Soil Alkalinization and Irrigation in the Sahelian Zone of Niger II: Agronomic Consequences of Alkalinity and Sodicity

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Soils of the terraces of the Niger River have locally undergone, prior to irrigation, a process of alkalinization. The use of the resulting nonsaline sodic soils [pH_s 8.5–9.8 (s is "on saturated paste"), EC_s = 2.2–3.2 dS m^{-1}, SAR = 12–28 (mmol L^{-1})$^{1/2}$, exchangeable sodium percentage (ESP) = 5–40] is greatly limited because of their alkalinity and sodicity. The mechanisms of degradation affecting the soil physicochemical properties, the water supply, and the mineral nutrition of crops were analyzed in the Lossa irrigation scheme in the Tillabery region in Niger. Increase in pH corresponds with an increase in the compactness and decrease in the permeability of the soils. In the subsoil a threshold effect is observed for an ESP ~10 or a pH ~8.5, and the hydraulic conductivity becomes very low, ~0.05 mm h^{-1}. Reducing conditions inhibit the mineralization of organic matter, favor denitrification, and cause a deficiency in nitrogen. The simultaneous increase in pH diminishes nutrient availability and causes deficiencies in phosphorus, then in potassium and zinc, in the most alkaline soils. While maize yield is greatly affected by soil degradation, an aquatic forage grass (Echinochloa stagnina) *seems to be more adapted to these nonsaline sodic soils.*

Keywords *Echinochloa stagnina,* irrigation, nutrient availability, sodic soils

Many arid and semiarid regions of the world are affected by soil salinization and/or alkalinization. Along the Niger River the geochemical mechanisms of soil degradation by

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Arid Soil Research and Rehabilitation, 12:139–152, 1998

0890-3069/98 $12.00 + .00

alkalinization have been presented by Barbiéro et al. (1995) and Marlet et al. (1996). When the soil solution becomes concentrated, calcite, fluorite and Mg-silicate precipitate, Ca^{2+} and Mg^{2+} molalities decrease, while pH increases. Ca^{2+} desorption is accompanied by Na^{+} adsorption on the exchange complex. Increase in pH leads to chemical imbalances and deficiencies in the mineral nutrition of crops, which causes deflocculation of clays by sodization and dispersion of clays, causing pore clogging by colloidal particles (MacNeal et al., 1966; Frenkel et al., 1978; Shainberg & Letey, 1984; Suarez et al., 1984; Agassi et al., 1985; Abu Sharar et al., 1987; Sumner, 1993). The soil becomes more compact and less permeable, and anaerobic conditions may result. Few references exist on the impact of these different phenomena on the fertility of these soils, especially in the natural environment and in regard to African nonsaline sodic soils.

The aim of this article is to analyze and try to quantify the main agricultural consequences of the alkalinization on the physicochemical properties of soils and the conditions of water supply and mineral nutrition of crops on the terraces of the Niger River in the Tillabery region in Niger.

Materials and Methods

Site

The study site, Lossa, is the experimental Nigerian National Institute of Agricultural Research (INRAN) station (1354°N, 135°E) located 75 km Northwest of Niamey, on the left bank of the Niger River (Figure 1). The climate belongs to the type III semiarid climate of the African zonation (Griffiths, 1972), with a short rainy season from June to September (400 mm rainfall). During the 8 months of the dry season, dry winds blowing from the northeast arise the annual potential evapotranspiration to 2400 mm. The mean annual temperature is about 33°C, although a maximum daily temperature of ~47°C has been recorded.

The sandy clay soils arise from the weathering of substratum bedrock, a calco-alkaline gneiss with biotites. The clay mineralogy (<2-μm fraction) consists mainly of smectite and kaolinite. The amount of kaolinite varies but smectite is always dominant. Small amounts of illite are observed. The soils had undergone alkalinization and sodization by the accumulation of weathering products due to the presence of a pond in the past and under the influence of aridity (Barbiéro, 1995). Locally, the accumulation of runoff favored salt lixiviation and reduced the alkalinity and sodicity of the soils (Barbiéro & Berrier, 1994). This results in a juxtaposition of two soil types: a nonsaline sodic soil, pH_s = 8.5–9.8 (s is "on saturated paste"), electrical conductivity (EC_s) = 2.2–3.2 dS m^{-1}, sodium adsorption ratio (SAR) = 12–28 (mmol $L^{-1})^{1/2}$, exchangeable sodium percentage (ESP) = 5–40); and a brown steppe soil, pH_s < 8.4, EC_s = 0.7–2.2 dS m^{-1}, ESP = 0.5–2 (Barbiéro, 1995). The latter is much more suitable for agriculture. Under the effect of irrigation/evaporation, the soil solution becomes concentrated; an increase in pH and sodium fixation on the exchange complex are observed (Marlet et al., 1996). There are major difficulties in using the soils for agricultural purposes: they are compact and impervious, and their pH is high (from 8.4 to 9.8). After 10 years of production in the Lossa irrigation scheme, the crops had obvious difficulties in patches, which are suspected to expand from year to year.

