelian zone. More often, the development of acid gley is observed below the Sahelian pond (Gavaud, 1977). Such differences are probably due to opposite water quality, organic matter and drainage conditions. The studied case differs from the interior delta in Mali, where a shallow water table is observed and where alkalization is in process (N'Diaye, 1987; Bertrand et al., 1993, 1994).

The 'Lossa' catchment is presently open on the alluvial valley of the river Niger and the soils are no longer in equilibrium with the local environmental conditions. The transformation of alkali soils into brown steppe soil expresses an evolution towards a new equilibrium. This natural evolution is a good model for a voluntary acceleration of the de-alkalization of some areas suitable for agriculture. This natural de-alkalization, fast at a soil formation time scale, was investigated further to improve the soils by proper management of irrigation and crop (Barbiéro et al., 1995). In spite of the natural trend towards de-alkalization, the irrigation with water of the river Niger may well lead to secondary alkalization, because of its chemical composition. The restoration of a chemical environment favouring a stable structure, is necessary for a long lasting improvement of alkali soils.

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