Preserving soil quality under irrigation in the Senegal River Valley.

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Received 16 May 1997; accepted 25 January 1998

Abstract

Soil quality under irrigation in the Senegal River Valley may become affected by salinization (Delta) and alkalinization (Middle Valley) processes. The salinity status of 158 irrigated rice fields in the Delta was measured with an electromagnetic conductivity meter (EM38). Double-cropped fields (two rice crops per year on the same field) were least saline (average horizontal EM38 reading: 0.6 dS m^{-1}), followed by single-cropped drained fields (1.6 dS m^{-1}), single-cropped non-drained fields (2.5 dS m^{-1}), non-cropped sites outside irrigation schemes (4.7 dS m^{-1}) and abandoned fields (5.7 dS m^{-1}). Results illustrated that when cultivating rice in the Delta, the ponded water on the soil surface blocks capillary rise of salt from the water table.

In the Valley, the difference in the total amount of carbonates in 1:50 soil extracts between cultivated and non-cultivated sites was used as an indicator for alkalinization risk in 27 irrigation schemes. Highest rates of carbonate accumulation (0.65 meq HCO_3^- (kg soil)$^{-1}$ cropping season^{-1}) and, therefore, greatest soil degradation risk were observed in schemes without drainage, compared to 0.10 meq HCO_3^- (kg soil)$^{-1}$ cropping season^{-1} in schemes with good irrigation and drainage facilities. Plot and scheme level recommendations that may preserve soil quality under irrigation are presented.

Résumé

Les sols irrigués de la Vallée du fleuve Sénégal peuvent être affectés par un processus de salinisation (Delta) et d'alcalinisation (Moyenne Vallée). La salinité de 158 rizières du Delta a été déterminée à l'aide d'un conductivimètre électromagnétique (EM38) ainsi que par des mesures de laboratoire à partir d'échantillons de sols. Les parcelles en double riziculture (deux cultures par an) se sont avérées moins salées (conductivité électrique EM38 moyenne de 0.6 dS m^{-1}), suivies des parcelles en simple riziculture (1.6 dS m^{-1}), des parcelles en simple riziculture non drainées (2.5 dS m^{-1}), des sols non cultivés hors de rizière (4.7 dS m^{-1}), et des parcelles abandonnées (5.7 dS m^{-1}). Les résultats obtenus mettent en évidence l'effet de la riziculture inondée, qui limite la remontée capillaire des sels depuis la nappe dans le Delta.

Dans la Vallée, la différence entre la teneur en carbonates des sols irrigués et celle des sols non cultivés de même type a été utilisée comme indicateur de risque d'alcalinisation. Les taux d'accumulation de carbonates les plus élevés, correspondant aux risques de dégradation les plus grands, ont été trouvés dans les périmètres privés non drainés : 0.65 meq HCO_3^- (kg soil)$^{-1}$ (cycle de culture)$^{-1}$, comparés à 0.16 meq HCO_3^- (kg soil)$^{-1}$ (cycle de culture)$^{-1}$ dans les périmètres disposant d'un réseau de drainage. Des recommandations pour préserver la qualité des sols irrigués, à l'échelle de la parcelle et de l'aménagement, sont données.

Keywords:
rice, irrigation, soil quality, salinity, alkalinity
Mots clés:
riz, irrigation, qualité des sols, salinité, alcalinité

Introduction

About 72,000 ha have been developed for irrigated agriculture (mainly rice, *Oryza sativa*) on the left, Senegalese bank of the Senegal river, covering Senegal River Delta, Lower Middle Valley and Upper Middle Valley (Anonymous, 1997, Figure 1). These regions together are part of what is known as the Senegal River Valley. Rice fields in the Senegal River Valley vary in size from 0.2 to 2 ha and are surrounded by bunds (0.3 m high and 0.4 m width) to keep irrigation water ponded on the soil surface. Ranked in order of decreasing development costs per ha, four types of irrigation schemes can be distinguished:

i. formerly state-controlled schemes (FSS) with generally good irrigation and surface drainage facilities (16,000 ha of which 13,800 ha in the Delta);
ii. intermediate schemes (IS) surrounded by a dike to protect the scheme from flooding, without drainage (4,200 ha, of which 630 ha in the Delta);
iii. village irrigation schemes (VIS) without drainage (18,000 ha, of which 2,750 ha in the Delta); and
iv. private schemes (PS) without drainage (33,600 ha, of which 27,500 ha in the Delta).