Experimental Design and Protocol

The experiment was designed to study the variability of soil physicochemical properties and their effect on crops in relation to the degree of alkalinization. A maize crop irrigated

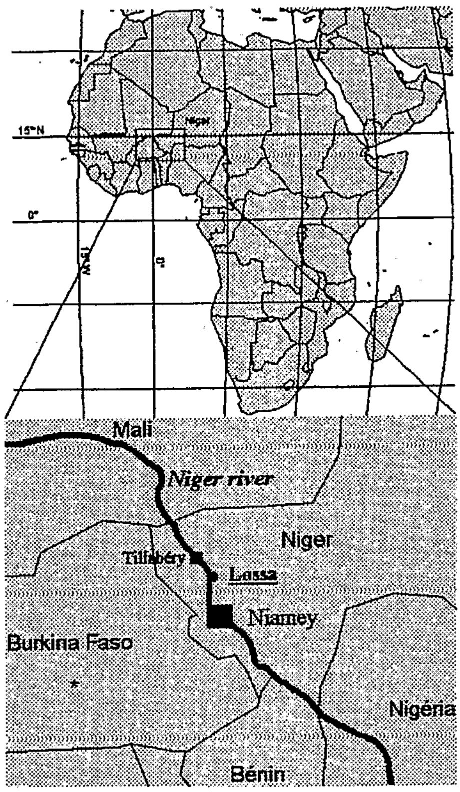

Figure 1. Location of the study area: Lossa irrigation scheme.

by furrow irrigation was compared to a burgu crop [*Echinochloa stagnina* (Retz.) P. Beauv (François et al., 1989)]. The "burgu" is a local perennial semiaquatic fodder grass. It was irrigated by flooding for 8 months. The fertilizer 90 kg N ha^{-1}, 20 kg P ha^{-1}, 37 kg K ha^{-1} for the maize crop and 180 kg N ha^{-1}, 20 kg P ha^{-1}, 37 kg K ha^{-1} for the burgu.

A 3-ha field of the Lossa station presenting sodic soil and brown steppe soil was chosen for the experiment. It was divided into 112 small plots, 96 plots of maize crop and 16 plots of burgu crop. During the fourth growing season, the dry season of 1991–1992, the yield of maize crop was calculated.

The initial characterization of the experimental field was carried out in April 1990. The method used is similar to that used by Barbiéro (1998) for the sodic soil survey along the Niger River. The soil was sampled in the center of each plot using an auger at a depth of 40 cm. The pH and EC were measured on a water-diluted 1:2.5 soil sample. The median of five repetitions is presented here. The following properties were measured: total carbon, total nitrogen, assimilable phosphorus using the Olsen method (Olsen et al., 1954), the cation exchange capacity (CEC), and exchangeable Ca^{2+}, Mg^{2+}, K^+, and Na^+ using cobalt hexamine.

The soil hardsetting in the upper 0.3 m of the soil was measured, in the same place, on dry soil using a percussion penetrometer. The method involved driving in a sharp rod by dropping a 5-kg weight from a height of 1 m and counting the number of times the 5-kg weight was dropped in order to drive the rod to a depth of 30 cm. Results are expressed in kg m^{-2} using the dutch formula (Billot, 1982)

$$RP = \frac{M^2 hn}{2(M+m)SZ}$$

where RP is the resistance to penetration (kg m^{-2}), h is the height from which the percuting weight falls (1 m), S is the section of the penetrometer (14.4×10^{-5} m^2), M is the percuting weight (5 kg), m is the weight of the penetrometer (5 kg), n is the number of hits, and Z is the penetration depth (0.3 m).

In the study site the sand and clay contents are known to be in close correlation, with a low silt content. The total sand content was measured on samples from 20- and 40-cm depths. During cultivation, redox potential and pH were measured together on five samples per plot. The samples were measured immediately after they were taken in order to avoid rapid oxidization. The median of five observations is used in the analysis. Deficiencies in the mineral nutrition of the maize plants were studied on randomly sampled plants on 11 plots 2 weeks after emergence, when the first symptoms appeared. Contents of N, P, K, Ca, Mg, S, Fe, Mn, Cu, Zn, and B in the plants were analyzed.

