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# Soil quality and rice productivity problems in Sahelian irrigation schemes

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# ABSTRACT

In irrigation schemes in the Sahel, rice yields and cropping intensity are still far from their potential and some of the 10–20 year old irrigation schemes experience declining yields. The large investments in irrigation infrastructure, made to improve food security, to generate income, and to reduce rice imports, are currently at stake. Many farmers and researchers suggested that the rice productivity problems might (partly) be due to salt-related soil degradation. Sahelian irrigation waters contain little salt, but are relatively rich in carbonates ($RA_{calcite} > 0$). In the hot and dry Sahelian climate, irrigation with such waters could lead to the formation of an alkaline (high pH) and sodic (high sodium content) soil, which has a low productivity. We investigated the causes of declining rice productivity in the irrigation schemes of Foum Gleita (Mauritania) and the Sourou Valley (Burkina Faso). We found that rice productivity problems in Foum Gleita were primarily caused by N and P deficiency, while Zn deficiency prevailed in the Sourou Valley. These nutrient deficiencies were caused by no or insufficient application of N, P and Zn fertilizers, in combination with low plant available N, P and Zn in the soil. The alkaline-calcareous nature of the studied soils likely contributed to the low availability of N through volatilization, and low availability of P and Zn through precipitation of or adsorption onto carbonate minerals. Application of ample N, P and Zn fertilizer increased yields at the study sites from 3–4 t $ha^{-1}$ to 5–6.5 t $ha^{-1}$. However, the required chemical fertilizers are often expensive or not available on the local markets, which hampers adoption of improved fertilizer recommendations by the resource-poor Sahelian rice farmers. Application of organic amendments (a.o. rice straw) at a rate of 5 t $ha^{-1}$ often improved yields at the study sites by 1–2 t $ha^{-1}$. In Foum Gleita, the yield increasing effect was attributed to improved N availability, while in the Sourou Valley, organic matter amendments improved Zn uptake.

Although rice productivity problems correlated with the alkaline-calcareous nature of the soil, we found no evidence that irrigated cropping increased the alkalinity of these soils. On the contrary, this study and literature sources indicate that alkalinity problems were inherited from the parent material and/or from the prolonged cultivation of non-flooded crops. At the study sites in Mauritania and Burkina Faso, concentration factors of irrigation waters are small (< 6). Moreover, detailed study in Foum Gleita showed that clayey rice soils seem to have a large buffer capacity against alkalinization. Adsorbed $Ca^{2+}$ at the exchange complex is desorbed with increasing salt concentrations in the soil solution, which leads to a decrease in soil solution alkalinity through precipitation of calcite. In addition, irrigated rice largely prevents the build-up of alkaline salts in the soil root zone through proton excretion. In a soil column trial, using soils from Foum Gleita and the Office du Niger (Mali), we found that irrigated rice cropping can be used to reclaim alkaline-sodic soils, provided some (natural) drainage is possible. These findings are in line with recent literature on changes in soils under flooded crops in Mali and Niger. Rice straw amendments accelerated the reclamation processes on soils that contained calcite. Anaerobic decomposition of straw increased $pCO_2$, dissolution of calcite, and consequently $Ca^{2+}$ in the soil solution. The $Ca^{2+}$ exchanged with adsorbed $Na^+$ and the latter was leached together with (bi)-carbonates.

Reduction of iron hydroxides could theoretically lead to ferrolysis and acidification of the upper horizons, but we found that the process was of little importance to the short term alkalinity changes of the studied soils.

# CONTENTS

# 1 GENERAL INTRODUCTION

## 1.1 Irrigated rice cropping in the Sahel

Rice is a crop with a long history in West-Africa. Traditional rice cropping using African rice (*Oryza Glabberima* Steud.) dates back 4500 years (WARDA, 1999). This traditional rice cropping was rainfed and was practiced in the Sudanian and Guinean climate zones (precipitation > 900 mm yr$^{-1}$) in both upland and lowland conditions. At present, the traditional rice-growing areas still account for most of the rice produced in West Africa, but the African rice varieties have been largely replaced by Asian rice varieties (*Oryza Sativa* L.), which have a higher yield potential and are also used for irrigated rice cropping.

Irrigated rice in West-Africa has a much younger history and is mainly limited to the Sahel (250–500 mm yr$^{-1}$) and Sudano Sahelian zone (500–900 mm yr$^{-1}$). Irrigated rice cropping became widespread by the 1970–1980s, after devastating droughts lead to crop failure and massive loss of cattle in the Sahelian countries. With the assistance of international donors, massive investments were made to establish large irrigation schemes (100–60.000 ha) along the borders of the main Sahelian rivers and their tributaries. Land in the schemes was often divided among the local population. Most farmers obtained between 0.5–2.0 ha, depending on family size. The objectives of these irrigation schemes were: (i) to improve food security during periods of drought, and (ii) to meet the growing demand for rice in the Sahelian countries. The increase in rice demand was particularly needed due to a rapid growing urban population. Still, the majority of the Sahelian countries have to import most of their rice, placing pressure on the limited foreign exchange resources (Reardon et al., 1997).

Irrigated rice production in the Sahel accounts for a relatively large share (17%) of the total rice production in West Africa on a relatively small fraction (7%) of total rice cultivated area (WARDA, 1999). The potential yield for irrigated rice in the Sahel is 5–12 t ha$^{-1}$, depending on season and site (Dingkuhn & Sow, 1997; Wopereis et al., 1999; Haefele, 2001). This high potential is due to the Sahelian climate, which is ideal for rice cropping; the minimal cloud cover allows for high radiation and the dry climate reduces the presence of pests and diseases. However, extreme temperatures (< 18°C or > 35°C) can result in cold or heat related spikelet sterility and lead to empty grains and yield losses up to 100% (Dingkuhn et al., 1995). To avoid cold- or heat-related sterility, farmers in the Sahel have to follow a strict cropping calendar.

Irrigated rice in the Sahel can be grown in both wet (± July−November) and dry season (± January–June). However, most farmers prefer the wet season. With the exception of Niger, only a small minority (< 15%) of Sahelian rice farmers practices double cropping (Dancette, 1999). This results in low cropping intensities both at field, scheme and regional level. There is not only a low cropping intensity at field, but also at a region level. For example, in the Senegal River valley, 70,000 ha have been developed for irrigated agriculture, of which 60,000 could be used immediately without major rehabilitation costs (Haefele et al., 2002). However, only between 20,000 and 28,000 ha are currently being used on an annual basis. Under-utilization of the irrigation schemes is attributed to several reasons, such as: poor social cohesion between farmers within a scheme (e.g., ethnic differences, caste systems, financial fraud), few agricultural contractors for soil tillage and pump maintenance, seasonal price fluctuations for paddy rice, difficulties reimbursing and obtaining credits, and competition with other income-generating activities (e.g., flood-recessive agriculture, small business, emigration). Apart from under-utilization of the irrigation schemes, total rice production in the Sahel has fallen short of expectations due to low yields (Donovan et al., 1999). Average yields are around 4–6 t ha$^{-1}$ (Haefele et al., 2002). The relatively large yield gap (i.e., potential minus actual yield) has often been related to sub-optimal crop management such as: absence of soil tillage, late sowing, late transplanting, low fertilizer doses, late timing of fertilizer application, insufficient weeding, the absence of drainage two weeks after flowering, and late and prolonged harvest (Wopereis et al., 1999; Diallo et al., 1999; Haefele et al. 2000, 2001 and 2002; Poussin and Boivin, 2002; Poussin et al., 2003). Haefele et al. (2000, 2001, and 2002) showed that improved fertilizer and weed management can increase yields by 1–2 t ha$^{-1}$ to about 6–7 t ha$^{-1}$. Diallo et al. (1999) combined improved cropping practices at the field level with a better (water) organization at scheme level and found that average yields increased from 4.2 to 7.2 t ha$^{-1}$. Many researchers (e.g., Wopereis et al., 1999; Diallo et al., 1999; Haefele et al. 2000, 2001 and 2002; Poussin and Boivin, 2002; Poussin et al., 2003) suggested that sub-optimal crop management was caused by lack of technical knowledge, limited access to credit and inputs, poor seed quality, late harvest of the previous season, difficulties selling the harvest of the previous season, late payment of the water fees, lack of (family) labor, poor functioning of farmer cooperatives and poor coordination of water management at the scheme level. Kebbeh and Miézan (2003) showed that the extent to which farmers are able to adopt improved crop management options is directly related to the degree of resource endowment.

Prior to the construction of the irrigation schemes, most farmers did not have any experience with irrigated rice cropping. Many of them were cattle holders, while others practiced rainfed or flood-recessive agriculture. The majority of the large irrigation schemes in the Sahel received technical backstopping from national extension services. In the first years after construction of the schemes, most of these extension services also organized inputs, credits, milling and marketing of the rice, and maintenance of the scheme. This approach was rather top down, with little decision freedom at the grassroots level (D'Aquino et al., 1999). During the last 10 years, the international donor community has increased pressure on state authorities to gradually disengage themselves from the daily management of the schemes and to transfer it to farmer organizations. This transition did not often bring the increase in long-term productivity that was hoped for. Farmer organizations often do not account for maintenance of the schemes, resulting in degradation of infrastructure and sometimes abandonment of the scheme (Legoupil et al., 1999). The lack of maintenance has often been attributed to the fact that the land of the irrigation schemes is state-owned, which makes farmers hesitant to invest in long-term maintenance (Diop Diagne et al., 2002).

Although irrigated rice production in the Sahel did not live up to the high expectations of donors and Sahelian governments, there seems little alternative for the hundred thousands Sahelian families that directly depend on irrigated rice for their income and food security. The good news is that in most Sahelian schemes, yields have increased over the last few decades due to improved crop management practices. For example, in the Senegal River valley, yields increased from an average 1.5 t $ha^{-1}$ in the 1970s to 4.6 t $ha^{-1}$ in the 1990s (la Société d'aménagement et d'encadrement du Delta de la Vallée du fleuve Sénégal -SAED-, unpublished). In Mali, yields increased from around 2 t $ha^{-1}$ in the mid-eighties to around 5 to 6 t $ha^{-1}$ nowadays, most notably due to a transfer from direct-seeded to transplanted rice, which reduced weed competition at early crop growth stages (Poussin and Boivin, 2002). However, during the last 10 years soil salinity and alkalinity problems were increasingly reported in many of the Sahelian irrigation schemes. The threat of salt-related soil degradation was rapidly worrying farmers, researchers and policymakers, as it could jeopardize the future of the Sahelian irrigation schemes. An overview of salt-related soil degradation problems in the Sahel is given in section 1.4, but first we will present a general overview of salt-related soil degradation processes and their interaction with irrigated rice cropping in sections 1.2 and 1.3, respectively.

## 1.2 Salt-related soil degradation processes

Three types of salt-related soil degradation occur in the Sahel, these are: (i) salinization, (ii) alkalinization and (iii) sodication. All processes are the result of (temporary) accumulation of salts in the soil. Natural accumulation of salts occurs mainly in dry climates where evapotranspiration exceeds precipitation in combination with restricted drainage. In the Sahel, potential evapotranspiration exceeds 2000 mm $yr^{-1}$, with a precipitation of less than 900 mm $yr^{-1}$. Human-induced salt accumulation can occur in irrigation schemes, when poor quality irrigation water is used, or when capillary rise from poor quality groundwater occurs as a result of an irrigation-induced rise of the groundwater table.

Salinization refers to the build up of pH neutral salts consisting mainly of $Na^+$, $Cl^-$ and $SO_4^{2-}$ ions. A soil is classified saline, following USDA classification, if the saturated soil paste has an electrical conductivity of 4 dS $m^{-1}$ (Richards, 1954). These soils are named ‘Solonchaks’ in the FAO classification (Driessen and Dudal, 1991). The adverse effect of high Na-salt content on plant growth is related to osmotic stress and $Na^+$ toxicity. Saline soils can rapidly form (i.e., in a few months to years) if irrigation water quality is poor, or if saline groundwater can reach the root zone through capillary rise. The reclamation of such soils is based on the leaching of excess salts with low saline irrigation water. Provided that natural or artificial drainage is possible, desalinization of the root zone can be a rapid process (i.e., in a few weeks to months).

Alkalinization refers to the build up of carbonate salts ($HCO_3^-$ and $CO_3^{2-}$) in combination with relative high levels of $Na^+$. The alkalinity of a solution is equivalent to the acid neutralizing capacity determined by titration with acid down to a pH of about 4.5. It can generally be considered equal to the sum of $HCO_3^-$ and $CO_3^{2-}$ in equivalents per liter solution ($mol_c\ l^{-1}$). The accumulation of carbonate salts results in the precipitation of calcite. If the alkalinity of a solution exceeds the $Ca^{2+}$ concentration, than such a solution has a positive calcite residual alkalinity ($RA_{calcite}$ = Alkalinity – $Ca^{2+}$ in $mol_c\ l^{-1}$) (Valles et al., 1991; Bertrand et al., 1993). The concentration of a $RA_{calcite}$ positive solution eventually leads to a depletion of $Ca^{2+}$ and an accumulation of $Na^+$ and $CO_3^{2-}$. Such a solution has a high pH (> 8.5) and a high $Na^+$ concentration in combination with a low $Ca^{2+}$ concentration, which leads to a high exchangeable sodium percentage (ESP), especially in the B-horizon. The increase in pH is often referred to as ‘alkalinization’, while the increase in ESP is often referred to as ‘sodication’. A soil with an ESP larger than 15% is classified sodic (or alkali), following USDA classification (Richards, 1954). Such soils are named ‘Solonetz’ in the FAO classification (Driessen and Dudal, 1991). Alkalinization eventually leads to the formation of a sodic soil. However, sodic soils can also develop in soils with low carbonate content, when $Na^+$ concentrations are (temporarily) high. Even when such (temporarily) saline-sodic soils are leached with a solution containing very little salt, the ESP can remain high (Van Uffelen, pers. comm.). A high ESP can lead to the collapse of the soil structure through dispersion of clay particles, especially if the soil solution contains little salt. Such a sodic soil hampers plant growth due to its low permeability and massive soil structure (Abrol et al., 1988). A high pH results in nutritional imbalances, mainly of N, P and Zn (Abrol et al., 1988).

The formation of alkaline-sodic soils is slow (i.e., some tens of years) and difficult to observe by the farmer. Reclamation of alkaline-sodic soils is possible but very difficult and time consuming. It is based on the leaching of excess exchangeable sodium and (bi)carbonate ions. However, the leaching is often very slow, as water movement through the soils is greatly inhibited by the degraded soil structure. Qadir et al. (2001) provided an extensive literature overview of common reclamation practices. These include: leaching without amendment application to ameliorate gypsiferous sodic soils, leaching with high electrolyte water containing divalent cations, using chemical amendments, using organic amendments, modifying the soil profile through tillage, surface flushing of low-permeability soils where vertical leaching is not efficient, passing electrical current through soils, and growing salt-resistant crops to ameliorate calcareous sodic soils through phytoremediation. Among these methods, chemical amendments (e.g., gypsum, calcium chloride, acids) are considered very effective in most conditions and are, therefore, extensively used worldwide. However, chemical amendments are often expensive and the high initial investment needed is often prohibitive (Qadir et al., 1996). This appears especially true for irrigated rice cropping in the Sahel, where profits are often small (Donovan et al., 1999) and chemical amendments not readily available. For the Sahelian farmers, phytoremediation, in combination with improved water and organic matter management seems to be the only way to reclaim alkaline-sodic soils. However, the best strategy is probably to develop crop and land management practices that would prevent alkalinization and sodication from occurring in the first place.