Figure 1.

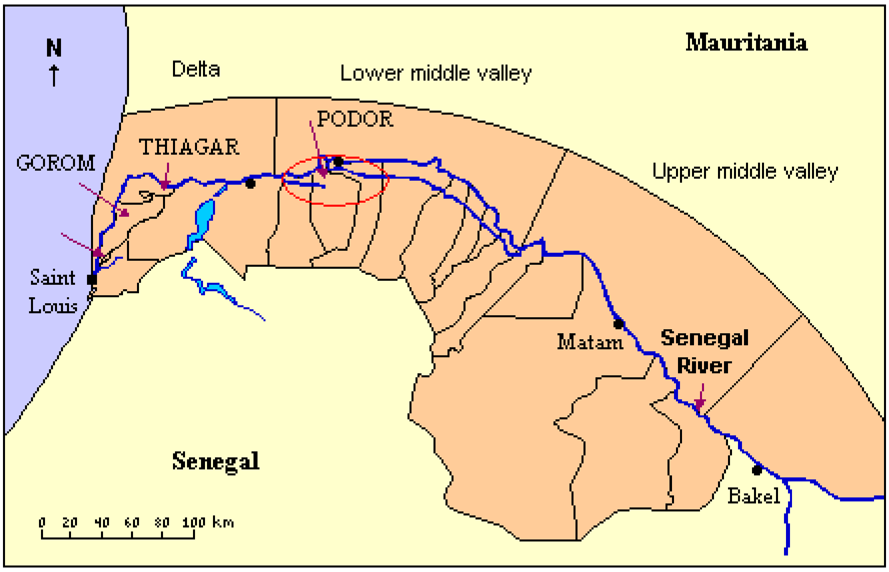

Figure 1. Map of the Senegal River Valley, showing the location of the survey sites (Thiagar, Gorom, Podor).
Figure 1. Carte de la vallée du fleuve Sénégal donnant la localisation des zones d'études (Thiagar, Gorom, et Podor).

The water of the Senegal river has a low salt content, but a positive residual alkalinity, i.e. it contains a relatively large amount of carbonate ions relative to calcium and magnesium ions. Concentration of this water may lead to precipitation of calcite, ultimately a rise in pH (alkalinization), and an increase in the soil's exchangeable sodium percentage (sodication). Soils that are relatively rich in calcium at the onset of irrigation have a certain buffer capacity against alkalinization. However, if soil leaching by the irrigation water is insufficient, and no preventive measures are taken, this buffer capacity will sooner or later run out (Boivin, 1997; Boivin *et al*., 1998).

In the Delta (Figure 1), farmers have to cope with neutral soil salinity (NaCl) due to the presence of a shallow and very saline water table (electrical conductivity exceeding 20 dS m^{-1}, Anonymous, 1990), the result of a sequence of regressions and transregressions of the Atlantic Ocean (Le Brusq, 1980). Soils are, therefore, naturally saline and generally have a good buffer capacity against alkalinization. Irrigation in the Delta, mainly remobilizes salts. Moving out of the Delta and upstream towards the Middle Valley (Figure 1), the influence of the saline water table becomes less and less pronounced and the soil buffer capacity against alkalinization decreases. Here, irrigation without protective measures, may induce severe soil degradation due to alkalinization and sodication. Soil quality under irrigation in the Senegal River Valley is, therefore, affected by a gradual decrease in natural salinization and a gradual increase in 'man-made' salinization hazard moving upstream from the Delta to the Middle Valley.

Soil degradation processes under irrigation are complex and have lead to misunderstanding, sometimes linking irrigated rice cropping directly with soil salinization (e.g. Madeley, 1993). Farmers in the Delta have mentioned soil salinity as one of the reasons to abandon double cropping (growing two rice crops per year on the same field), next to problems to obtain credit, a tight cropping calendar, and a decline in soil fertility (Ceuppens *et al*., 1997). Private, non-drained schemes in the Delta are often abandoned after a few years. Farmers either quit or move on to new areas ('shifting irrigation'). This is often blamed on salinization, as rice is grown without drainage (e.g. Le Gal, 1992; Raes *et al.*, 1992).