At the end of the experiment, infiltration was measured in the center of each plot using a buffered cylinder infiltrometer. The results were fitted to a Kostiakov-Lewis distribution using a least squares method, and the stabilized infiltration rate was calculated. The saturated hydraulic conductivity was measured using a Guelph permeameter (Reynolds & Elrick, 1985) at a depth of 40 cm.

In order to validate our results about mineral nutrition of the maize crop, applications of N, P, K, and Zn (45 kg N ha^{-1}, 16.5 kg P ha^{-1}, 50 kg K ha^{-1}, and 20 kg Zn ha^{-1}) as a supplement to the control fertilization (90 kg N ha^{-1}, 20 kg P ha^{-1}, and 37 kg K ha^{-1}) were evaluated using a block balanced design with five replications.

Results and Discussion

Soil Physical Properties

The initial data from the plots underwent a principal component analysis (PCA). The results show that the pH, EC, and resistance to penetration of the soils are closely correlated on the first axis of the PCA (Table 1). This indicates the degree of alkalinization of the soil and represents 44.3% of the total variance. The pH at 40 cm is a good indicator of

Table 1

Description of the initial state of the soils: Results of the principal component analysis (96 individuals, 7 variables)

Principal axes	Axis 1	Axis 2
Contribution to total variance (%)	44.3	23.1
Correlations between the variables and the principal axes		
Total sand at 20 cm	0.089	0.889
Total sand at 40 cm	0.169	0.886
Resistance to penetration	–0.766	0.182
pH at 20 cm	–0.820	0.072
pH at 40 cm	–0.913	0.021
Electrical conductivity at 20 cm	–0.641	–0.018
Electrical conductivity at 40 cm	–0.751	0.028

the degree of soil alkalinization. The texture, strongly correlated on the second axis of the PCA, appeared to be independent of pH and EC, whereas RP is slightly correlated with sand content. These results tally with those presented by Barbiéro (1995).

With increasing pH, a degradation of the physical properties of the soil is observed. (1) The median resistance to penetration of the upper layer is 100 kg m^{-2} for the less alkaline soils and increases up to 250 kg m^{-2} above a pH of 8.5 (Figure 2*a*). (2) The stabilized infiltration rate decreases continuously with the increase of pH. The median values vary from 1 mm h^{-1} for the most alkaline soils to 7 mm h^{-1} for low pH (Figure 2*b*). (3) The median saturated hydraulic conductivity at 40-cm depth decreases from 3 to 0.05 mm h^{-1}, which is 60 times less than for the nonsodic soils (Figure 2*c*).

These results show the considerable effect of alkalinization in degrading the physical properties of soils. Nevertheless, this degradation took different forms and intensities, depending on upper or underlying horizons. The degradation of the surface horizons appeared to be progressive and relatively low, illustrated by the evolution of the compactness (Figure 2*a*) and the stabilized infiltration rate at the soil surface (Figure 2*b*). These properties of the uppermost part of the soil can be due to alternation of drying and wetting periods, soil lixiviation, and biological activity, which improve their structure. Degradation, however, is much more important, and a threshold effect appeared for the hydraulic conductivity (HC) of the underlying horizons (Figure 3). This threshold corresponds to an ESP close to 10. Above this value, no effect of ESP on HC is detected in these data.

Soil Chemistry and Evolution of Organic Matter

The results of the analyses of the 46 soil samples were expressed according to pH, showing the intensity of the alkalinization. Only the results on evolution of organic matter (C/N) (Figure 4*a*), assimilable phosphorus (Figure 4*b*), and the exchangeable potassium (Figure 4*c*) are given.

The C/N ratio increases with the intensity of alkalinization (Figure 4*a*). This indicates that the mineralization of organic matter is much more difficult when the soil becomes alkaline, compact, and reducing. The decrease in assimilable phosphorus content seems to become more pronounced for the most alkaline pH (Figure 4*b*). Soil alkalinization, accompanied by calcite precipitation and an increase in pH, favors the evolution of phosphorus toward dicalcic and octocalcic phosphates or apatites. The evolution was linked to a severe loss of solubility. Although high sodium amounts are registered on the exchange complex, sodium in solution is too low for Na_3PO_4 formation.

The stability of potassium present when the soil solution becames concentrated indicates a geochemical control, which was noted and discussed in a previous article (Marlet et al., 1996). However, adsorption of sodium and desorption of potassium are observed for the most alkaline solutions. The control mechanism must not be interpreted as its fixation onto the cation exchange complex, but as a nonreversible fixation that is even more probable, as illites occur in the clay fraction.