## 1.3 Rice cropping on saline and alkaline-sodic soils

Although rice is not very tolerant to excess salinity, it is often used to reclaim saline soils when irrigation water with a low salt content can be used (Abrol et al., 1988). Irrigation with such water rapidly leads to the leaching of salts from the first centimeters of the soil. This desalinized zone is sufficient for the rice crop to grow without salt stress, due to its shallow rooting depth (± 0.2 m). The continuous flooding favors the leaching of salts from the soil profile, especially if drainage is available.

On alkaline-sodic soils, irrigated rice cropping offers some unique advantages over non-flooded crops. Rice is moderately to highly tolerant for growing in sodic soils with an ESP up to 20 to 40% (Pearson, 1960). Due to its limited rooting depth, the rice plant avoids much of the adverse physical properties of the sodic B-horizon. For non-flooded crops, the presence of a sodic B-horizon prevents adequate deep rooting and largely reduces water availability for the plant. However, water availability for rice growing in a pounded water layer is never a problem. Therefore, if rice performs poorly on alkaline-sodic soils this is most likely caused by alkalinity-induced N, P, and Zn nutrient deficiencies and not by the sodicity-induced deterioration of the soil structure. The low permeability of sodic soils is even considered an advantage to rice, because water losses due to deep percolation are restricted (Abrol et al., 1988).

McNeal et al. (1966) found that rice cultivation indirectly facilitates the removal of exchangeable sodium through leaching by increasing the cross-sectional area of conducting pores, resulting in increased permeability. The drop in ESP is further enhanced by the anaerobic conditions in the flooded soils. Upon flooding, the $CO_2$ pressure increases, resulting in a decrease of the pH to around 7 (Ponnamperuma et al., 1966). Proton excretion by plants also helps to acidify the root zone (Barbiéro et al., 2001). The decrease in pH enhances the dissolution of native calcite (if present), thereby increasing the $Ca^{2+}$ concentration in the soil solution (Chhabra and Abrol, 1977). The dissolved $Ca^{2+}$ exchanges with $Na^{+}$ adsorbed on the exchange complex, thereby decreasing the ESP. The decrease in pH also improves the availability of P and Zn. Abrol et al. (1988) concluded that its relative shallow and superficial root system, its high alkalinity-sodicity tolerance and its reclamative action make rice an ideal crop during reclamation of sodic soils.

## 1.4 Salt-related soil degradation in the Sahel

Saline soils are found in the Sahel's coastal areas, most notably in the Senegal River delta (Figure 1.1). The sediments of the Senegal River delta were deposited during a sequence of regressions and transgressions of the Atlantic Ocean. The marine origin of the deposits rendered the groundwater saline (Loyer, 1989). During the wet season, water tables rise to <1 m at many sites, resulting in potentially high upward fluxes of salt (Ceuppens et al., 1999). In the mid-nineties, irrigated-rice farmers in the Senegal River delta increasingly complained about soil salinity. The abandonment of poorly designed schemes without drainage facilities suggested that irrigated rice contributed to the salinization of these soils. However, Ceuppens et al. (1997) and Ceuppens and Wopereis (1999) showed that the soil salinity levels decreased with increasing rice cropping intensity. The presence of drainage facilities further contributed to a lowering in soil salinity levels. The positive effect of rice cropping is related to the low salt concentration ($0.07 > EC < 1.24$ dS $m^{-1}$; Haefele, 2001) of the irrigation water. Alkaline-sodic soils are found throughout the Sahelian zone. Earliest reports of alkaline sodic soils came from the Office du Niger in Mali (Bertrand et al., 1993). During its 70 years of existence, the groundwater levels in the inland river delta rose from 45 m depth initially to less than 3 m depth (Ndiaye, 1999a). Initially, cotton was the major crop grown, but its large-scale cultivation was abandoned in the 1970s (Barral, 1997). Currently 90% of the 60,000 ha are used for rice cultivation. Capillary rise from the alkaline sodic groundwater caused alkalinization of the initially slightly acidic soils (Ndiaye, 1999a). In the early 1980s, a large part of the scheme was restored and drainage facilities increased (Marlet, 1999a). As a result, alkalinity of the clayey soils used for rice cropping decreased slightly, but increased in the adjacent coarse-textured soils that were mostly used for vegetable cropping (Marlet, 1999a). In Niger, alkaline

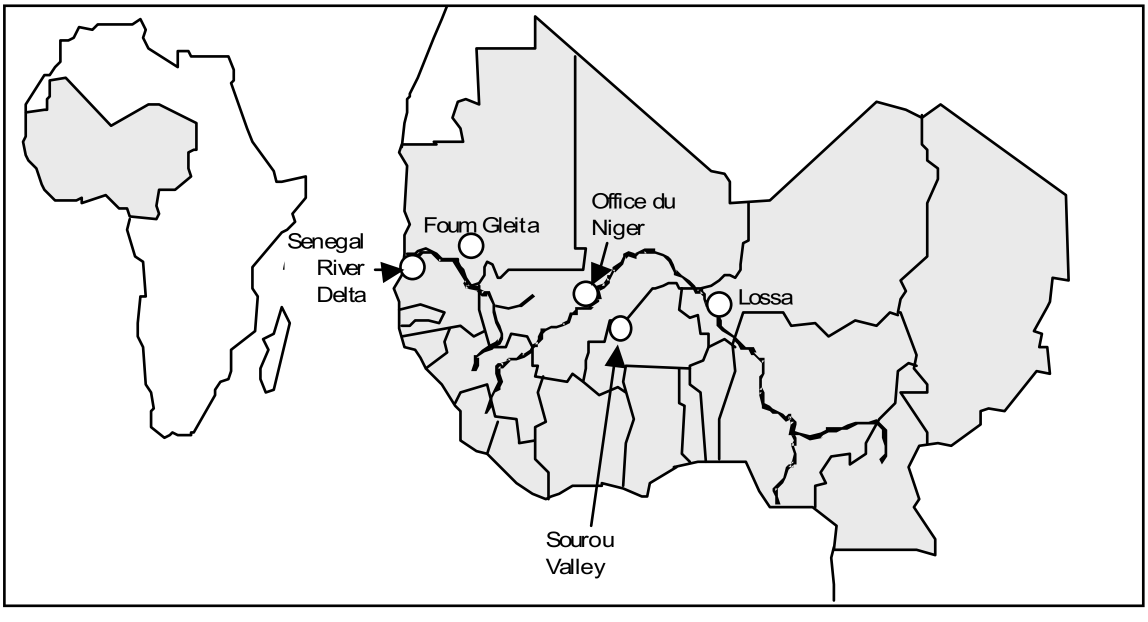

*Figure 1.1: Map of West Africa depicting the Sahelian irrigation schemes where salt-related soil quality problems have been reported or are suspected.*

sodic soils were found on the terraces of the river Niger, in particularly in the Lossa irrigation scheme and part of the Sona irrigation scheme (Bertrand et al., 1993). Barbiéro and Van Vliet-Lanoe (1998) found that the alkalinization and sodication was no longer occurring, and that the salts originated from the underlying bedrock.

So far, little is known on the relationship between soil alkalinity, soil fertility and rice yield loss in the above mentioned schemes (Bruckler, 1999). Marlet (1999b) reported that yields progressively decreased when *in situ* pH values increased above a pH 7.0–7.5 threshold value in the Office du Niger scheme. They suggested that it might be related to increased volatilization losses. Despite the little evidence of actual yield decrease caused by ongoing alkalinization, the ‘doom scenario’ of massive degradation of the Sahel’s irrigated rice schemes gained rapid popularity during the mid-nineties. National and international scientists in Senegal, Mauritania, Mali and Niger spend increasingly more time on the quantification of the alkalinization threat. A large part of the research was conducted by the French backed-up network ‘Pôle Systèmes Irrigués’. Within this network, a total of 10 West-African and 5 French scientists worked on the soil degradation issues from 1996 to 2000 (Legoupil, 1999). Their work mainly focused on the Office du Niger in Mali, the Senegal River valley in Senegal, and the Lossa scheme in Niger. One if their major findings was that over the last 20 years, irrigated rice cropping has not lead to any significant increase in soil pH or ESP in all of the studied schemes (Marlet, 1999a). Only where non-flooded crops were cultivated on more sandy soils, signs of ongoing alkalinization and sodication were observed. Marlet (1999a) concluded that observations of salt efflorescences in the Office du Niger (Mali) initially led to excessive alarming messages. Later on, these salt efflorescences proved to be caused by fossil neutral salts and not by ongoing alkalinization as a result of concentrating irrigation water.

## 1.5 Scope and outline

Despite the lack of substantial evidence of ongoing alkalinization and sodication of irrigated rice soils in the Sahel, it is still commonly believed that the positive $RA_{calcite}$ of the Sahelian irrigation water poses a threat to the sustainability of the Sahelian irrigation schemes (e.g., Boivin et al., 2002, Ndiaye, 1999b). Therefore, care has to be taken when productivity and soil quality problems are reported in the Sahelian irrigation schemes that might indicate ongoing alkalinization and sodication.

Farmers of two Sahelian irrigation schemes reported problems with salt-related soil degradation, only five to ten years after construction of the schemes. In Foum Gleita, Mauritania, average wet season yields dropped from 4.6 t $ha^{-1}$ in the early years (1985–1991) to 3.8 t $ha^{-1}$ between 1992 and 1999 (Société Nationale de Développement Rural -SONADER-, unpublished data). Similarly, average annual yields in the oldest sections of the Sourou Valley scheme in Burkina Faso dropped from 5.7 t $ha^{-1}$ in 1991 to yields between 2.2 and 4.4 t $ha^{-1}$ from 1995 onward (Autorité de Mise en valeur de la Vallée

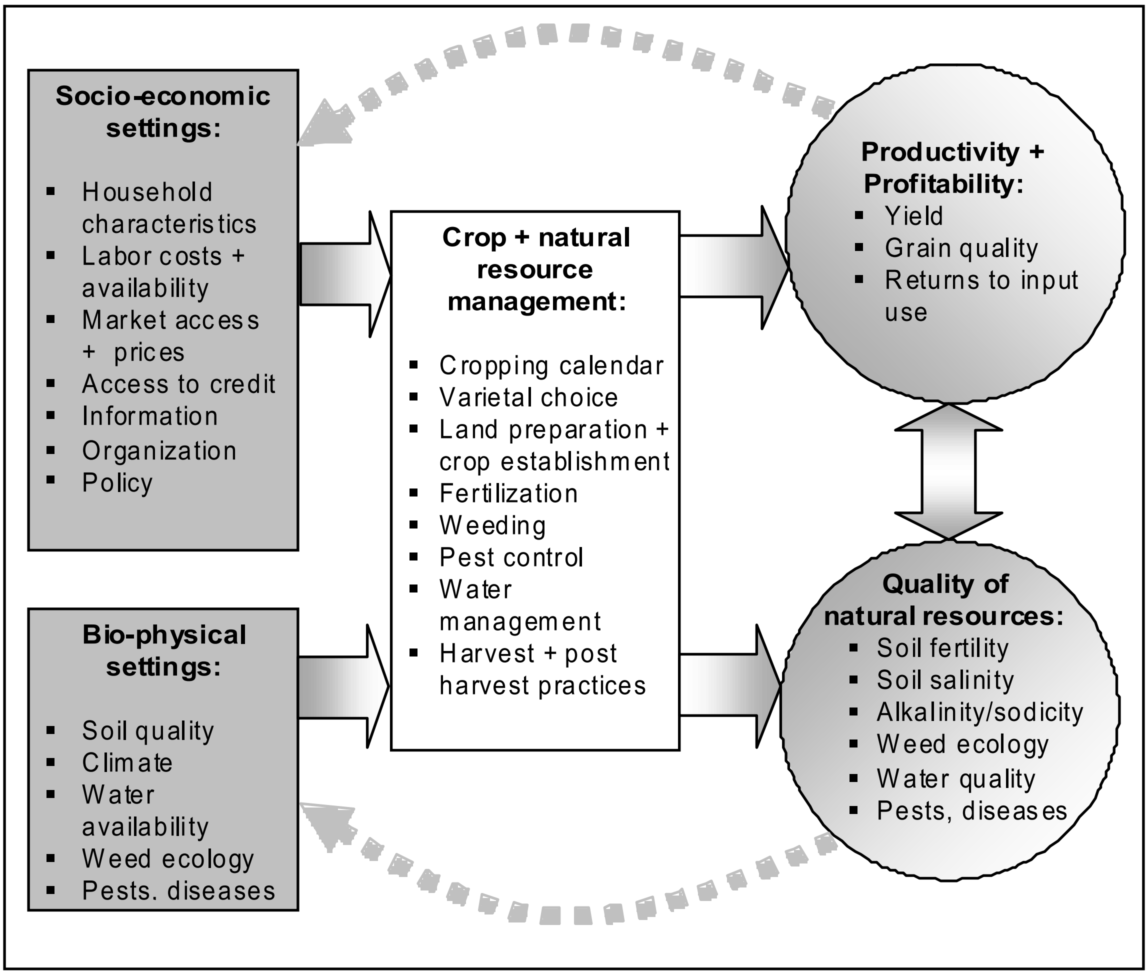

*Figure 1.2: Interdependency of socio–economic and bio–physical settings, farmers choice of crop and resource management, productivity and profitability o the production system, and quality of the natural resources.*

du Sourou -AMVS-, unpublished data). Farmers related their yield decline to salt efflorescences on the soil surface, but little was known about the salinity and alkalinity of their soils and the actual reasons for the observed yield decline. The farmer observations provoked the following research questions:

(i) Are declining yields in these Sahelian schemes indeed caused by salt-related soil degradation, as farmers suggest, or are low yields related to sub-optimal crop and land management?
(ii) If soil salinity or alkalinity is a problem, then what is the source and geographic distribution of these (alkaline) salts?
(iii) What are the potential changes of these soils under current and alternative crop management practices?
(iv) Can improved crop and natural resource management options be developed to improve yields and reverse or mitigate salt-related soil quality problems that fit both the local biophysical and socio-economic settings?

These research questions cover a large part of the rice production context as shown in Figure 1.2. This figure shows that farmer crop and natural resource management are determined by the socio-economic and biophysical settings. The crop and natural resource management directly affect the productivity and profitability, as well as the quality of the natural resource base, which again has direct impact on yield. One could say that in one cropping season, the flowchart is passed from left to right. At the end of the season, the productivity and profitability, and changes in the quality of the natural resource base affect the socio-economic and bio-physical settings for the following season (represented by the dotted arrows). The flowchart shows that farmers risk ending up in a vicious circle, whereby poor crop and natural resource management (e.g., lack of fertilizer, drainage, etc.) result in low yield and a decrease of the quality of the natural resource base (nutrient depletion, salt accumulation), which creates financial difficulties for the following season and further decreases the quality of crop an natural resource management practices.

The first research question "Are rice productivity problems caused by salt-related soil degradation and/or sub-optimal crop and land management?" is discussed in Chapters 2 and 3. Chapter 2 focuses on rice productivity problems in Foum Gleita, Mauritania, while Chapter 3 deals with rice productivity problems in the Sourou Valley, Burkina Faso. In both studies, we combined the results of workshops, farmer surveys, farmer-managed trials and researcher-managed trials to identify the major cropping constraints and to identify short-term solutions that can be adopted by farmers. In Chapter 4, we take a close look at the potential role of improved organic matter management as a means to improve yields and nutrient availability in Foum Gleita.