In the Middle Valley, problems with soil degradation have not yet been reported, but they need to be anticipated, given the poor permeability of soils under irrigation, the general lack of adequate drainage facilities, and the high evaporative demand of the air, all factors that may cause concentration of irrigation water in the soil profile. Given the positive residual alkalinity of the Senegal river water, concentration of irrigation water may ultimately lead to soil alkalinization and sodication (Boivin, 1997; Boivin *et al.*, 1998).

Preserving soil quality under irrigation requires insight in irrigation water quality, soil characteristics, cropping system, plot management practices, condition of irrigation and drainage infrastructure and groundwater table fluctuations. A range of socio-economic factors may be added to this list. For example, in Senegal, farmers do not own the land they cultivate. Effective control of soil degradation involves, therefore, interventions at plot, irrigation scheme and policy level. Control may involve measures to prevent, reverse or mitigate the effects of soil degradation. The main problem in the Delta is an excess of easily soluble neutral salts, which can be removed by surface drainage. The amount of salt in the root zone depends mainly on the depth of the saline water table. Due to the natural salinity of the Delta, mitigating measures are most appropriate. Rehabilitation of sodic, alkaline soils is extremely difficult and expensive. Control of soil alkalinization in the Middle Valley should, therefore, focus on prevention.

The purpose of this article is to:

i. illustrate the effect of cropping system and surface drainage on soil quality in the Senegal River Valley,
ii. formulate recommendations for farmers and extension agents, and
iii. target future research.

Materials and methods

The climate in the Senegal River Valley is characterized by a wet season (approximately 200-400 mm rainfall) from July to September, a cold dry season from October to February, and a hot dry season from March to June. The main rice growing season starts in July-August with harvest in November-December. Growing two rice crops per year on the same field (double cropping) requires meticulous planning by the farmer. Only 10% of rice fields in the Senegal River Valley are double cropped. Irrigation schemes are mainly located on heavy clay soil, vertic or typic Xerofluvents or typic Salorthids (Anonymous, 1975), locally known as Hollaldé or Faux Hollaldé; or on a lighter clay soil, i.e. typic Xeropsamments (Anonymous, 1975), locally known as Fondé.

Delta surveys

Two soil salinity surveys (Table 1) were conducted in the Delta using conventional sampling and laboratory techniques and a Geonics EM38 electromagnetic induction meter (McNeill, 1980a, b). Survey 1 (40 rice fields) was conducted in February-April 1995 in the 900 ha formerly state-controlled rice perimeter of Thiagar (16.25°N, 15.70°W, Figure 1) because of large scale abandoning of double cropping by the farmers. Four land use groups were distinguished: double cropping (until 1994) with drainage (DC-D), single cropping with drainage (SC-D), single cropping without drainage (SC-ND), and abandoned fields (A), because of salinity problems.

Survey 2 covered 118 rice fields and focused on private, non-drained, single-cropped schemes, which are often abandoned after only a few years. We investigated whether this 'shifting irrigation' practice is caused by a build-up of soil salinity, by comparing non-cultivated sites outside irrigation schemes (N-C) with neighboring fields under irrigation (land use group; SC-ND). The survey was conducted in the Gorom region on a 2000 ha study area (16.15°N, 16.37°W, Figure 1) in June 1996 and November 1996 (shortly after harvest of the wet season crop). Additional information on these surveys can be found in Ceuppens *et al.* (1997) and Ceuppens & Wopereis (1998).

Middle Valley survey

For this survey (Table 1), 27 irrigation schemes in the Senegal River Middle Valley were selected, i.e. 3 private schemes, 8 village irrigation schemes, 6 intermediate schemes, and 10 schemes within the large formerly state-controlled irrigation scheme of Nianga (1200 ha) near Podor (16.40°N, 15.00°W, Figure 1). In each scheme 5 cropped rice fields and 5 non-cropped sites just outside the scheme were selected at random. Soil samples were taken in November 1993 and 1994 at the end of the main rice growing season at 0-20 cm depth. These samples were analyzed for soil pH (H_2O and KCl), exchangeable sodium percentage (ESP) and total amount of soluble carbonates (titration of 1:50 soil extracts with 0.1 N HCl). Values for the total amount of soluble carbonates found for rice fields inside a given scheme were compared with those for non-cultivated sites, just outside the scheme on a similar soil type. Differences were assumed to be equivalent to the amount of carbonates accumulated as a result of irrigation. More information on this survey is given in Boivin *et al.* (1998).