The redox diagram of nitrogen (Figure 5) (Pourbaix, 1963) indicates that the redox potential of the soil is controlled by a denitrification process throughout the range of soils studied. Major losses are to be expected because of both the volatilization of ammonia nitrogen in an alkaline environment and the biological denitrification.

Mineral Nutrition of Maize Crop

The emergence of the maize plants was generally satisfactory. The first symptoms appeared about 2 weeks after emergence. The patches of infertility first became apparent by

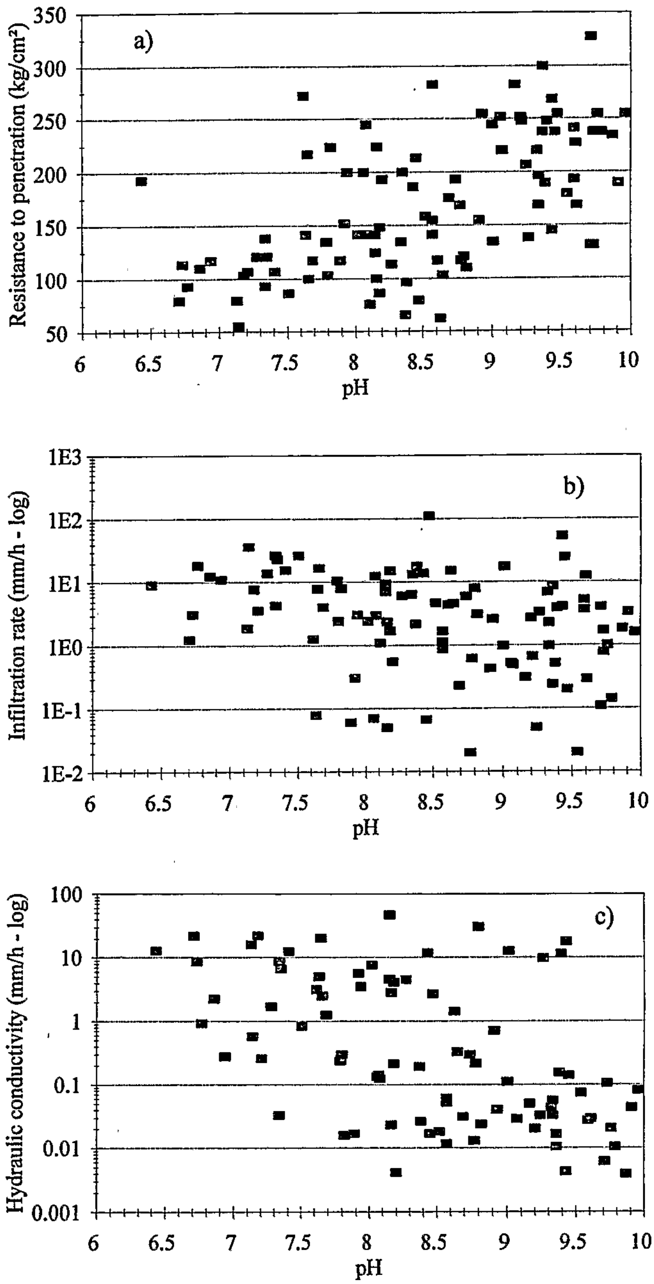

Figure 2. Influence of soil pH on the degradation of soil physical properties: (*a*) resistance to penetration of the first 30 cm, (*b*) stabilized infiltration rate, and (*c*) saturated hydraulic conductivity at 40-cm depth.

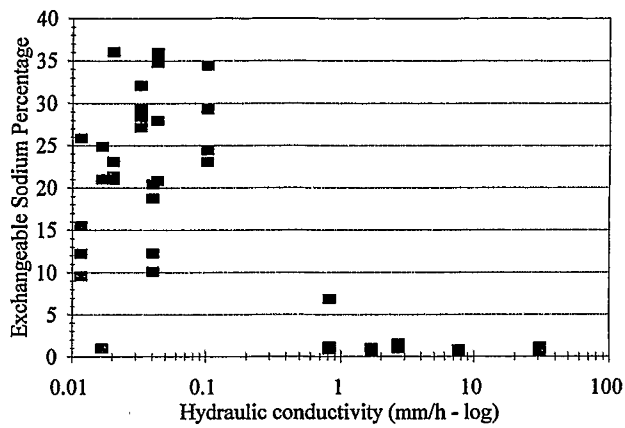

Figure 3. Relationship between the exchangeable sodium percentage and the saturated hydraulic conductivity at 40-cm depth.