The second en third research questions, dealing with the distribution, the origin of salt-related soil degradation and changes under current and alternative crop and land management, are treated in Chapters 5 and 6. Chapter 5 looks in detail at the actual distribution of salts in the Foum Gleita landscape and combines it with a geochemical modeling exercise aimed at quantifying the potential changes of the degradation processes. In Chapter 6, we take a close look at the effect of irrigated rice cropping in combination with organic matter amendments on the alkalinity of alkaline soils in Foum Gleita, Mauritania, and in the Office du Niger, Mali.

Partial answers on the fourth research question "Can improved crop and natural resource management options be developed that can be adopted by resource-poor farmers without significantly increasing production costs?" are provided in Chapters 2, 3, 4 and 6. General conclusions on the combined results of these Chapters are provided in Chapter 7.

# 2 EXPLAINING YIELD GAPS ON FARMER-IDENTIFIED DEGRADED AND NON-DEGRADED SOILS IN A SAHELIAN IRRIGATED RICE SCHEME

*P.J.A. van Asten, M.C.S. Wopereis, S. Haefele, M. Ould Isselmou, M.J.Kropff*

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Farmers in an irrigation scheme in southern central Mauritania experienced declining rice yields, and within a decade after its construction 12% of the scheme's land has been abandoned. Actual yields (≤ 4.0 t $ha^{-1}$) are low compared with potential yield (ca. 8 t $ha^{-1}$) and yields elsewhere in the Sahel (4–6 t $ha^{-1}$). Farmers related the productivity problems to salt efflorescences on the soil surface. Rice yields on the 'upper and middle slope' soils were low (3.4 t $ha^{-1}$) when compared to yields on soils further down slope (> 4.2 t $ha^{-1}$). Farmers classified the 'upper and middle slope' soils as degraded, but the soils could not be classified saline nor sodic following USDA classification. Low yields on the 'degraded' soils are related to co-limitation of N and P, due to low soil N supply (± 18 kg $ha^{-1}$), low soil P supply (± 8 kg $ha^{-1}$), occasional low N fertilizer doses (35 kg N $ha^{-1}$) in combination with low N fertilizer recovery efficiency (0.3 kg $kg^{-1}$), and non-application of P fertilizer. On the 'non-degraded' soils, soil P supply (± 16 kg $ha^{-1}$) is higher and N-deficiency prevails, despite higher soil N supply (± 32 kg $ha^{-1}$) and N fertilizer recovery efficiency (0.4 kg $kg^{-1}$). Higher contents of carbonate salts in the 'degraded' soils increase soil pH (> 7.5) and are, therefore, likely to contribute to low soil P supply and low N fertilizer recovery efficiency.

**Keywords** *Oryza sativa* L., alkalinization, crop management, boundary line analysis, Mauritania

## 2.1 Introduction

Over the last 20 years, irrigated rice cropping (*Oryza sativa* L.) has been introduced on a large scale in the Sahel. The justification of the massive investments in irrigation infrastructure was to improve food security, but currently the focus has shifted more towards economic sustainability and income generation. However, actual rice yields remain well below the anticipated levels (Matlon et al., 1996), and declining yields have been observed in some irrigation schemes. Several authors (Wopereis et al., 1999; Haefele et al., 2000; Rigourd et al., 2002) showed that timing of several cropping practices (sowing, transplanting, weeding, fertilizer application) was often late and fertilizer dose too low, resulting in large yield gaps (potential minus actual yield). In addition, soil alkalinization has often been mentioned as a (potential) production constraint jeopardizing sustainable rice yields in the Sahel (Bertrand et al., 1993; Boivin, 1995; Boivin et al., 2002). However, up to date, there have been few studies investigating the effect of soil alkalinity on rice yields in the Sahel.

Rice cropping in the Sahel requires large amounts of water due to the high evapotranspiration in the hot and dry climate. Sahelian irrigation water contains little dissolved salt but often possesses a positive residual calcite alkalinity ($RA_{calcite}$ = Alkalinity – $Ca^{2+}$ in $mol_c\ l^{-1}$) (Valles et al., 1991; Bertrand et al., 1993). Concentration of such waters in the soil root zone may lead to the formation of an alkaline (high pH) and sodic (high sodium content) soil. Such a soil is less productive because of the pH-induced low availability of several plant nutrients (e.g., N, P, Zn), and the poor physical properties of the sodic horizon (Abrol et al., 1988).

In this study we will focus on the irrigation scheme of Foum Gleita, Mauritania, which is one of the many typical large (> 1000 ha) Sahelian irrigation schemes. The scheme covers 1950 ha and was built between 1985 and 1989. Plans to extend the irrigation scheme to 3600 ha have so far not been materialized, partly because of productivity

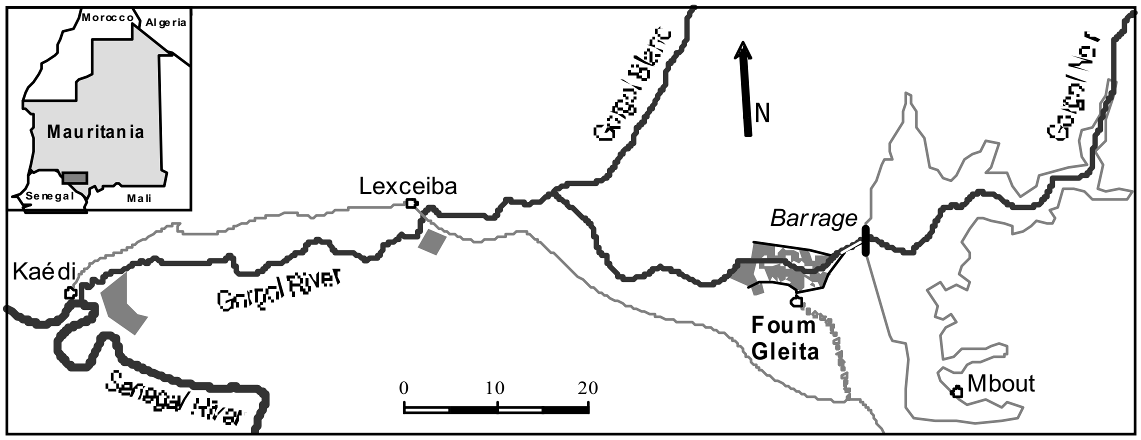

*Figure 2.1: Map showing the location of the Foum Gleita barrage and irrigation scheme within the Gorgol River catchment, some 80 km upstream of Kaédi, Mauritania.*

problems. The main crop is rice, cultivated in both the wet and dry season. Average wet season yields dropped from 4.6 t $ha^{-1}$ in the first years (1985–1991) to 3.8 t $ha^{-1}$ between 1992 and 1999, while the cropped area decreased from 95% to 60%. Dry season yields increased from 2.2 t $ha^{-1}$ to 3.2 t $ha^{-1}$ during the same period, but the cropped area remained relatively unimportant (25%). The Foum Gleita yields are below the 4 to 6 t $ha^{-1}$ range observed in most Sahelian irrigation schemes (Wopereis et al., 1999; Haefele et al., 2000; Rigourd et al., 2002). Since the installation of the Foum Gleita scheme, farmers increasingly complained about declining yields and by 1993 about 12% of the area had been abandoned (SONADER, 1998). Farmers related their production problems to salt efflorescences on the soil surface and considered soils affected by this problem to be degraded.

The $RA_{calcite}$ of Foum Gleita irrigation water varies between 0.5 and 1.2 mmol $l^{-1}$, which is up to three times higher than $RA_{calcite}$ values reported by Marlet et al. (1998b) and Boivin et al. (2002) for the Niger and Senegal River, respectively. If alkalinization through concentration of irrigation water is an ongoing process in Sahelian irrigation schemes, then it is likely to be more rapid in Foum Gleita than elsewhere. Hence, the appearance of alkalinity problems at this site could be an early warning for what might happen later in other Sahelian irrigation schemes.

The objective of this study was to identify to what extent rice productivity problems are caused by soil quality problems (with emphasis on soil alkalinity) on the one hand and sub-optimal crop management on the other hand. We monitored yields and management practices in farmer fields and compared them to model predictions on optimal management and potential yield. We used the boundary line approach to compare the impact of both soil quality and management practices on yield. In addition, researcher nutrient omission trials were conducted to asses the soil fertility and yield potential.

## 2.2 Materials and methods

### Site description

Some 500 $Mm^3$ water are retained behind the Foum Gleita dam (16°08'N, 12°46'W) in central southern Mauritania (Figure 2.1), allowing gravimetric irrigation to arable land downstream. The climate in Foum Gleita is typically Sahelian with erratic rainfall (ca. 250 mm $yr^{-1}$) in the wet season (July–October), followed by a short cool period (November–February) with minimum daily air temperatures as low as 10°C and a hot dry season (March–June) with daily maximum air temperatures up to 46°C. Annual reference evaporation is 2700 mm $yr^{-1}$. The landscape around Foum Gleita is characterized by the presence of small rock outcrops (schist, quartzite) and large slightly sloping (< 2%) barren plains, which drain their surface runoff in small valleys. Shallow

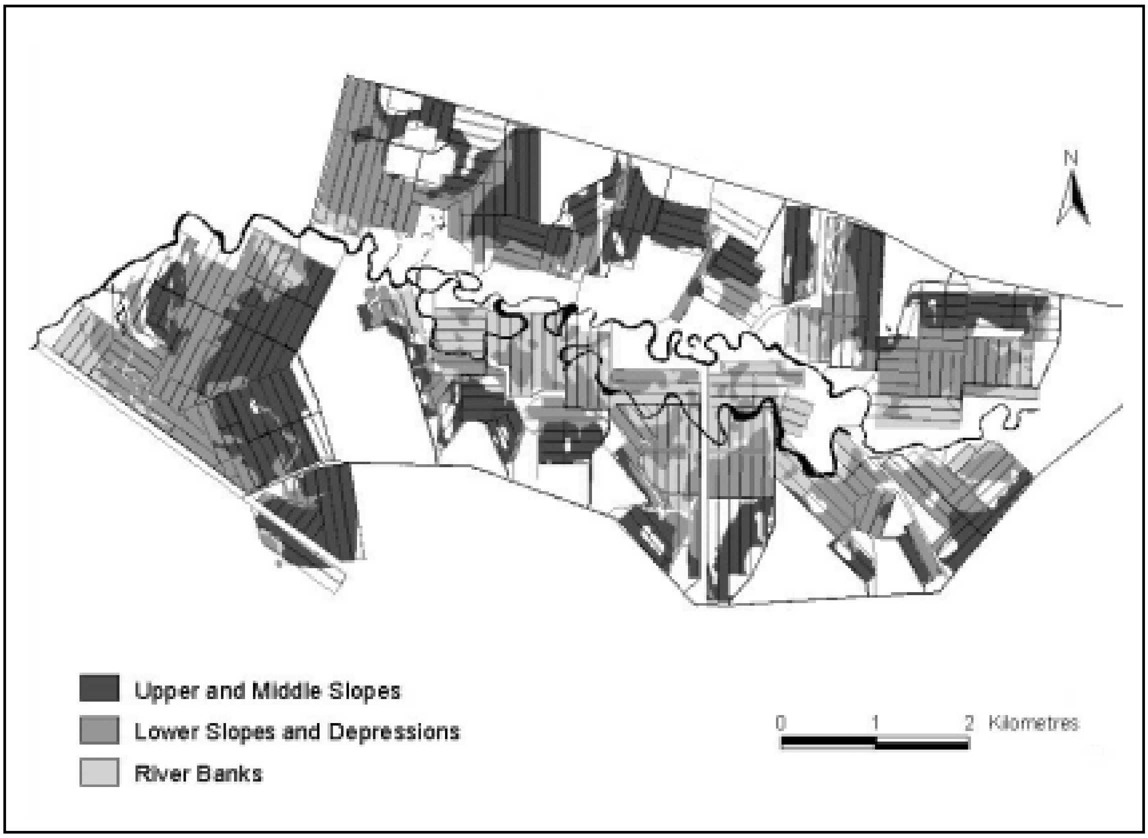

*Figure 2.2: Foum Gleita irrigation scheme infrastructure and geomorphologic map (adapted from BCEOM, 1986)*

soils (< 1.2m) have formed *in situ* from the schist parent material on the upper and middle slopes. Alluvial deposits increase soil depth (1.2–4 m) on the lower slopes, depressions and river banks (BCEOM, 1986) (Figures 2.2 and 2.3). Soil texture is silty clay loam to clay loam and shows little vertical and horizontal variation. Land in the newly constructed irrigation scheme was distributed amongst the local population. Farmers obtained between 0.5 and 1.5 ha, depending on family size. The majority of the people were semi-nomadic cattle holders and unfamiliar with rice cropping practices.

### Potential yield and optimal timing of agronomic practices

Potential yields, limited by solar radiation and temperature only, were estimated using the ORYZAS model (Dingkuhn and Sow, 1997) for transplanted rice (variety Jaya) in the wet and dry season. The Rice Development model (RIDEV) (Dingkuhn, 1997) calculated the percentage of spikelet sterility due to cold or heat stress at flowering. Furthermore, RIDEV gave predictions on growth duration and timing of phenological stages of the rice crop, which were used to derive optimal timing of transplanting, N fertilizer application, drainage and harvest. Input weather data for both RIDEV and ORYZAS simulations were from Foum Gleita (1989–1993) and Matam (1972–1982), located 70 km southwest of Foum Gleita.

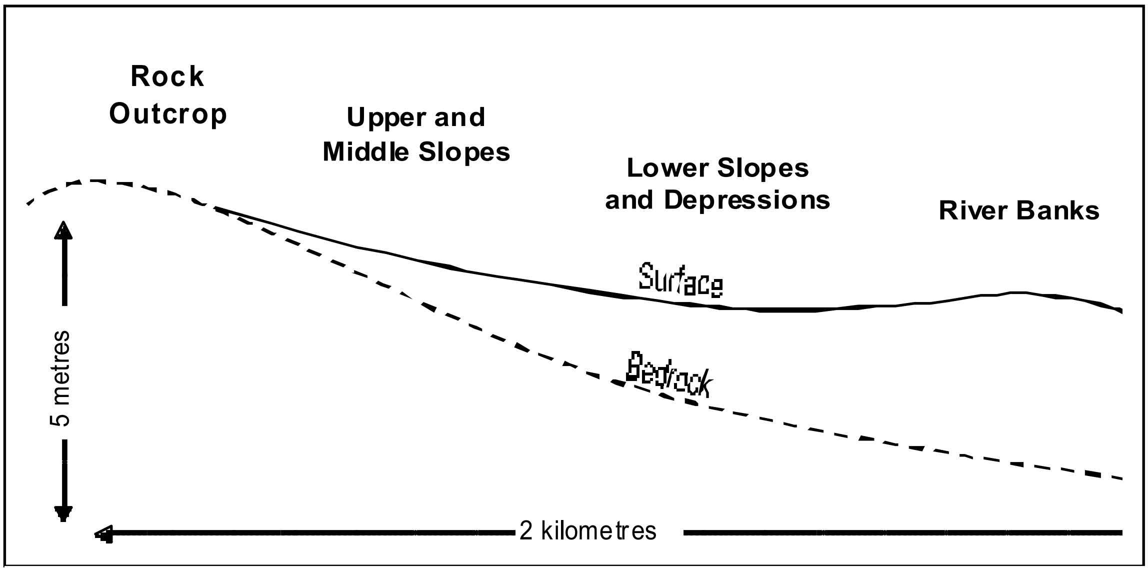

*Figure 2.3: Schematic cross section and corresponding geomorphological units of the Foum Gleita landscape.*

Farmer surveys and farmer trials

Sixty farmers distributed throughout the irrigation scheme volunteered to participate in surveys and trials before the start of the 1998 wet season. Participants were asked to establish in their field a special plot (10m x 10m) that received no fertilization, but was otherwise managed as usual by the farmer (T0 plots). The rest of the field was managed by the farmer, including fertilization (TF). Farmer surveys were repeated with another group of 33 farmers during the 1999 dry season, but no farmer trials were conducted.