Table 1. Background information on surveys conducted in the Senegal River Delta and Middle Valley. EM38 = electromagnetic conductivity meter, EC = electrical conductivity, EC_p = saturated paste electrical conductivity, PS = private irrigation scheme (no drainage), FSS = formerly state-controlled scheme (with drainage), VIS = village irrigation scheme (no drainage), IS = intermediate scheme (no drainage).

Tableau 1. Informations générales sur les zones étudiés et les suivis effectués dans le Delta et la Vallée du fleuve Sénégal.

	Survey site		
	Gorom (Delta)	Thiagar (Delta)	Podor (Middle Valley)
Type of irrigation scheme	PS	FSS	FSS, VIS, IS, PS
Production systems	Single-cropped, non-drained	Double-cropped, drained Single-cropped, drained Single-cropped, non-drained	Double-cropped, drained Single-cropped, drained Single-cropped, non-drained
Number of rice fields sampled	118	40	13
Sampling dates	June, November 1996	February-April 1995	November 1993, 1994
Measurements	EM38, EC^p	EM38, EC^p	ESP, pH (H_20 and KCl), total amount of carbonates
EC irrigation water ($dS\ m^{-1}$)	0.2	0.2	0.2
EC water table ($dS\ m^{-1}$)	> 20	> 20	highly variable

Results and discussion

Figure 2.

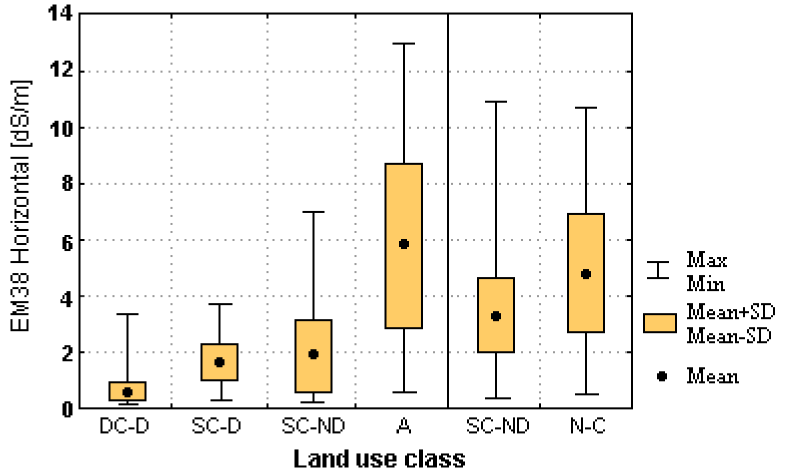

Figure 2. Box-plots of EM38 measurements (horizontal mode) in Surveys 1 (Thiagar) and 2 (Gorom) as a function of land use. DC-D = double cropping with drainage; SC-ND = single cropping without drainage; A = abandoned field; N-C= non-cultivated.

Figure 2. Box-plots des mesures EM38 en mode horizontal, de Suivi 1 (Thiagar) et du Suivi 2 (Gorom) en fonction du type de mise en culture. DC-D= duoble culture draineé; SC-D = simple culture non draineé; A = parcelle abandonée; N-C = non cultivée.

Delta surveys

Average horizontal EM38 readings per field ranged from 0.4 to 8.0 dS m^{-1} in Thiagar, and from 0.3 to 10.8 dS m^{-1} in Gorom. Both cropping system and drainage had a strong effect on soil salinity. Horizontal mean EM38 readings increased in the following order: double-cropped, drained, Thiagar (0.6 dS m^{-1}) < single-cropped, drained, Thiagar (1.6 dS m^{-1}) < single-cropped, non-drained, Thiagar (1.8 dS m^{-1}) < single-cropped, non-drained, Gorom (3.2 dS m^{-1}) < non-cultivated sites, Gorom (4.7 dS m^{-1}) < abandoned fields, Thiagar (5.7 dS m^{-1}).

Fields under double cropping were, therefore, least saline, contrary to farmers' thinking in Thiagar. Results can be explained by the ponded water layer on the soil surface when cultivating rice, which blocks capillary rise of salt from the shallow very saline water table in the Delta. Another important observation was that in Gorom, rice fields were less saline than neighboring, non-cultivated sites, indicating a beneficial effect of non-drained rice cropping on soil quality. The real reasons for the 'shifting irrigation' practice in the Delta need, therefore, further investigation.