the plants' reduced growth, then by a purplish coloring at the foot of the plants and main veins while the rest of the plant remained a strong green color. In places, the tip and then the edges of the leaves turned yellow and became dry. As the crop gradually grew, this symptom became more marked on the older leaves, which dried out completely and died. In the most affected areas, the plants died in a few weeks. Plants growing close to these areas had limited size, and their growth was greatly affected. Whole maize plants were sampled and analyzed as soon as the symptoms appeared. The samples were taken in a range of diverse situations on 11 plots. The mineral composition of the plants reflected the pH of the surface horizon (0–20 cm) measured at the same time, showing the intensity of alkalinization. Only N (Figure 6*a*), P (Figure 6*b*), K (Figure 6*c*), Zn (Figure 6*d*), N/P ratio (Figure 6*e*), and K/Mg ratio (Figure 6*f*) are shown. The other elements analyzed did not have any relation to the appearance of the crop or pH values in the soil.

The influence of the different N, P, K, and Zn applications (Figure 7) was assessed according to seed and straw production of a maize crop compared with the control fertilization. Despite large differences, we did not observe any significant difference between treatments because of the considerable variability of the environment.

With pH beyond 7.5, the fast decrease of P content (Figure 6*b*) and the continued increase in the N/P ratio show that phosphorus should be considered as the principal limiting factor. The symptoms of this deficiency in maize have been clearly identified in the Lossa irrigation scheme. "Bluish-green or bronze color of the foliage. The leaves of the base are the first affected and have a red or purple color. Short slender stems" (Duthil, 1973). These observations were confirmed by how strongly a maize crop reacted to a phosphorus application in low-alkaline soil conditions (Figure 7).

For the most alkaline pH, the decreases in K content (Figure 6*c*) and K/Mg ratio (Figure 6*f*) indicate a clear potassium deficiency. The expected symptoms—"short internodes and relatively long leaves. The edges and end of the leaves turn brown" (Duthil, 1973)—are consistent with our observations. In low-alkaline soil conditions, little reaction to a potassium supplement is observed (Figure 7).

Problems of nitrogen nutrition, partially covered by problems of phosphorus and potassium nutrition, still remain one of the principal limiting factors in production in these

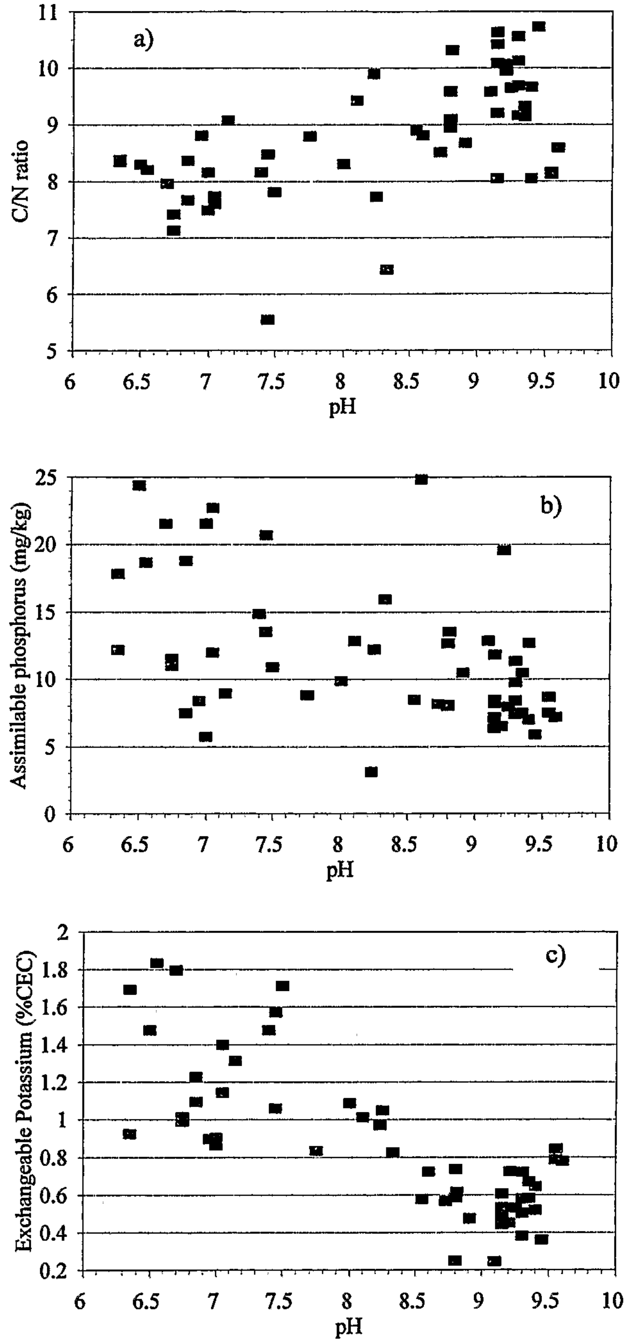

Figure 4. Influence of soil pH on the chemical properties of the soil: (*a*) evolution of the C/N ratio, (*b*) assimilable phosphorus (Olsen method), and (*c*) exchangeable potassium percent.