Both plant and soil samples were analyzed from the 1998 farmer trials. Flag leaf samples were taken at heading for P analysis. Grain yields were measured from a 6 $m^2$ area harvested in each T0 and TF plot at maturity. Grain yields were corrected to 14% moisture content. Harvest index was determined from oven-dry (3% moisture content) straw and grain weight of a 12-hill sub-sample. Concentration of N in grain ($N_{GRAIN}$) and straw ($N_{STRAW}$) at maturity were determined using the Micro-Kjeldahl method (Bremner, 1996). Plant phosphorus concentrations ($P_{GRAIN}$ and $P_{STRAW}$) were measured using the method described by Yoshida et al. (1976). Soil N supply was estimated from total N uptake in T0 plots. Recovery efficiency for applied N fertilizer (REN) was based on the difference in N uptake between T0 and TF. A composite topsoil sample (0–0.2 m) was taken from each T0 plot before the onset of the growing season. These samples were analyzed for pH and pH-KCl in a 1:2.5 paste, EC in a 1:5 paste, P-Olsen and P-Bray1. Exchangeable cations ($Ca^{2+}$, $Mg^{2+}$, $K^+$, $Na^+$) were determined using an atomic adsorption spectrophotometer (AAS) after extraction with ammonium chloride. Cation exchange capacity (CEC) of the samples was determined as described by Chapman (1965). Exchangeable sodium percentage (ESP) was calculated using exchangeable $Na^+$

and CEC. The Walkey-Black method (Nelson and Sommers, 1996) was used to determine %C. Total N was determined using a macro version of the Kjeldahl method modified to include nitrate and nitrite using thiosulfate (Dalal et al., 1984). Descriptive statistics for both crop management and soil properties and correlation coefficients (Pearson bivariate correlation) with respect to TF and T0 yield were calculated, using SPSS software for Windows 10.0.

During a workshop, farmers indicated the location of farmer-identified degraded land on a map of the irrigation scheme. As these lands were mainly situated on the upper and middle slope units of the BCEOM map (1986), major soil and crop management variables of the 1998 farmer trial were classified according to topographic position; i.e., (i) upper and middle slope, (ii) lower slope and depressions, and (iii) river banks. Means for soil and crop data according to geomorphological class were compared with the Newman-Keuls test using the STATISTICA software.

### Boundary line analysis of the farmer-managed trials

The boundary line approach was used to obtain a semi-quantitative estimate of the contribution of both crop management and soil properties to T0 and TF yield gaps. This approach was first described by Webb (1972). The principle is that the upper limit of points in a scatter diagram delineates the response of the dependent variable (TF and T0 yield) to a particular independent variable (soil and crop management) if other variables are not limiting. The approach was first employed to determine critical values of nutrient balances in plant diagnostic models (Møller-Nielsen and Frijs-Nielsen, 1976; Frasor and Eaton, 1983; Walworth et al., 1986). Later the approach was used to describe the relationship between soil nutrient concentrations and yields (Evanylo and Summer, 1987; Evanylo, 1990).

Standardized, statistically sound methods for constructing boundary lines are still lacking (Schmidt et al., 2000). Chambers et al. (1985) used hand drawn lines. Casanova et al. (1999) and Schmidt et al. (2000) used an approach, in which they split the data set into equidistant groups (8 to 10 sections on the x-axis), after which they calculate boundary points as the upper 95% or 99% percentiles. A regression line was then fitted through the boundary points of each group. Considering the semi-quantitative objective of our study and the relative limited amount of cases, a simpler procedure was used here. The upper points were manually selected in a scatter diagram, after which a regression line (linear, logarithmic or polynomial) was fitted. Only soil and crop management variables that had a correlation coefficient $\geq 0.3$ with T0 and TF yields were taken into account. The resulting boundary functions for selected soil and crop management variables were used to calculate the maximum attainable T0 and TF yields for each farmer and for each variable. This procedure allowed identifying the most limiting variable and the corresponding maximum attainable yield for each farmer. Comparison of all limiting variables resulted in an estimate of the relative importance of both soil quality and crop management with respect to productivity problems in Foum Gleita. The difference between potential and actual yield (i.e., yield gap) can largely be explained using the boundary line approach. However, if the maximum attainable yield exceeds the actual yield, then this difference can be called the non-identified yield gap (Cassanova et al., 1999). The non-identified yield gap gives an idea of the explanatory value of the approach; a large non-identified gap indicates that other important variables have not been taken into account.

### Researcher-managed nutrient omission trials

Researcher-managed nutrient omission trials were conducted in the 1998 wet season, the 1999 dry season, and the 2000 dry season at two sites that were identified by farmers as degraded (DG) and non-degraded (NDG). According to the BCEOM map (1986), the DG trial site is located on the upper slope and the NDG trial site on the lower slope.

The rice variety IR-13240-108-2-2-3, in Mauritania known as Sahel 108, was used. The trial consisted of the following six fertilizer treatments replicated four times: (T0) no fertilizer added; (T1) N, P, K and Zn; (T2) as T1, but no N; (T3) as T1 but no P; (T4) as T1 but no K; (T5) as T1, but no Zn; The total N fertilizer (urea) dose was 175 kg ha$^{-1}$, divided in three split applications (40% three weeks after sowing, 40% at panicle initiation and 20% at heading). P, K and Zn were applied before transplanting (basal application); P fertilizer dose was 26 kg ha$^{-1}$ in the form of triple super phosphate (TSP), K fertilizer dose was 53.8 kg ha$^{-1}$ in the form of KCl and Zn fertilizer dose was 5.5 kg ha$^{-1}$ in the form of ZnO. In the 1999 and 2000 dry season, no Zn was applied to any of the treatments, due to non–availability. In the 2000 dry season, only the T0, T1 and T3 of the nutrient omission trials were repeated. The number of replications was reduced from four to three. Individual plot size was 5m x 5m. Estimation of yield and determination of plant nutrient uptake, soil nutrient supply and fertilizer recovery efficiency were similar to the methods used in the farmer trials. Concentrations of Zn and K in the straw were measured in a 1N HCl extract using an AAS (Yoshida et al., 1976). Fertilizer recommendations for N and P were developed for the DG and NDG soil, using a 6.0 t ha$^{-1}$ target yield and taking into account the average soil N and P supply, and average recovery efficiency of applied N and P fertilizer of the researcher nutrient omission trials. The N (87 kg ha$^{-1}$) and P uptake (14.5 kg ha$^{-1}$) that corresponded to a 6.0 t ha$^{-1}$ target yield were based on average nutrient uptake in irrigated rice in the Sahel and in Asia (Haefele, 2001; Witt et al., 1999).

Two topsoil samples (0–0.2m) of each plot were taken before the start of the 1998 trials and analyzed for pH in a 1:2.5 paste and EC in a 1:5 paste. Means of different treatments were compared with the Newman-Keuls test using the STATISTICA software.

## 2.3 Results

Simulated potential yields

The potential yield in the wet season, as simulated with ORYZAS, varied across years between 7.0 t ha$^{-1}$ and 8.4 t ha$^{-1}$ with an average of 8.0 t ha$^{-1}$. Dry season potential yield showed higher variability (between 6.0 t ha$^{-1}$ and 8.4 t ha$^{-1}$ with an average of 7.8 t ha$^{-1}$) with low yields being caused by high spikelet sterility due to heat stress. Simulated potential yields for other varieties used in Foum Gleita were almost similar as Jaya (< 0.8 t ha$^{-1}$ difference).

Farmer survey and farmer trials

Only 34 out of 60 volunteering farmers started the wet season campaign in 1998. According to farmers, the primary reasons for not starting were, in order of importance: non-availability of machinery for land preparation (9 farmers), delay of the wet season preparations due to late harvest of the previous dry season, followed by strong rains (7 farmers), no irrigation water in the secondary canals (7 farmers) and non-payment of the annual water fees (3 farmers). Farmers never mentioned soil quality problems as primary reasons for not starting the campaign. Six of the remaining 34 fields were excluded from the analysis due to severe crop damage by birds and rats (3 farmers) or non-respect of the trial setup (3 farmers). Descriptive statistics of key crop and soil

*Table 2.1: The main crop and soil management variables for the 1998 wet season rice crop at Foum Gleita and their linear correlation with T0 and TF yield.*

| | n | Mean | SD[1] | Min | Max | Corr. coeff.[2] | |
|---|---|---|---|---|---|---|---|
| | | | | | | T0 | TF |
| Cultivated area (ha) | 28 | 1.2 | 1.0 | 0.3 | 4.0 | 0.10 | 0.29 |
| Sowing date | 28 | 27 July | 13 d | 10 June | 19 Aug | −0.24 | −0.03 |
| Sowing density (kg ha$^{-1}$) | 28 | 40 | 7 | 28 | 60 | 0.31 | 0.45*[3] |
| Seedling age at transplanting (days) | 28 | 32 | 9 | 14 | 52 | 0.09 | − 0.17 |
| Timing Urea-1 (DAT[4]) | 28 | 18 | 11 | 7 | 52 | n.a.[5] | − 0.15 |
| Urea-1 (kg ha$^{-1}$) | 28 | 125 | 41 | 100 | 250 | n.a. | 0.40* |
| Timing Urea 2 (DAT) | 28 | 50 | 14 | 22 | 87 | n.a. | 0.16 |
| Urea-2 (kg ha$^{-1}$) | 26 | 116 | 40 | 50 | 250 | n.a. | 0.34 |
| Urea-tot (kg ha$^{-1}$) | 28 | 226 | 75 | 100 | 500 | n.a. | 0.47* |
| Growing period (days) | 28 | 131 | 12 | 108 | 166 | 0.11 | 0.04 |
| T0 yield (t ha$^{-1}$) | 28 | 2.18 | 0.89 | 0.33 | 4.28 | n.a. | 0.69** |
| TF yield (t ha$^{-1}$) | 28 | 4.04 | 1.41 | 1.49 | 7.50 | 0.69** | n.a. |

[1] SD = standard deviation.

[2] Pearson bivariate correlation coefficient.

[3] * = significant at $P < 0.05$; ** = significant at $p < 0.01$.

[4] DAT = days after transplanting.

[5] n.a. = not applicable.

*Table 2.2: The main crop and soil management variables for the 1999 dry season rice crop at Foum Gleita and their linear correlation with T0 and TF yield.*

| | n | Mean | SD[1] | Min | Max | Corr. coeff.[2] |
|---|---|---|---|---|---|---|
| | | | | | | TF |
| Cultivated area (ha) | 33 | 0.8 | 0.5 | 0.5 | 2.5 | 0.11 |
| Sowing date | 33 | 10 Mar | 16 d | 15 Febr | 4 April | 0.25 |
| Sowing density (kg ha$^{-1}$) | 33 | 30 | 17 | 17 | 72 | 0.02 |
| Seedling age at transplanting (days) | 33 | 28 | 6.6 | 19 | 51 | -0.27 |
| Timing Urea-1 (DAT[3]) | 33 | 26 | 11 | 7 | 59 | 0.03 |
| Urea-1 (kg ha$^{-1}$) | 33 | 56 | 35 | 25 | 250 | 0.37 |
| Timing Urea-2 (DAT) | 13 | 50 | 11 | 35 | 73 | 0.32*[4] |
| Urea-2 (kg ha$^{-1}$) | 13 | 49 | 9 | 24 | 65 | 0.04 |
| Urea-tot (kg ha$^{-1}$] | 33 | 75 | 41 | 25 | 250 | 0.47* |
| Growing period (days) | 33 | 131 | 12 | 111 | 162 | -0.23 |
| TF - yield (t ha$^{-1}$) | 28[5] | 2.4 | 0.6 | 0.9 | 4.2 | n.a.[6] |

[1] SD = standard deviation.

[2] Pearson bivariate correlation coefficient.

[3] DAT = days after transplanting.

[4] * = significant at p < 0.05.

[5] No data available for 5 fields.

[6] n.a. = not applicable.

*Table 2.3: Chemical data of topsoil samples (0–0.2 m) from farmer fields at the onset of the 1998 wet season at Foum Gleita and their linear correlation with T0 and TF yield.*

| | n | Mean | SD[1] | Min | Max | Corr. coeff.[2] | |
|---|---|---|---|---|---|---|---|
| | | | | | | T0 | TF |
| pH 1:2.5 | 28 | 7.49 | 0.56 | 5.62 | 8.40 | −0.30 | −0.47**[3] |
| pH−KCl 1:2.5 | 28 | 6.41 | 0.57 | 5.01 | 7.50 | −0.37 | −0.53** |
| EC 1:5 (dS m$^{-1}$) | 28 | 0.13 | 0.05 | 0.06 | 0.27 | −0.37 | −0.50** |
| Ca (cmol$_c$ kg$^{-1}$ soil) | 28 | 11.5 | 3.1 | 7.3 | 18.4 | −0.48* | −0.30 |
| Mg (cmol$_c$ kg$^{-1}$ soil) | 28 | 4.4 | 1.3 | 2.6 | 7.0 | −0.06 | 0.24 |
| K (cmol$_c$ kg$^{-1}$ soil) | 28 | 0.36 | 0.07 | 0.24 | 0.47 | 0.20 | 0.24 |
| Na (cmol$_c$ kg$^{-1}$ soil) | 28 | 0.51 | 0.21 | 0.22 | 1.06 | −0.16 | −0.40* |
| CEC (cmol$_c$ kg$^{-1}$ soil) | 28 | 15.4 | 3.7 | 6.2 | 22.2 | −0.14 | −0.07 |
| Base saturation (%) | 28 | 111 | 23.5 | 84 | 178[4] | −0.18 | −0.09 |
| ESP (%) | 28 | 3.4 | 1.3 | 1.6 | 6.7 | −0.09 | −0.38* |
| P-Bray1 (mg kg$^{-1}$) | 28 | 3.9 | 2.3 | 1.1 | 8.6 | 0.55** | 0.22 |
| P-Olson (mg kg$^{-1}$) | 28 | 4.4 | 1.4 | 2.5 | 7.2 | 0.64** | 0.54** |
| N total (g kg$^{-1}$) | 28 | 0.6 | 0.1 | 0.3 | 0.7 | 0.14 | 0.06 |
| C (g kg$^{-1}$) | 28 | 3.4 | 0.8 | 1.8 | 5.6 | −0.18 | −0.15 |

[1] SD = standard deviation.

[2] Pearson bivariate correlation coefficient.

[3] * = significant at $p < 0.05$; ** = significant at p < 0.01.

[4] Values higher than 100 are due to dissolved CaCO$_3$.