Table 2. Saturated paste electrical conductivity, EC_p, for soil samples taken at 0-10 cm depth in Surveys 1 (Thiagar) and 2 (Gorom) as a function of land use. DC-D: double-cropped, drained fields, SC-D: single-cropped, drained fields, SC-ND: single-cropped, non-drained fields, A: abandoned fields for salinity reasons, NC: never cultivated, NotC-96: not cultivated in 1996. Any two means having a common letter are not significantly different at $P < 0.05$.
Tableau 2. Conductivité électrique de la pate saturée, EC_p, des échantillons prélevés à la profondeur 0-10 cm à Thiagar et Gorom en fonction du type de mise en culture. DC-D: Double Culture Drainée, SC-D: Simple Culture Drainée, SC-ND: Simple Culture Non Drainée, A: Parcelles Abandonnées, NC: zone Non Cultivé et NotC-96: parcelles non cultivées en 1996. Les moyennes avec un indice identique ne sont pas significativement différentes pour une $P < 0.05$.

		Dry season				Wet season			
Location	Land use class	Number of samples	EC_p mean (dS/m)		Std. Dev.	Number of samples	EC_p mean (dS/m)		Std. Dev.
THIAGAR	DC-D	28	1.31	a	1.03	-	-		
	SC-D	26	7.55	b	10.98	-	-		
	SC-ND	14	12.06	b	10.17	-	-		
	A	10	59.90	d	41.38	-	-		
GOROM	SC-ND in 96	235	14.03	b	13.41	29	4.47	a	3.50
	N-cult96	-	-			13	8.22	a	3.40
	N-Cult	12	57.40	d	36.57	18	14.28	c	8.77

Saturated paste electrical conductivity values (EC_p) showed the same trend in soil salinity as the EM38 readings (Table 2). Rice yields can be expected to decline if average EC_p > 3 to 4 dS m^{-1} (Anonymous, 1992). From Table 2, it can be seen that salinity levels in drained fields are low. Much higher salinity levels were found for single-cropped, non-drained fields in Thiagar and Gorom. These samples were, however, taken in the dry season, i.e. before the start of the wet growing season. EC_p data were much lower at harvest stage (Table 1), illustrating a beneficial effect of the ponded water layer on root zone salinity during the rice growing season. Slight yield declines due to salinity may still have occurred, as average EC_p was 4.5 dS m^{-1} (Table 1). Installation and maintenance of surface drainage facilities may, therefore, not always be worth the investment in the Delta.

Middle Valley survey

The survey in the Middle Valley focused on anticipated problems with soil alkalinization. Soil solution pH was generally higher for cropped than for non-cropped sites, but spatial and temporal variability was large. No clear relationship between ESP or pH and cropping history or type of irrigation scheme was found (data not shown). The total amount of soluble carbonates accumulated in the topsoil was closely correlated with the type of irrigation scheme and cropping history (number of years under cultivation; single or double cropping).

Accumulation of carbonates indicates that the internal drainage capacity of the soil is insufficient. This implies that irrigation water is concentrating in the soil profile, which may ultimately result in alkalinization, if the buffer capacity of the soil in terms of calcium ions runs out. The accumulation rate differed from scheme to scheme but highest values, were found for village and private schemes, which have no drainage facilities, i.e. on average 0.65 meq HCO_3^- (kg soil)$^{-1}$ cropping season^{-1}. Lowest accumulation rates were found in formerly state-controlled schemes, which have good drainage facilities, i.e. on average 0.10 meq HCO_3^- (kg soil)$^{-1}$ cropping season^{-1}.

Recommendations for farmers and farmers' cooperatives

In the Delta, soil salinity may cause severe damage to the rice crop. During the growing season relatively cheap field conductivity meters may be used to monitor flood water salinity levels in the Delta. Such equipment should be within financial reach of farmers' cooperatives. Floodwater EC measurements during critical periods (early seedling growth, reproductive phase) may avoid large yield reductions by indicating the need for renewal of the ponded water layer. In areas without surface drainage facilities and / or in areas where natural soil salinity is excessive, rice varieties tolerant to moderate levels of salinity developed by WARDA's station in Senegal can be employed. Varieties currently in use in the Senegal River Delta and Valley (Jaya, IR1529, Sahel108) are relatively sensitive to salinity (Anonymous, 1996).