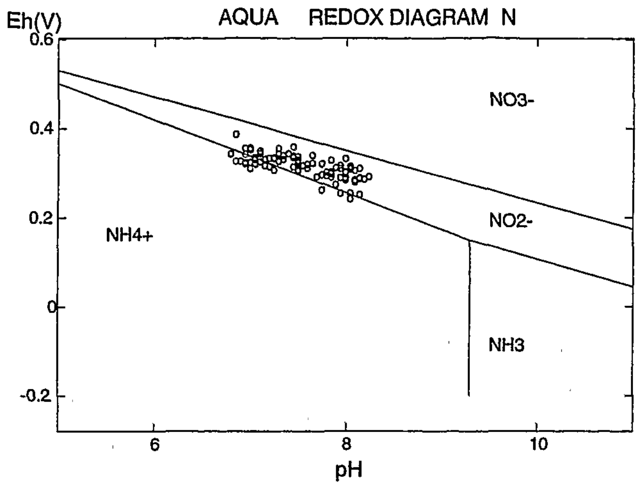

Figure 5. Eh-pH diagram (Pourbaix, 1963) for nitrogen.

soils. This deficiency is illustrated in a moderate-alkaline environment by maize's strong reaction to a nitrogen supplement (Figure 7) and in a highly alkaline environment by a reduction in the N content (Figure 6*a*).

The decrease in zinc concentrations and values lower than 16 mg kg^{-1} in the plant mean that there is probably a zinc deficiency in the most alkaline soils (Mehrotra et al., 1986) (Figure 6*d*). This deficiency is confirmed (Figure 7) by the favorable effect of applying zinc sulfate to maize crop. These observations can be explained by an expected reduction in zinc's activity as the pH increases. Under these conditions, zinc can be distinguished from other oligoelements. When alkalinization becomes intense and the physical properties of the soil deteriorate, the passage of metals other than Zn, Pb, etc., in a reduced and more soluble form partly compensates for the loss of solubility linked to the rise in pH.

Crop Performance

Under these conditions, the yield of a maize crop decreased considerably as alkalinity increased, from 2000 kg ha^{-1} under favorable conditions to less than 500 kg ha^{-1} for alkaline soils (Figure 8*a*). This seemed to be the result of numerous constraints previously identified. These include the degradation of physical properties—infiltration and redistribution of water, compactness affecting root growth, and searching for water and mineral resources—as well as the availability of the different nutrients N, P, K, and Zn.

The performance of a burgu grass crop evolved differently (Figure 8*b*). This local semiaquatic forage grass, requiring continuous submersion, seemed to be much better adapted to the least permeable soils. It showed notable tolerance to alkaline pH, which could be explained by soil reduction moderating the conditions favorable to denitrification, a dilution of the soil solution limiting alkalinity, and major development of its bunched root system, enabling it to efficiently search for mineral reserves in the soil. However, this mineral reserve is no doubt rapidly depleted because of production of dry matter of nearly 30 Mg ha^{-1} yr^{-1} (Seguin, 1986). This silage, yielding a large amount of biomass, great-