*Table 2.4 Spatial distribution of yield, soil properties and crop variables*[1] *along the toposequence of the farmer–managed trials in the 1998 wet season.*

| | Upper and middle slope | Lower slopes depressions | River banks | p–level[2] |
|---|---|---|---|---|
| *Farmer performance* | | | | |
| Participants | 26 | 28 | 6 | – |
| Abandoned (%) | 62 | 50 | 33 | – |
| T0 yield (t ha$^{-1}$) | 1.56c | 2.35b | 4.22a | <.005 |
| TF yield (t ha$^{-1}$) | 3.42 | 4.22 | 5.34 | n.s. |
| *Soil properties* | | | | |
| EC 1:5 (dS m$^{-1}$) | 0.17a | 0.14ab | 0.09b | <.05 |
| pH 1:2.5 | 7.64a | 7.17b | 7.13ab | <.05 |
| P-Bray1 (mg kg$^{-1}$) | 2.63c | 4.37b | 7.39a | <.05 |
| P-Olson (mg kg$^{-1}$) | 3.37c | 4.78b | 6.49a | <.05 |
| $Ca^{++}$ (cmol kg$^{-1}$ soil) | 12.8 | 11.0 | 9.4 | n.s. |
| $N_{TOTAL}$ | 0.06b | 0.05ab | 0.07a | <.10 |
| *T0 crop variables* | | | | |
| $N_{STRAW}$ (g kg$^{-1}$) | 4.3 | 3.9 | 2.8 | n.s. |
| $P_{STRAW}$ g kg$^{-1}$) | 0.5b | 0.7a | 0.6b | <.05 |
| *TF crop variables* | | | | |
| $N_{STRAW}$ (g kg$^{-1}$) | 5.0 | 5.3 | 5.9 | n.s. |
| $P_{STRAW}$ (g kg$^{-1}$) | 0.6c | 0.9b | 1.1a | <.05 |
| *Farmer management* | | | | |
| P applied (kg ha$^{-1}$) | 0 | 0 | 0 | n.s. |
| N applied (kg ha$^{-1}$) | 102 | 92 | 109 | n.s. |
| REN[3] | 0.31 | 0.33 | 0.39 | n.s. |

[1] CEC, $K^+$, $Na^+$, C%, $N_{GRAIN}$ and $P_{GRAIN}$ for TF and T0 are not significantly different ($p<0.10$)

[2] Newman–Keuls test. Values in the same row followed by the same letter are not statistically different at the level indicated in the last column. n.s. = not significant.

[3] N recovery efficiency (kg uptake kg$^{-1}$ fertilizer applied)

management variables at Foum Gleita are given in Table 2.1. Since farmer selection in the 1999 dry season only started at the onset of the season, all volunteering farmers cropped their fields. The results of the 1999 dry season survey are summarized in Table 2.2. Both tables show large differences in crop management practices amongst farmers and correlation of crop management variables with yields. Transplanting, fertilizer applications and harvest were delayed when compared with the RIDEV recommendations (Figure 2.4). Basic statistics on the chemical characteristics of topsoil samples from the 1998 farmer surveys are given in Table 2.3. The analysis of the spatial distribution of yield, soil properties and crop variables from the farmer managed trials

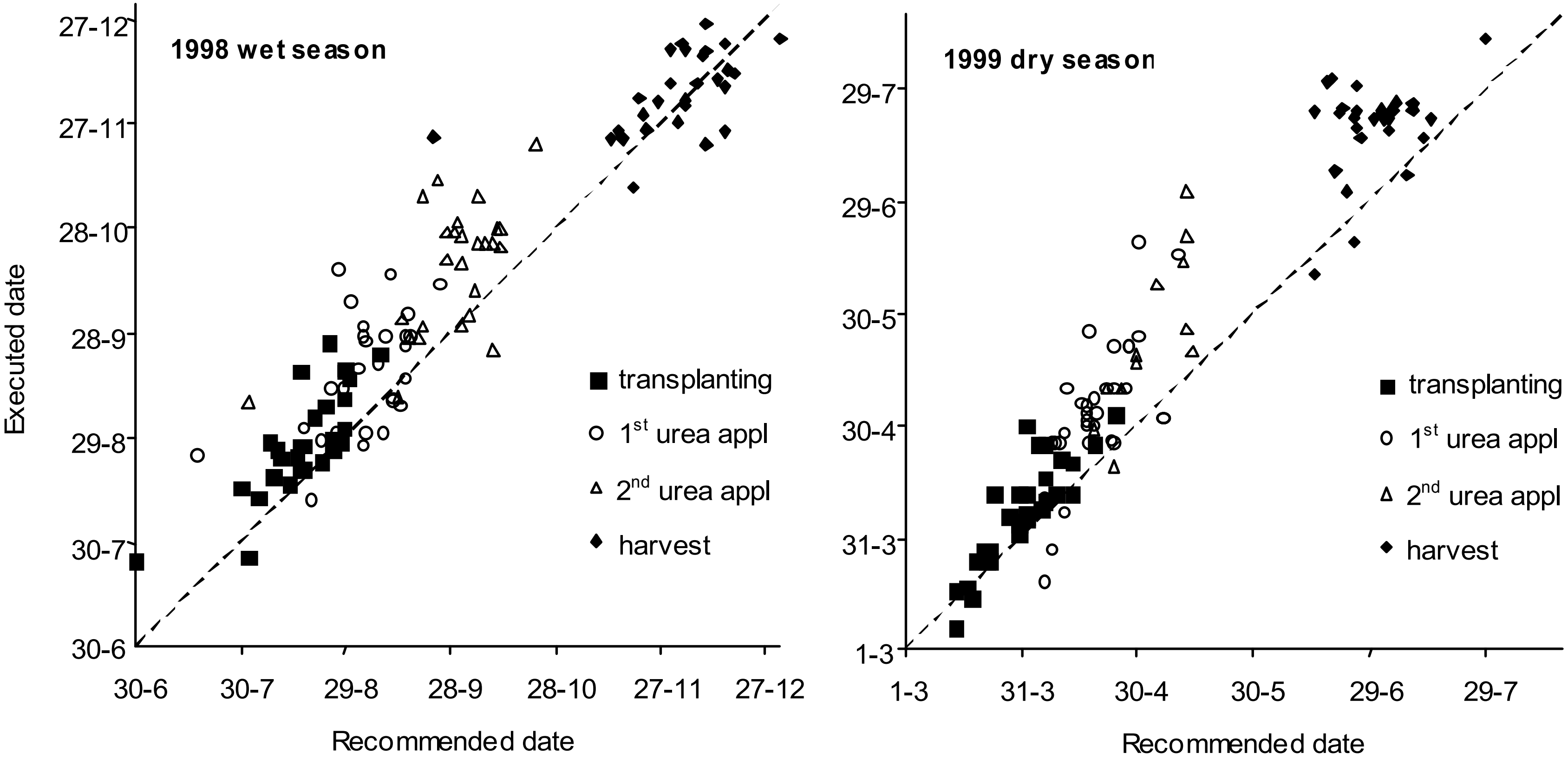

*Figure 2.4:* *Dates of cultivation practices by farmers compared with RIDEV recommendations for the 1998 wet season and 1999 dry season. Points above the dashed line indicate a delay of farmer practices when compared with RIDEV recommendations.*

in the 1998 wet season revealed the existence of strong spatial relationships (Table 2.4).Yields, P-Olsen and P-Bray1 increase, moving from the 'upper and middle slopes' down to the 'river banks'. The percentage of farmers not starting the campaign (abandoned %) shows the reverse trend. Similarly, pH, EC and Ca all decrease moving from the top to the bottom of the toposequence. The straw N and P concentrations ($N_{STRAW}$ and $P_{STRAW}$) increase moving from the top to the bottom of the toposequence, except for $N_{STRAW}$ in the T0 treatment that shows the reverse trend, although not significant. Plant analyses revealed that P plant concentrations are low. A third (32%) of the P concentrations in the straw ($P_{STRAW}$) was lower than 0.6 g $kg^{-1}$, indicating P deficiency (Kanareugsa, 1980) at maturity. In 88% of the flag leaf samples P concentrations were below 1.8 g $kg^{-1}$, indicating P deficiency during vegetative growth (Dobermann and Fairhurst, 2000).

### Analysis of the farmer trials

The variables taken into account in the T0 boundary line analysis (correlation coefficient $\geq 0.3$) were: sowing density, pH, pH-KCl, EC, Ca, P-Bray1 and P-Olsen. The variables used in the TF boundary line analysis were: sowing density, first urea

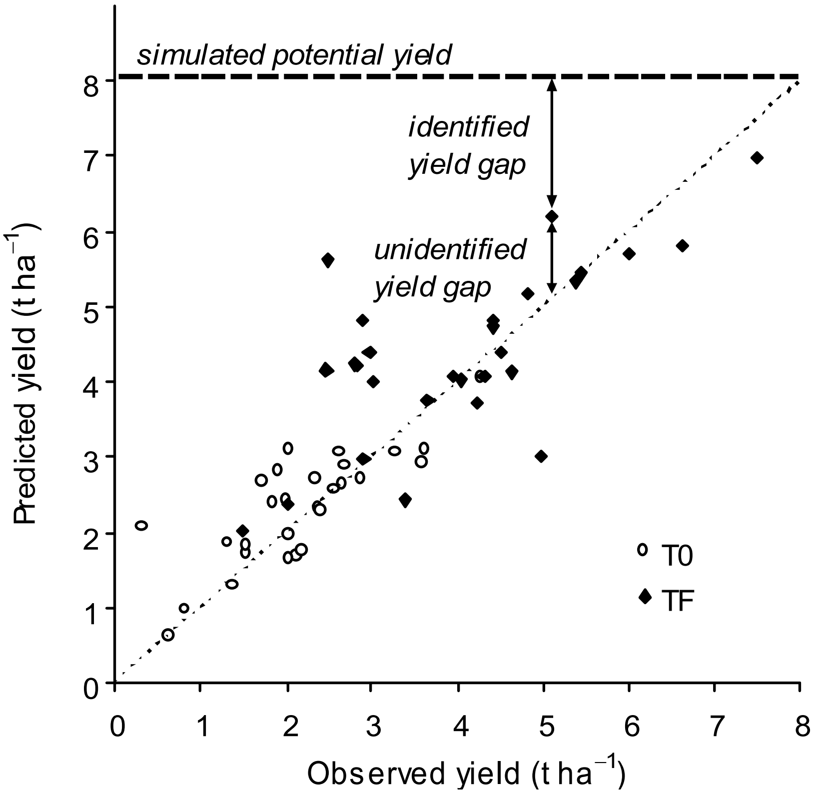

*Figure 2.5: Comparison of predicted yields, using the boundary line approach, and observed farmer yields (TF and T0), with a graphical presentation of the potential yield (dashed line), the identified yield gap and the unidentified yield gap. Points above the dotted 45° line represent yields that could not fully be explained by the variables used in the boundary line approach.*

application (Urea-1), second urea application (Urea-2), total urea application (Urea-Tot), pH, pH-KCl, EC, $Ca^{2+}$, Na+, ESP, P-Olsen and P-Bray1. The variables limiting maximum attainable T0 yields were, in order of importance: P-Olsen (32% = 9 out of 28 farmers), $Ca^{2+}$ (25%), P-Bray (14%), pH (10%), pH-KCl (7%), EC (7%) and sowing density (4%). The variables limiting maximum attainable TF yield were: P-Olsen (18%), pH (18%), $Ca^{2+}$ (14%), EC (14%), pH-KCl (10%), sowing density (7%), Urea-Tot (7%), Urea-1 (4%), Urea-2 (4%) and ESP (4%). Figure 2.5 shows the calculated predicted T0 and TF yields plotted against actual T0 and TF yields. Linear regression between maximum attainable and actual yields (line not shown) explained 63% and 48% of the rice yield variation for T0 and TF, respectively.

Researcher-managed nutrient omission trials

Topsoil samples of the nutrient omission trials showed that the pH on the DG soil (pH 8.26) was distinctly higher than on the NDG soil (pH 6.12). Soil depth at the DG site was 0.6–0.8 m and > 2.5 m at the NDG site. At both sites, only N and P (when combined with N) fertilizer had a yield increasing effect. Average paddy yields and nutrient recovery efficiencies for different seasons and treatments T0 to T3 are summarized in Table 2.5. Yields, N uptake and P uptake for T4 and T5 are not shown, but were similar as in T1. At both sites, K application did not affect yield and K concentrations in the straw (15–36 g $kg^{-1}$) were independent of treatment and exceeded the critical level for deficiency (>15 g $kg^{-1}$) (Dobermann and Fairhurst, 2000). Omission of Zn fertilizer reduced Zn concentrations in the flag leaf at panicle initiation from 25–30 mg $kg^{-1}$ to 15–18 mg $kg^{-1}$ on both soils. However, application of Zn did not

*Table 2.5: Paddy yields (t $ha^{-1}$) for the nutrient omission trials in the wet season of 1989 and the dry seasons of 1999 and 2000 on non–degraded and degraded soils. For the specification of the four treatments T0, T1, T2 and T3 see text.*

| | 0N/0P (T0) | | 175N/26P (T1) | | 0N/26P (T2) | | 175N/0P (T3) | |
|---|---|---|---|---|---|---|---|---|
| | Mean | SD[1] | Mean | SD | Mean | SD | Mean | SD |
| *Wet season 1998* | | | | | | | | |
| Non-degraded soil | 3.34b[2] | 0.99 | 5.92a | 0.41 | 3.44b | 0.81 | 5.34a | 0.65 |
| Degraded soil | 0.84c | 0.19 | 4.77a | 0.26 | 1.27c | 0.09 | 2.86b | 1.14 |
| *Dry season 1999* | | | | | | | | |
| Non-degraded soil | 1.64b | 0.72 | 5.37a | 0.92 | 1.34b | 0.56 | 5.69a | 1.23 |
| Degraded soil | 0.84bc | 0.17 | 6.60a | 0.65 | 0.91bc | 0.42 | 2.31b | 1.82 |
| *Dry season 2000* | | | | | | | | |
| Non-degraded soil | 1.29c | 0.39 | 6.44a | 0.69 | – | – | 4.97b | 0.16 |
| Degraded soil | 1.63b | 0.72 | 5.68a | 0.86 | – | – | 3.73a | 0.98 |

[1] SD = standard deviation.

[2] Means in the same row followed by a the same letter are not statistically different (Newman–Keuls; $p < 0.05$).