Our results showed that in the absence of drainage in the Middle Valley, carbonate accumulation rates are high. The installation of surface drainage facilities to preserve soil quality in village, private and intermediate schemes is, therefore, strongly recommended. Field measures to prevent concentration of irrigation water and, therefore, soil alkalinization in the Middle Valley include: surface water drainage cycles before and during the growing season; precise leveling to avoid stagnation of water in depressions; adequate land preparation to facilitate flushing of salts from the root zone; and avoidance of drying fields by evaporation at the end of the growing season.

Recommendations for extension agency

As a follow-up on this research, technical reports in French for extension agents of the national irrigation and extension authority (Société nationale d'Aménagement et d'Exploitation des terres du Delta du fleuve Sénégal et des vallées du fleuve Sénégal et de la Falémé, SAED) to assist with salinity surveys have been prepared. The use of EM38 conductivity meters is recommended to determine salinity 'hot spots' in the Delta. These observations may guide the installation and/or need for maintenance of surface drainage facilities. Likewise areas requiring additional flushing before crop establishment may be identified in that way. A cost-benefit analysis is required to weigh installation or maintenance costs of drainage facilities against benefits of increased rice yield.

Water table depths should be closely monitored in the Delta. A network of piezometers is in place, a large percentage of which is still operational (authors' unpublished data). No measurements have been taken since 1989. Re-use of the piezometer network is especially urgent if the water height in the Senegal River were to be increased from 1.75 to 2.5m, to irrigate Delta schemes by gravity instead of by pumping. The impact of such an increase in hydraulic head on water table depth and corresponding soil salinity should be investigated at scheme and regional levels.

Growing rice on relatively permeable Fondé soil should be discouraged, as this may lead to a rapid increase in water table depth. Double cropping of rice may be promoted on Hollaldé and Faux-Hollaldé soil.

Recommendations for future research

Development of measures to prevent the water table from rising into the root zone is a research priority. Installation of subsurface drainage systems to drain the water table artificially is not a realistic option as it is too expensive and risky due to the presence of reduced mangrove deposits in the subsoil (especially in the Delta). Upon oxidation these deposits become highly acid (Raes & Deckers, 1993). Instead, planting trees may help to control water table depth. Good results have been obtained in Australia, where *Eucalyptus* trees lowered water tables by 1-2 m in 10 years (Bari & Schofield, 1992). Research is needed to investigate if this would be an option in the Delta. The few remaining acacia trees in the lower Delta are usually in bad shape, most probably due to salt stress.

Crop diversification, use of green manure, lime, gypsum, acidifying fertilizers etc. may be effective in reversing and preventing soil alkalinization (e.g. Ghassemi *et al.*, 1995). There is an urgent need to test such agronomic options under Sahelian conditions. Valuable work in this area has already been done in the Office du Niger in Mali (Ndiaye, 1996).

Existing simulation models need to be validated to help develop alternative low-cost land and water use systems for the Senegal River Valley, preserving soil quality under irrigation. Such alternative land and water use systems should avoid concentration of irrigation water in the field, while maintaining the water table at a depth well below the root zone. Simulation models are needed that can simulate e.g. the impact of perimeter size, distribution of major soil types, water management, and density of trees on groundwater table fluctuations. WARDA and NARS of the region are currently installing simple soil and water quality monitoring systems (piezometers, periodic soil sampling and analyses) in key irrigation schemes in the Sahel. Data from these monitoring systems give insight in soil degradation rates and can be fed directly into simulation models, for validation purposes and to predict future trends as a function of current and alternative land and water use scenarios.

Conclusions

In the Senegal River Delta, soils are affected by natural salinization due to capillary rise of salts to the soil surface from a saline water table. Rice farming reduced this natural salinity, even if conducted without drainage. Strongest reduction was obtained in surface-drained, double-cropped fields. Given its importance on soil salinity, water table levels in the Delta need to be monitored. In the Senegal River Middle Valley, soil alkalinization hazard as measured by the accumulation rate of total soluble carbonates in the topsoil, was highest in non-drained schemes. Irrigation without drainage in the Middle Valley should be discouraged, as soil alkalinization and, ultimately soil sodication may lead to an almost irreversible decline in soil quality. Recommendations for farmers, extensionists and future research were formulated.

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Acknowledgements

Part of this research was supported by the Federal Ministry for Economic Cooperation (BMZ) through the German Agency for Technical Cooperation (GTZ) and the European Fund for Development (FED). The research project Gestion de l'Eau is financed by the Belgian Agency for Development and Cooperation (ABOS). We thank D. Sagna (WARDA) and M. Diouf (WARDA) for assistance with lab and field work.