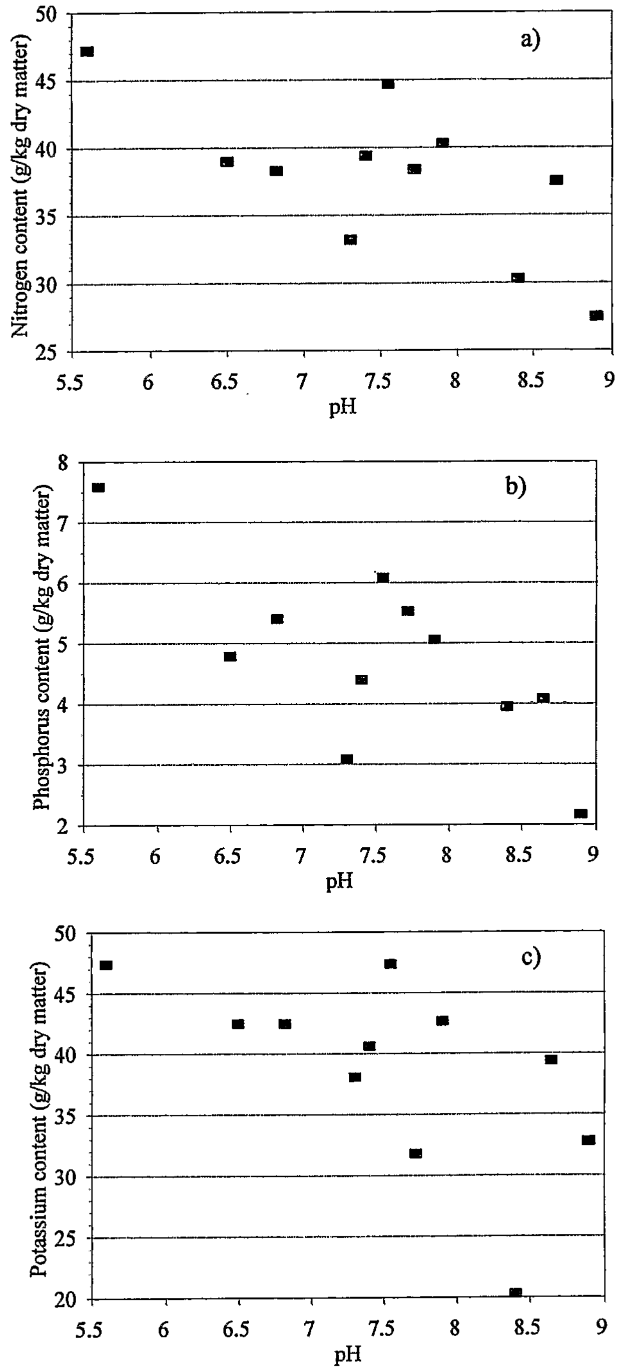

Figure 6. Influence of soil pH on the chemical composition of the maize crop: (*a*) nitrogen, (*b*) phosphorus, (*c*) potassium, (*d*) zinc, (*e*) N/P ratio, and (*f*) K/Mg ratio.

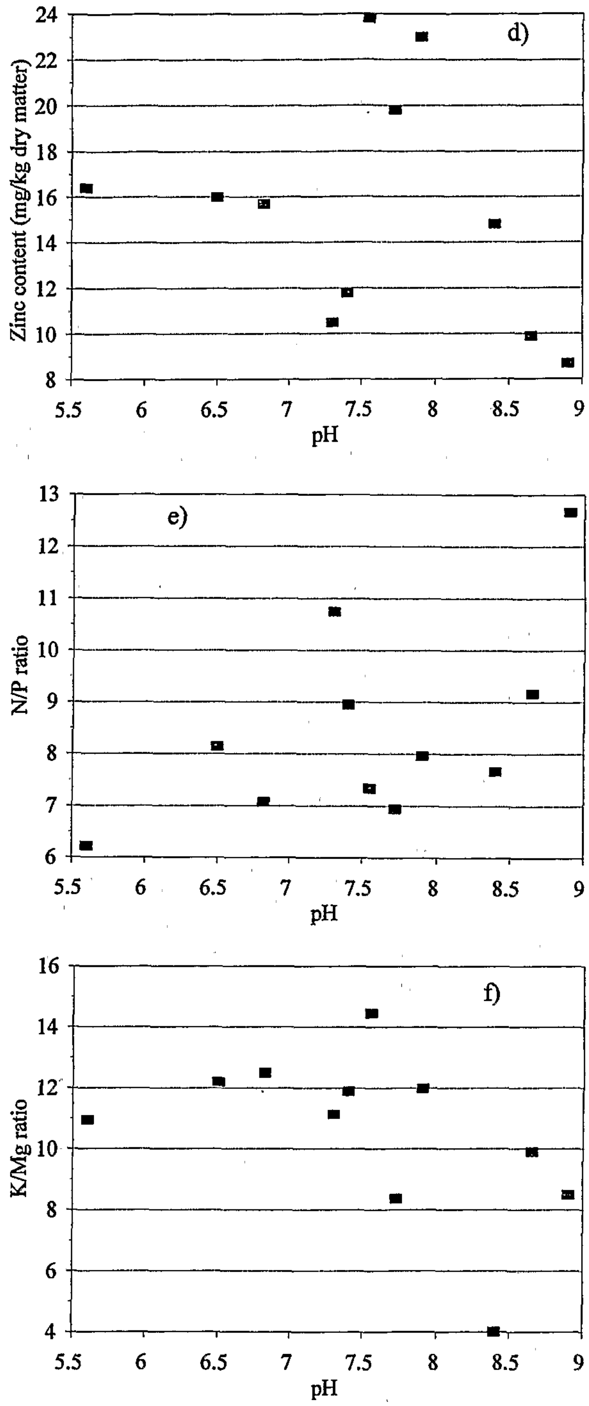

Figure 6. (*Continued*)