*Table 2.6: N and P uptake (kg ha$^{-1}$) and recovery efficiencies (kg nutrient taken up per kg nutrient applied) for rice in the omission trials of 1998 and 2000 on non–degraded and degraded soils. For the specification of the four treatments T0, T1, T2 and T3 see text.*

| | 0N/0P (T0) | | 175N/26P (T1) | | 0N/26P (T2) | | 175N/0P (T3) | |
|---|---|---|---|---|---|---|---|---|
| | N | P | N | P | N | P | N | P |
| *Wet season 1998* | | | | | | | | |
| Non-degraded soil | | | | | | | | |
| Uptake | 42 | 10 | 105 | 20 | 42 | 9 | 102 | 14 |
| Recovery efficiency | – | – | 0.36 | 0.23 | – | 0.19 | 0.34 | – |
| Degraded soil | | | | | | | | |
| Uptake | 14 | 3 | 62 | 9 | 20 | 4 | 41 | 6 |
| Recovery efficiency | – | – | 0.24 | 0.14 | – | 0.06 | 0.12 | – |
| *Dry season 2000* | | | | | | | | |
| Non-degraded soil | | | | | | | | |
| Uptake | 22 | 5.7 | 101 | 24 | – | – | 84 | 18 |
| Recovery efficiency | – | – | 0.45 | 0.21 | – | – | 0.35 | – |
| Degraded soil | | | | | | | | |
| Uptake | 21 | 4.2 | 71 | 12 | – | – | 58 | 9 |
| Recovery efficiency | – | – | 0.28 | 0.11 | – | – | 0.21 | – |

have an effect on yield. Plant analyses of the 1998 wet season and 2000 dry season trials, showed that on the DG site, average $P_{STRAW}$ concentrations were low (0.5–0.7 g kg$^{-1}$) for zero N treatments (T0 and T2) and very low (0.2–0.4 g kg$^{-1}$) for treatments T1 and T3. $P_{STRAW}$ on the NDG soil was higher, but varied widely (0.4–1.2 g kg$^{-1}$) for all treatments. Plant P uptake and recovery efficiency of applied P fertilizer (REP) are higher on the NDG soils when compared with the DG soils (Table 2.6). N concentrations in straw were also lower at the DG than at the NDG site. At the DG site, $N_{STRAW}$ varied between 3.5 g kg$^{-1}$ and 4.4 g kg$^{-1}$ independent of fertilizer treatment. At the NDG site $N_{STRAW}$ varied between 4.4 g kg$^{-1}$ and 6.2 g kg$^{-1}$, with lowest N concentrations measured in treatments without N application (T0 and T2). Plant N uptake and REN were distinctly higher on the NDG than on the DG site (Table 2.6). The low soil N supply (= N uptake in T2), soil P supply (= P uptake in T3), REN, and REP significantly increase fertilizer needs on the DG soils, when compared with the NDG soils. To obtain the target yield of 6.0 t ha$^{-1}$, farmers on the DG soil need to apply 265 kg N ha$^{-1}$ and 50 kg P ha$^{-1}$, compared with 138 kg N ha$^{-1}$ and 0 kg P ha$^{-1}$ on the NDG soil.

## 2.4 Discussion

Average simulated potential yields in Foum Gleita are high in the wet (8.0 t ha$^{-1}$) and dry season (7.8 t ha$^{-1}$). Farmer yields (TF) in the 1998 wet season (4.0 t ha$^{-1}$) and 1999 dry season (2.4 t $ha^{-1}$) were low, but the large variability amongst farmers yields and the important yield gap show that there is considerable scope for improvement.

The boundary line analysis revealed that both soil quality (EC, pH, pH-KCl, Ca, Na, ESP, P-Olsen and P-Bray1) and crop management (sowing density, Urea-1, Urea-2 and Urea-Tot) contributed to the productivity problems in Foum Gleita. Although yields were negatively correlated to EC, Ca, Na and ESP, it is unlikely that these soil variables form a direct production constraint considering their current low values; i.e., top soils in Foum Gleita were not saline ($EC_e < 4$ dS $m^{-1} \approx EC < 0.63$ dS $m^{-1}$), nor sodic ($ESP < 15$; $pH < 8.5$) following USDA classification (Richards, 1954). However, the accumulation of alkaline salts simultaneously increases EC, Ca, Na, ESP and pH. The increase in pH decreases N availability due to volatilization (Reddy and Patrick, 1984) and decreases P availability due to chemisorption of P on calcite and the formation of poorly soluble Ca-P minerals (Fixen and Grove, 1990; Samadi and Gilkes, 1999). EC, Ca, Na and ESP might therefore be indirectly related to N and P deficiency problems.

A qualitative analysis of crop management practices revealed that they were often sub-optimal. When compared with RIDEV recommendations, farmers transplanted up to 5 weeks late. In both seasons, a 1–2 week delay in the second urea application was observed when compared with RIDEV recommendations. Late timing of urea application decreases its efficiency. Similarly, harvest was often delayed and harvest period was often prolonged (data not shown). The average urea application in the 1998 wet season (226 kg urea $ha^{-1}$) was close to local recommendations (250 kg urea $ha^{-1}$), but quantities applied in the dry season (average 75 kg $ha^{-1}$) were distinctly lower due to non-availability on the local market. Total N fertilizer dose in the dry season showed significant linear correlation (0.47) with yield, indicating that low N doses largely contributed to the observed yield gap. P fertilizer was not applied, as it did not form part of local recommendations. However, P-Olsen values (average 4.4 mg P kg $soil^{-1}$) for irrigated rice are low (Dobermann and Fairhurst, 2000). P-Olsen was the primary constraint limiting farmer TF and T0 yields, according to the boundary line analysis. This corresponds to the large percentage of flag leaf samples (88%) and straw samples (32%) with P concentrations below the deficiency limit. The boundary line analysis led to a good prediction of actual yields; the regression model for T0 and TF yield explained 63% and 48% of the rice yield variation, which is similar to findings of other studies where soil properties were used to explain irrigated rice yield variation (Casanova et al., 1999; and Dobermann, 1994). Nonetheless, two critical remarks can be made with respect to the use of boundary line analysis in this type of study. Firstly, at some fields a large part of the yield gap remains unidentified, which may be related to measurement errors, methodological errors, or variables such as bird damage and weed pressure, that have not been taken into account. Secondly, omission of N fertilizer in the T0 plots could not be identified as a production constraint, which indicates that omission of an important variable from the analysis does not necessarily lead to a large unidentified yield gap if the particular variable does not vary amongst farmers (i.e., no boundary function can be established).

T0 and TF yield both show a strong spatial distribution. Yields increase when moving from the 'upper and middle slopes' down to the 'river banks'. Besides, the percentage of farmers leaving their field uncultivated decreased moving from the 'upper and middle slopes' to the 'river banks', although neither soil quality problems nor topographic position were mentioned as a primary constraint for not starting the agricultural campaign. We suspect that lower yields in the past resulted in a situation where farmers upslope had more problems finding the financial resources and motivation necessary to start the campaign. The qualitative analysis and boundary line analysis of the farmer trials clearly highlighted sub-optimal N management and non-application of P fertilizer as major cropping constraints. However, since cropping practices did not significantly differ throughout the toposequence, differences in yield must be related to differences in soil quality. Soil quality variables that influence the availability of N and P all showed a strong spatial distribution. On the 'upper and middle slopes' soil pH and $Ca^{2+}$ were significantly higher ($p < 0.05$), and P-Olsen and P-Bray1 were significantly lower ($p < 0.05$) when compared with soils further down slope. These observations correspond to the low P concentrations (0.6 g $kg^{-1}$) in the straw of farmer fields (TF) on the 'upper and middle slopes'. Similarly, P concentrations in the straw of the nutrient omission trials on the DG soil were very low (<0.4 g $kg^{-1}$) and average yield decreased from 5.7 t $ha^{-1}$ to 3.0 t $ha^{-1}$, when P fertilizer was omitted (T3). All of the above observations indicate that P deficiency is a major cropping constraint on the 'upper and middle slopes', when 175 kg N fertilizer $ha^{-1}$ is applied. To obtain a yield of 3.0 t $ha^{-1}$, an N fertilizer dose of 98 kg N $ha^{-1}$ instead of 175 kg N $ha^{-1}$ would have been sufficient given the average soil N supply (18 kg $ha^{-1}$) and REN (0.26) on the DG soil. This N dose corresponds to farmer practices. Hence, co-limitation of N and P is likely in farmer fields at the 'upper and middle slopes' given the current fertilizer practices. The low N straw concentrations in farmer fields (TF) on the 'upper and middle slopes' strengthen the hypothesis of co-limitation. On the soils of the 'lower slopes and depressions' and of the 'river banks', $N_{STRAW}$ is very low in the T0 plots, indicating that N has been diluted at maximum. N deficiency at low N fertilizer dose is likely to be the major constraint limiting yields in farmer fields on these NDG soils. P fertilizer application only had a positive effect at high yield levels (> 5.3 t $ha^{-1}$). K and Zn fertilizer application had no effect on yields, but low Zn concentrations on the DG soil in treatments with both N and P, but without Zn fertilizer application, indicated a likely Zn deficiency (Yoshida, 1981), which may become a problem if high yields are sustained over a longer period. Zn deficiency in irrigated rice is often observed on alkaline calcareous soils (Dobermann and Fairhurst, 2000).

From the farmer and nutrient omission trials, it follows that yield levels and nutrient availability are significantly lower on the DG than on the NDG soils. Hence, the farmer classification terms 'degraded' and 'non-degraded' reflect well production constraints in the irrigation scheme, but do not refer to international standards on salinity or sodicity. Rice yields are not directly influenced by EC, Ca, Na and ESP, but merely reflect an alkalinity induced nutrient constraint.

On the DG soil, low average soil N supply, soil P supply, REN and REP resulted in high N fertilizer (265 kg N ha$^{-1}$) and P fertilizer (50 kg P ha$^{-1}$) recommendations when target yield is 6 t ha$^{-1}$. On the NDG soil, average soil N supply and REN were much higher, resulting in moderate N fertilizer recommendation (138 kg ha$^{-1}$), for a target yield of 6 t ha$^{-1}$. At present, P fertilizer on the NDG soil is not needed, since soil P supply (16 kg ha$^{-1}$) still exceeds P uptake (14.5 kg ha$^{-1}$) at 6 t ha$^{-1}$. The fertilizer recommendations for the DG soils are unlikely to be adopted by farmers, as they will not be able to support the high costs. These recommended fertilizer doses would be smaller (e.g., similar to T1 in the researcher nutrient omission trial), if maximum dilution of N and P in the rice plant was taken into account. Alternatively, fertilizer recommendations can be lowered when target yield is smaller and/or when recovery efficiency of applied fertilizer increases through improved organic matter management (Chapter 4). Nonetheless, the fertilizer recommendation calculations are instrumental, as they reveal a strong contrast in fertilizer needs of DG and NDG soils.

## 2.5 Conclusions

Large yield gaps between actual farmers' yield and simulated yield proved that there is considerable scope for improvement in rice yield and productivity in Foum Gleita. Low dose and late timing of N fertilizer application and non-application of P fertilizer were identified as the main agronomic constraints. Low phosphorus availability and alkalinity were the main soil quality variables contributing to the observed productivity problems. These soil quality variables showed strong relation to topographic position, explaining lower yields and more abandonment of land on the 'upper and middle slope'. Highest yields obtained in nutrient omission trials on these farmer-identified degraded soils were not significantly lower than on soils further down slope, but REN and REP were. We suspect that low REN and REP are related to volatilization of N and immobilization of P; processes that will be more important on the more alkaline soils of the 'upper and middle slope'. Due to the low N and P uptake, sub-optimal fertilizer management will more easily be translated into yield loss on the DG soils. Recommended N and P fertilizer doses to obtain a 6 t ha$^{-1}$ target yield are much higher on the DG than on the NDG soil.

This study showed that analysis of crop management practices should be integrated in studies that relate yield gaps to soil quality problems. In combination with farmer surveys and nutrient omission trials, the boundary line analysis proved to be an excellent tool to obtain a semi-quantitative idea on the importance of different production factors. The boundary line analysis had a good predictive capability, comparable to those found in similar studies. This study is one of the first Sahelian studies to relate actual yield gaps in irrigated rice to soil alkalinity; a relationship that has often been mentioned in Sahelian studies, but was little investigated. Although we conclude that soil alkalinity contributes to low yields in Foum Gleita, we cannot draw any conclusions on the origin of the alkaline salts or the potential changes in soil salinity. Detailed research on the salt and water balance will be needed in order to understand the changes of these soils under the present land use management, and in order to understand to what extent Foum Gleita could function as an early warning system for other Sahelian irrigation schemes.

# 3 Using farmer knowledge to combat low productive spots in rice fields of a Sahelian irrigation scheme

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In the oldest sections of Burkina Faso's largest irrigation scheme in the Sourou Valley (13°10'N, 03°30'W) rice (*Oryza sativa* L.) yields dropped from about 5 to 6 t $ha^{-1}$ in the early 1990s, shortly after establishment of the scheme, to 2 to 4 t $ha^{-1}$ from 1995 onwards. Farmers blamed this yield decline on the appearance of 2 to 20 m diameter low productive spots. According to farmers and field measurements, the low productive spots decreased yields by 25–50%. The low productive spots are caused by Zn deficiency. Low Zn availability is related to very low DTPA-extractable Zn content of the soil (0.08–0.46 mg $kg^{-1}$), the alkaline-calcareous character of the soil, the non-application of Zn fertilizers, and a relatively large P fertilizer dose (21 kg P $ha^{-1}$). Farmers were correct in relating the calcareous nature of the soil to the presence of the low productive spots. They were instrumental in identifying application of decomposed organic resources (e.g., rice straw at 5 t $ha^{-1}$) as a short term solution that increases yields by 1.5 to 2.0 t $ha^{-1}$. Application of Zn fertilizer (10 kg Zn $ha^{-1}$) in 29 farmer fields in the 2001 dry season eradicated the low productive spots and increased yields from 3.3 to 6.0 t $ha^{-1}$. Application of Zn fertilizer is, therefore, strongly recommended. However, Zn fertilizer is not available in Burkina Faso at present. Despite the relative recent introduction of irrigated rice cropping, most farmers showed a good understanding of cropping constraints and possible solutions. Both farmers and researchers mutually benefited from each others' knowledge and observations.

**Keywords**: *Oryza sativa* L., Zn deficiency, Burkina Faso, organic matter management

## 3.1 Introduction

Increasing demand for rice (*Oryza sativa* L.), particularly in urban centers, is forcing the majority of Sahelian countries to import rice, draining scarce foreign exchange resources (Reardon et al., 1997). In Burkina Faso, annual paddy production during recent years (1996 to 2000) was about 100 Mt yr$^{-1}$, with imports ranging from 105 to 240 Mt yr$^{-1}$ (FAO, 2002). To bridge this large gap between rice demand and local production, investments were made in irrigation infrastructure in Burkina Faso from the mid-1980s onwards. However, rice yields in irrigation schemes often fall short of expectations, raising questions about the viability of these costly irrigation schemes (Bélières et al., 1995).

Burkina Faso's largest irrigation scheme is located in the Sourou Valley, which accounts for 10% to 15% of national rice production. The current 3,000 ha scheme has been gradually developed from the mid-1980s onwards. Plans exist to extend the irrigation scheme to a total of 30,000 ha (Traoré, 2002). Irrigated rice occupies about two thirds of the irrigated area, grown during the wet season (January–May) and during the dry season (June–November). Averaged over the two seasons, yields in the older sections of the scheme continuously increased from 3.8 t ha$^{-1}$ in 1986 to 5.7 t ha$^{-1}$ in 1991, followed by a steady decline to yields ranging from 2.2 to 4.4 t ha$^{-1}$ from 1995 onward (AMVS, unpublished data; Nebié, 1997). These yields are small compared to both simulated potential yields (7 to 9 t ha$^{-1}$) and actual yields in most other Sahelian schemes (4 to 6 t ha$^{-1}$) (Haefele et al., 2000). For farmers in the Sourou Valley to make a profit, average rice yields per season need to at least range from 2.8 to 3.8 t ha$^{-1}$ (Rigourd et al., 2002). Farmers and the local irrigation and extension authority 'Aménagement et Mise en valeur de la Vallée du Sourou' (AMVS) blamed the yield decline to an increasing appearance of low productive spots in the rice fields. Some farmers related the low productivity of such spots to salinity problems, pointing at the occurrence of white efflorescence and nodules at the soil surface. Medium to high soil salinity and alkalinity levels were earlier observed in parts of irrigation schemes in Mali, Mauritania and Senegal, but so far there has been little evidence that salinity or alkalinity causes significant direct yield losses in Sahelian schemes (see Chapter 1). In the Sourou Valley, irrigation water contains very little salt (EC < 0.1 dS m$^{-1}$) and concentration factors are small (< 6), suggesting that alkalinization is not an ongoing process (Barro et al., 2000). However, nutrient deficiency problems (N, P, and possibly Zn) were earlier observed on other alkaline-calcareous soils in the Sahel (Chapter 2) and could be a possible reason for the appearance of the low productive spots.