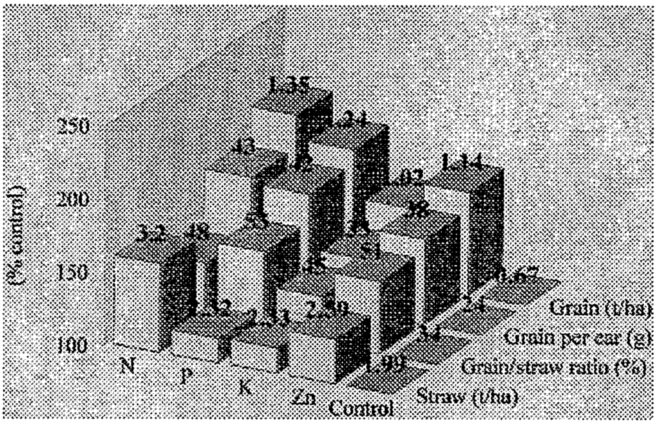

Figure 7. Influence of various amendments (N, P, K, or Zn) on the yield of a maize crop, compared to the control.

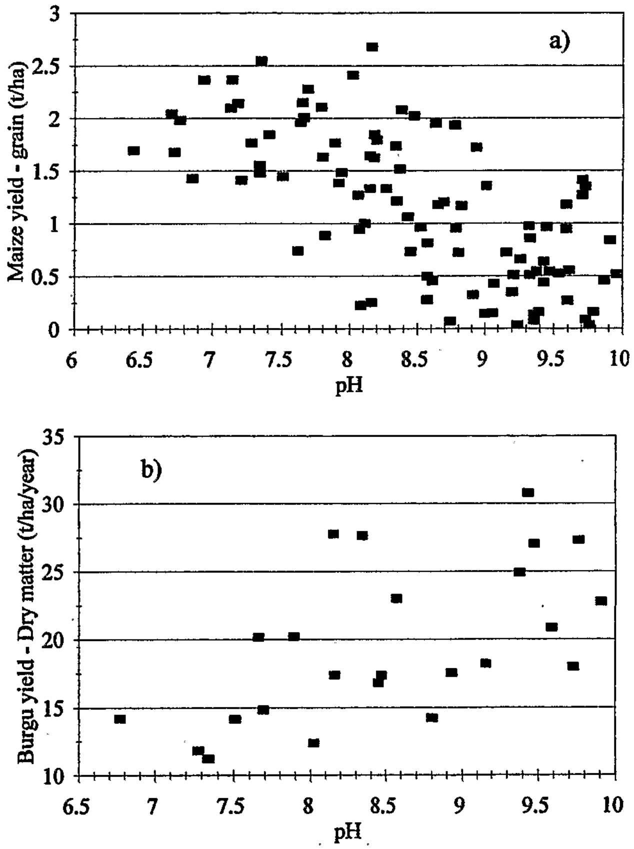

Figure 8. Influence of soil pH on crop yield: (*a*) maize (*Zea mais*) and (*b*) burgu (*Echinochloa stagnina*).

ly appreciated by the local population (François et al., 1989), could represent an interesting opportunity to develop alkalinized areas.

Conclusion

Soil alkalinization on the Niger River terraces is accompanied by a major degradation of their physical and chemical properties, which affects the water supply and mineral nutrition of the crops. It shows the influence of two interdependent phenomena. The sodization of soils accompanies a degradation of the structure. This suddenly becomes obvious when sodium comprises 7–10% of the exchange complex. It is accompanied by an increase in the compactness of soils and a decrease in infiltrability and hydraulic conductivity. These phenomena lead to the following:

- a decrease in the water supply during irrigation and rainfall (increase in runoff);
- less root growth and a decrease in the depth of wet soil, implying a decrease in easily accessible water and the capacity of crops to mobilize water and mineral reserves;
- the appearance of asphyxiating conditions, limiting the mineralization of organic matter and favoring biological denitrification of nitrogen; and
- a decrease in leaching, which can induce secondary alkalinization (Ribolzi et al., 1993).

The increase in pH resulted in certain deficiencies in N, P, K, and Zn. The deficiencies are due to an evolution of phosphorus in the form of poorly soluble compounds and to the volatilization of nitrogen, the fixation of nonexchangeable potassium, and a decrease in the activity in zinc in the most alkaline pH conditions.

The seriousness of these phenomena and their incidence on soil fertility and the evolution of soil under irrigation necessitate that different techniques be implemented, if not to improve, at least to preserve the physicochemical properties of the soils. Various physical, chemical, or biological procedures have been tested. These results will be presented in another article.

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