Several authors (e.g., Wopereis et al., 1999; Haefele et al., 2000, 2002; Poussin and Boivin, 2002; Poussin et al., 2003; Rigourd et al., 2002; Chapter 1) proposed that small rice yields in Sahelian irrigation schemes were often related to sub-optimal crop and soil management practices. These authors related sub-optimal management to a multitude of socio-economic and biophysical constraints, both at plot and scheme level. Haefele et al. (2000, 2001) showed that improved soil fertility and weed management raised farmers' yield by about 2 t $ha^{-1}$ in the Senegal River valley, without significant increase in production costs. They suggested that improved rice technologies are still needed to boost rice production. This is contested by Poussin and Boivin (2002), who believe that technologies are already available and that sub-optimal crop management is primarily due to poor collective organization and decision making at the scheme level. However, all authors agree that better access to information, agricultural inputs and decision making will largely increase irrigated rice production in the Sahel.

Farmers in the Sourou Valley received technical backstopping from the local irrigation and extension authority AMVS and the 'Programme Spécial pour la Sécurité Alimentaire' (PSSA) of the United Nations Development Program. However, prior to the construction of the schemes, farmers had no knowledge of irrigated rice cropping. The question rises to what extent farmers can properly identify factors contributing to the small yields and the presence of the low productive spots. Many researchers have observed earlier that most African farmers have thorough knowledge of their cropping systems and that this knowledge is dynamic, rather than static (e.g., Scoones and Thompson, 1994; Chambers et al., 1989). Furthermore, there are several examples of how researchers used farmer knowledge of traditional cropping systems to guide scientific research and develop solutions that would better fit farmer needs (e.g., Veldhuizen et al., 1997; Steiner, 1998; Quansah et al., 2001). Defoer et al. (2000) have shown that within the framework of integrated soil fertility management, combining outcomes of participatory action research and quantitative analysis can be beneficial for all stakeholders involved, including farmers, extension agents, researchers and policy makers. However, it is yet unknown to what extent farmers correctly perceive production problems in relatively new irrigated rice cropping systems and whether their knowledge, observations and experiences can be used to guide scientific research.

The objectives of this study were to: (i) assess the impact of the low productive spots on yield, (ii) understand the origin and dynamics of their appearance (iii) evaluate farmers' perceptions of the problem and (iv) identify and test potential solutions combining farmer knowledge and scientific evidence. To reach the objectives, we conducted farmer surveys and combined them with researcher trials, such as the detailed monitoring of low productive spots and organic matter trials. Analyses of data from these trials revealed similarities with Zn deficient rice plants, as reported earlier in Asia. To test the hypothesis of Zn deficiency we conducted trials in farmer fields.

## 3.2 Materials and methods

### Site description

The Sourou Valley (13°10'N, 03°30'W) is situated in the North-Western part of Burkina Faso. The Sourou River is a tributary to the Mouhoun River (former Black Volta) and its water level is artificially maintained by a dam 30 km further downstream, allowing pump irrigation all year round. The climate is typically Sahelian with erratic rainfall

(630 mm $yr^{-1}$) in the wet season (May–October), followed by a short cool period (November–February) with minimum daily temperatures as low as 15 °C and a hot dry season (March–April) with maximum daily temperatures up to 45 °C. The majority of the soils in the Sourou Valley has formed in thick (> 30 m) alluvial calcareous-rich deposits and can be classified Vertisol and Gleysol (FAO, 1990a). Their high clay content (35–50%) and moderately high CEC (15–20 $cmol_c$ $kg^{-1}$) make them very suitable for rice cultivation (Leprun, 1968). This chapter focuses on the D1 (50 ha) and D2 (140 ha) sections of the schemes that were the first to be used for continuous rice cropping. These sections were constructed between 1986 and 1988. The Sourou Valley was originally occupied by the Marka and the Samo people, but with the construction of the scheme, people from other ethnic groups (Mossi, Peulh) from within Burkina and Mali moved into the area (Marchal, 1976). Most ethnic groups had no experience with rice cropping. Land in the newly constructed irrigation scheme was distributed amongst the population. Farmers generally obtained between 0.5 and 1.5 ha.

### Farmer perceptions and practices

In July 1998, a meeting was organized bringing together farmers, extension workers and scientists to identify cropping constraints and set research priorities. Based on the outcome of the workshop, we conducted interviews with 69 farmers using a pre-designed questionnaire. We used open questions to assess farmers' perception of the impact and dynamics of the low productive spots. We also asked farmers to quantify the impact and effectiveness of indigenous measures to combat the low productive spots, using a pre-determined set of classes. For example, farmers were asked to rate their perception of the impact of low productive spots on yield, using five levels of rating: 0–10, 10–25, 25–50, 50–75, >75% yield loss. Farmers were also asked to judge the effectiveness of possible intervention methods using four levels of rating: not effective, little effective, effective, and very effective. Furthermore, crop management practices (i.e., date of sowing, transplanting, harvest, and dosage and timing of fertilizer and herbicide applications) were closely monitored by local extension workers throughout 2000 dry season (20 farmers) and wet season (20 farmers). Rice yields were estimated on the basis of the number of bags harvested multiplied by the average bag weight. Farmer cropping practices were compared to (local) recommendations (Table 3.1).

### Detailed monitoring of low productive spots

At the onset of the 1999 dry season, two fields (309 and 312) in the D1 section were selected that were affected by low productive spots according to the farmers. One low productive spot per field was monitored from transplanting onward. The spots that were monitored were not located near the bunds of the field in order to avoid border effects. Plant development (shoot biomass, height, tiller number and development stage) was monitored throughout the season. Date of appearance, type and intensity of plant

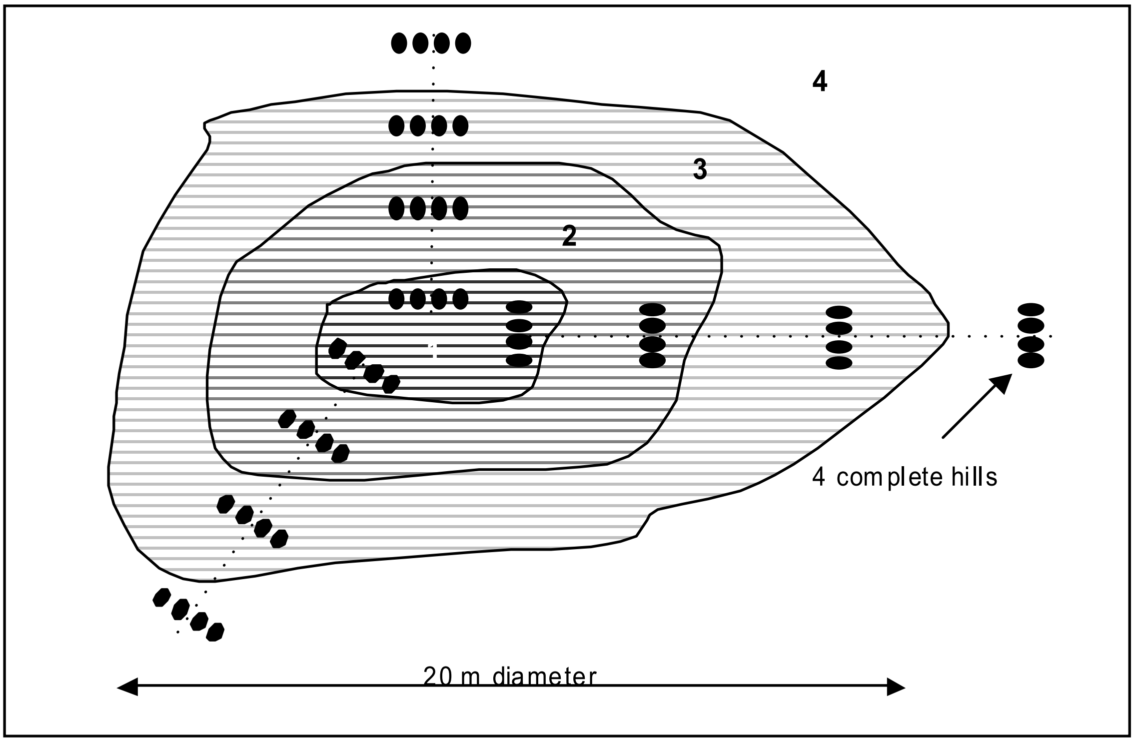

*Figure 3.1: Schematic birds-eye view of a low productive spot. Each axe represents a sampling sequence, comprising of 4 hills (black dots) at 4 regular intervals from the center (1) to outside the low productive spots (4) shortly before panicle initiation, flowering and maturity.*

diseases were monitored. Shoot samples were taken at different development stages, i.e., shortly before panicle initiation, at flowering and at maturity. Plant samples (above-ground rice biomass) were taken at four points along transects at ± 3m interval from the center to outside the low productive spot (Figure 3.1). Samples taken at the same distance of the center of the low productive spot were bulked, resulting in four composite plant samples per spot and per development stage. At maturity, plant roots and the 0 to 0.2 m topsoil were sampled as well following the same sampling and bulking procedure. Plant samples were dried (80 °C) and P and Zn were extracted with a 1 N HCl extraction (Yoshida et al., 1976). Zn was analyzed using an automatic absorption spectrophotometer (AAS) and P was determined colorimetrically. Soil samples were dried and sieved (< 2 mm) and analyzed for pH, electrical conductivity (EC in a 1:5 extract), $CaCO_3$ (gravimetric loss of $CO_2$), C% (Walkey and Black, 1934), exchangeable $Ca^{2+}$, $Mg^{2+}$, $K^+$, and $Na^+$ (AAS after $NH_4Cl$-extraction), CEC (Chapman, 1965), and soil texture (pipette method). Available phosphorus (P-Olson and P-Bray1) was analyzed using a spectrophotometer. Total Zn (aqua regia digestion) and DTPA-available Zn (Lindsay and Norvell, 1978) were determined using an atomic emission spectrophotometer (AES). In addition to the soil samples taken at maturity in the monitored spots, top soil samples (0-0.2 m) were taken in six other fields, both inside and outside low productive spots.

Researcher-managed trials

Based on the outcome of the 1998 farmer interviews, researcher-managed organic amendment trials were conducted in two farmer fields (308 and 516) in the 1999 dry and wet seasons. The trial sites were located in fields of the D1 section where low productive spots had appeared in the previous seasons. The medium duration (125 days) rice cultivar ITA123 was used, which was commonly used by farmers and locally known as FKR 28. Three different organic amendments were applied, resulting in the following four treatments: T1 = control; T2 = fresh rice straw; T3 = compost; T4 = cattle manure. Treatments were replicated four times in a randomized block design. Minimum size of the individual plots was 4 × 6 $m^2$. The organic matter application was 5 t dry weight $ha^{-1}$. The 'fresh' straw originated from the previous harvest. Compost ingredients were rice straw and cattle manure. Organic amendments were manually incorporated into the topsoil two weeks before transplanting, using a hoe. The timing of organic amendment incorporation was in compliance with soil tillage practiced by farmers. Mineral fertilizer applications were close to common farmer practices. It comprised 200 kg $ha^{-1}$ basal application of composite cotton fertilizer (12%N, 24%$P_2O_5$, 12%$K_2O$) shortly before transplanting, and topdressing of 150 kg $ha^{-1}$ urea fertilizer (about 69 kg N $ha^{-1}$), divided in two split applications (50% three weeks after sowing and 50% at panicle initiation). Paddy yields were estimated from a 2 × 3 $m^2$ harvest area in the center of each plot. Harvest index was determined from oven-dry (3% moisture content) straw and grain weight of a 12-hill sub-sample. Straw yield was derived from the harvest index and the 6 $m^2$ grain yield. The relative surface area affected by the low productive spots was determined throughout the growing season (i.e., at panicle initiation, heading, and flowering) for all treatments. Results of both fields and seasons were averaged and standard error was calculated from the season × field averages.

Farmer-managed trials

Based on plant observations in the low productive spots we hypothesized that these spots were caused by Zn deficiency. In the 2000 wet season, we pre-tested Zn fertilizer applications (foliar spray and basal application) at a rate of 20 kg Zn $ha^{-1}$ in two farmer fields with low productive spots. Both farmers and researchers appreciated the very positive visual effect of basal application of Zn fertilizer on plant growth. Therefore, we decided to continue testing basal application of Zn fertilizer in farmer fields on a larger scale. In the 2001 dry season, 29 farmers volunteered to participate in these farmer-managed trials. The farmers were located in the D1 and D2 sections and were not necessarily the same as monitored in the 2000 dry and wet season. Participants were asked to establish three mini-plots (10 m × 10 m) in their field, receiving 10 kg Zn $ha^{-1}$ ($T_{10-Zn}$), 20 kg Zn $ha^{-1}$ ($T_{20-Zn}$), and 5 t $ha^{-1}$ of decomposed straw (TS), respectively. The remainder of the field received neither Zn fertilizer nor organic amendments (TF). Zn fertilizer ($ZnSO_4.7H_2O$) was applied shortly before transplanting as basal application. The application of decomposed straw corresponded to farmer practices of leaving fresh straw during one cropping season in a heap in the rice field for decomposition, before spreading it over the field at the onset of the following season. All plots were otherwise managed as usual by the farmer, including fertilization of N, P and K. Rice variety and farmer crop management (date of sowing, transplanting, weeding, and harvest) and soil fertility management (dose and timing of fertilizers) were monitored by a project technician using a survey form. Grain yields were measured from a 6 $m^2$ area harvested in the centers of the plots at maturity. Harvest index was determined from oven-dry straw and grain weight of a 12-hill sub-sample. Concentrations of P and Zn in the plant were measured as described in the 'detailed monitoring of low productive spots' section. Plant N concentrations were determined using the Micro-Kjeldahl method (Bremner, 1996).

### Evaluation of the impact of earthworms on plant growth

Based on the of the 1998 farmer interviews, we decided to evaluate the impact of earthworm populations on rice growth. Shortly after transplanting, farmers helped identifying two fields in the 50 ha section (D1) that, according to them, suffered from the excessive presence of earthworms in the soil root zone. In both fields, farmers identified zones heavily infested by earthworms and zones with supposedly few earthworms. In each zone, 10 hills were sampled at mid-tillering stage. Plant height and tiller number were measured. A soil sample with a diameter of 0.1 m was taken of the root zone (0 to 0.2 m) at each plant sample site. The soil sample was rinsed and the number of earthworms was counted.

### Statistical analyses

All statistical analyses were conducted using the software package SPSS for Windows (Version 10.0). Levene's test for homogeneity of variance was conducted for yield data of researcher-managed and farmer-managed trials. Treatment effects on yields were analyzed using ANOVA ($p = 0.05$) with subsequent LSD test for post-hoc comparison. The same procedure was used to compare means of Zn and N concentrations of the farmer-managed zinc trials. The relation between earthworm number and plant tillering was modeled with a linear regression after log transformation of the earthworm data.

## 3.3 Results

### Farmer perceptions and practices

The July 1998 meeting and the subsequent structured interviews revealed that in the early 1990s, farmers observed for the first time the appearance of the low productive spots. The size and number of low productive spots had increased over time and spots often appeared at the same place in the field the following season. Most farmers (73%)

estimated the yield loss between 25 and 50%, based on the reduction in bags harvested. Farmers related the appearance of the spots to either poor drainage, salinization, soil fertility decline, the presence of excessive amounts of earthworms, or to a combination of these factors. Farmers tried to combat the low productive spots through the application of manure (10%), compost (12%), straw (33%) or a combination of these different organic matter sources (22%). A considerable number of farmers (19%) combined the application of organic amendments with the removal of calcareous nodules from the soil surface. The majority of farmers (55%) were not or little satisfied with the results of their countermeasures, as effects were noticeable for one to two cropping seasons only. Despite the general dissatisfaction, farmers perceived improved soil organic matter management as their only option to increase yields.

Farmer yields in the 2000 DS and 2000 WS averaged 4.7 and 3.4 t ha$^{-1}$, respectively. In many cases, cropping practices showed little or no variation amongst farmers (Table 3.1). In general farmer practices corresponded reasonably well to local recommendations. At the onset of the cropping seasons all farmer fields were mechanically tilled. In both seasons, nearly all farmers (> 80 %) used the medium duration ITA123 variety (± 125 days). The other variety used was TOX 728-1, which has a slightly shorter growing cycle (± 116 days) and is locally known as FKR 19. Transplanting and first urea applications were up to one week delayed when compared to recommendations. The harvest was 2–4 weeks late, most notably in the dry season. Weeding was generally done shortly before urea application, as is recommended. The first weeding often comprised chemical weeding (Londax or Herbextra) and the second weeding was mostly manual. Farmers applied 40–100 kg ha$^{-1}$ less NPK fertilizer than recommended (300 kg ha$^{-1}$). Farmers applied urea as topdressing in two equal splits. In the 2000 dry season, urea dose was 30 kg ha$^{-1}$ higher and in the 2000 wet season 50 kg ha$^{-1}$ lower, than the recommended 150 kg ha$^{-1}$.

### Detailed monitoring of low productive spots

The low productive spots appeared shortly after transplanting. Plants inside the spots did not or slowly recover from the transplanting shock (Figure 3.2). Some plants died and plant biomass, height and tiller number of the remaining plants increased at a much slower rate inside than outside the spots (data not shown). Plants inside the spots reached panicle initiation and flowering one to four weeks later than plants outside the spots. Plants showed stunted growth and a dark-brown coloration of the older leaves, often preceded by the white coloration of the leaf midrib (chlorosis). These observations are very similar to what is commonly seen in Zn-deficient rice plants (Dobermann and Fairhurst, 2000). In the course of the growing season, signs of rice blast and brown leaf spot were seen, but appearance of these diseases was not specific to the low productive spots. Grain yield of plants in the center of the low productive spots was less than 20% of grain yield outside the low productive spots (Figure 3.3).

*Table 3.1: The main crop and soil management variables for 2000 dry (DS) and wet season (WS) surveys and the 2001 dry season farmer trials.*

| | | | 2000 dry season | | | 2000 wet season | | | 2001 dry season | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Units | Local Recommend. | n | Mean | SD[1] | n | Mean | SD | n | Mean | SD |
| Cultivated area | ha | – | 20 | 0.5 | 0.1 | 20 | 0.7 | 0.3 | 29 | 0.5 | 0.0 |
| Sowing date | | DS 1–15 Jan<br>WS < 30 Jul | 20 | 16 Jan | 4 | 20 | 16 Jul | 2 | 29 | 6 Jan | 1 |
| Transplanting | DAS[2] | 20–25 | 20 | 33 | 4 | 20 | 31 | 4 | 29 | 47 | 10 |
| Harvest date | DAS | ± 125 | 20 | 158 | 12 | 20 | 136 | 9 | 29 | 176 | 73 |
| Transplanting density | cm×cm | < 20×20 | 20 | 15×20 | 22 | 20 | 15×20 | 75 | 29 | 15×20 | 46 |
| NPK basal application | DAT[3] | 0–14 | 20 | 2 | 1 | 20 | 5 | 2 | 29 | 9 | 6 |
| 1st Urea topdressing | DAT | 15–25 | 20 | 27 | 3 | 20 | 31 | 4 | 29 | 21 | 5 |
| 2nd Urea topdressing | DAT | 38–45 | 20 | 46 | 3 | 20 | 48 | 3 | 29 | 54 | 10 |
| Applied NPK | kg ha$^{-1}$ | 300 | 20 | 260 | 104 | 20 | 200 | 0 | 29 | 200 | 0 |
| Applied Urea | kg ha$^{-1}$ | 150 | 20 | 180 | 100 | 20 | 100 | 4 | 29 | 150 | 0 |
| Timing 1st weeding | DAT | 13–23 | 20 | 27 | 5 | 20 | 30 | 9 | 29 | 19 | 8 |
| Timing 2nd weeding | DAT | 36–43 | 20 | 41 | 5 | 20 | 39 | 10 | 29 | 52 | 11 |
| Weeding | | – | 20 | 70% chemical<br>30 % manual | | 20 | 55% chemical<br>45% manual | | 29 | 93% chemical<br>7% manual | |
| Yield | t ha$^{-1}$ | – | 20 | 4.7 | 0.9 | 20 | 3.4 | 0.8 | 29 | 3.4 | 1.0 |

[1] SD = standard deviation
[2] DAS = days after sowing
[3] DAT = days after transplanting

*Figure 3.2: Even ± 4 weeks after transplanting, many plants had not or slowly recovered from the transplanting shock.*

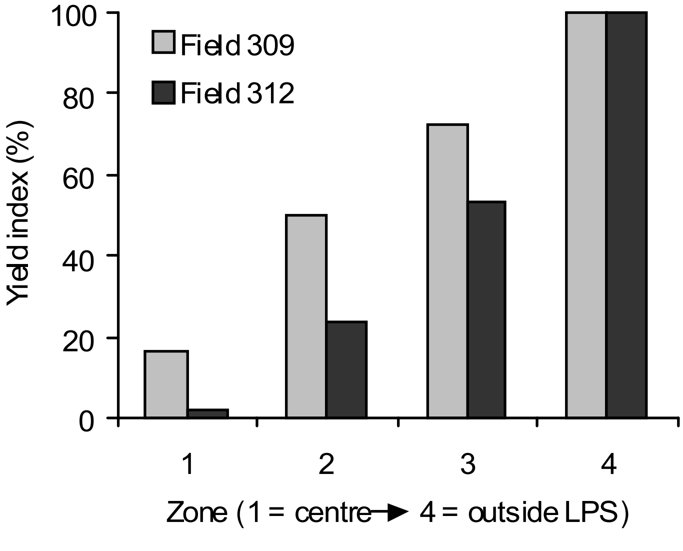

*Figure 3.3: Rice yields in the low productive spots (LPS), as a percentage of yields measured outside the LPS of two fields (nr. 309 and 312) in the 1999 wet season.*

*Table 3.2: Average basic parameters for the studied topsoils (0–40 cm).*

| | n | Mean | SD[1] | Range |
|---|---|---|---|---|
| Clay (%) | 20 | 42.3 | 6.2 | 37.3 – 52.2 |
| Silt (%) | 20 | 31.8 | 5.8 | 23.5 – 29.2 |
| Sand (%) | 20 | 25.9 | 3.5 | 23.5 – 31.4 |
| $Ca^{2+}$ ($cmol_c\ kg^{-1}$) | 20 | 10.6 | 1.7 | 7.5 – 13.3 |
| $Mg^{2+}$ ($cmol_c\ kg^{-1}$) | 20 | 5.5 | 1.6 | 2.2 – 8.2 |
| $K^+$ ($cmol_c\ kg^{-1}$) | 20 | 0.18 | 0.03 | 0.14 – 0.21 |
| $Na^+$ ($cmol_c\ kg^{-1}$) | 20 | 0.04 | 0.01 | 0.01 – 0.05 |
| CEC ($cmol_c\ kg^{-1}$) | 20 | 17.9 | 2.3 | 13.3 – 21.8 |
| pH-$H_2O$ | 20 | 8.0 | 0.3 | 7.1 – 8.3 |
| pH-KCl | 20 | 6.5 | 0.4 | 5.5 – 7.4 |
| EC ($dS\ m^{-1}$) | 20 | 0.3 | 0.1 | 0.1 – 0.6 |
| $CaCO_3$ (%) | 20 | 0.2 | 0.1 | 0.06 – 0.38 |
| $P_{Olson}$ ($mg\ kg^{-1}$) | 20 | 4.8 | 1.0 | 3.3 – 6.8 |
| $P_{Bray1}$ ($mg\ kg^{-1}$) | 20 | 2.4 | 1.9 | 0.6–9.5 |
| $Zn_{total}$ ($mg\ kg^{-1}$) | 20 | 24.3 | 3.1 | 21.0 – 28.7 |
| $Zn_{DTPA}$ ($mg\ kg^{-1}$) | 20 | 0.21 | 0.10 | 0.08 – 0.46 |

[1] SD = standard deviation

Grain yield of plants in the center of the low productive spots was less than 20% of grain yield outside the low productive spots (Figure 3.3). Shoot samples taken at the end of the vegetative growth stage (i.e., 45 days after transplanting) contained 2.6 ± 0.3 g P $kg^{-1}$ and 15.7 ± 2.3 mg Zn $kg^{-1}$ independent of sample site. At maturity, P and Zn concentrations in the straw had decreased to 1.0 ± 0.5 g $kg^{-1}$ and 11.8 ± 2.1 mg $kg^{-1}$ respectively. Analysis of the soils inside and outside the low productive spots revealed no significant differences (not shown) in soil texture and basic chemical parameters (Table 3.2). The pH was slightly alkaline (7.5–8.5), but EC (< 0.2 dS $m^{-1}$) and exchangeable sodium percentage (ESP < 3) were both small. Both inside and outside the low productive spots, few to moderate amounts (FAO, 1990b) of calcareous nodules (5–20 mm) were found. Calcite was present in the sieved fraction (< 2 mm) of all soil samples, but $CaCO_3$ content was generally small (0.2%) in the sampled topsoil (0–20 cm).

Researcher-managed trials

Averaged over the two fields and seasons, yields of T1 (3.5 t $ha^{-1}$) and T2 (3.7 t $ha^{-1}$) were significantly ($p < 0.001$) smaller than yields of T3 and T4 (both 5.0 t $ha^{-1}$) (Figure 3.4). Treatment, field, season and field × season interaction all had significant effects ($p < 0.001$) on yield. All other interactions (field × treatment, season × treatment, field × treatment × season) were not significant. The surface area of the low productive spots seemed to decrease in time for all treatments (Figure 3.5), but more so in treatments T3 and T4.

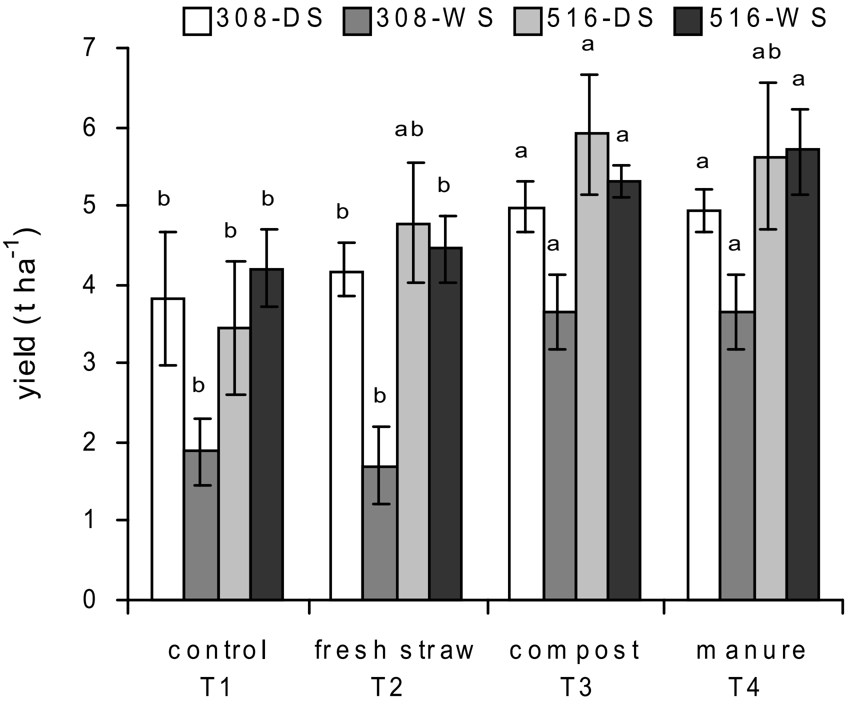

Figure 3.4: *Average paddy yields ± standard deviation for different organic amendment applications (5 t ha$^{-1}$) treatments in the 1999 dry season (DS) and wet season (WS) at two sites (fields 308 and 516). Letters represent LSD test significant differences ($p<0.05$) between treatments for each field ×season combination.*

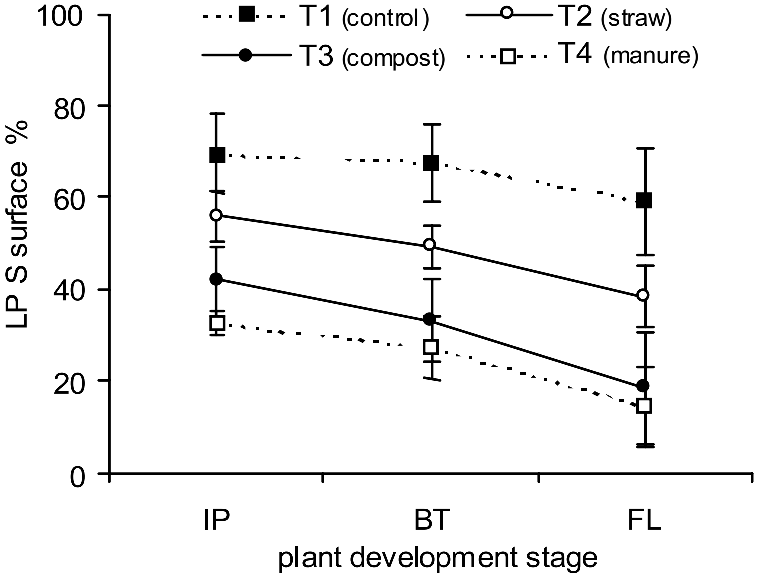

Figure 3.5: *The percentage surface area of the field that is part of the low productive spots (LPS) ± standard error for different organic matter applications at panicle initiation (PI), heading (BT) and flowering (FL).*

## Farmer-managed trials

Most farmers (27) used the ITA123 rice cultivar and a minority (2 farmers) used variety TOX728-1. Transplanting was generally three weeks delayed, when compared to recommendations. The prolonged growing cycle (176 instead of 125 days) showed that crop development was delayed; a phenomenon that generally occurs with low temperatures, Zn deficiency or P deficiency. Fertilizer use was similar for all farmers and was close to local recommendations (Table 3.1). However, the second urea application was somewhat delayed. The application of 10 kg Zn $ha^{-1}$ increased farmer yield (TF) by 80% from 3.4 to 6.0 t $ha^{-1}$ (Figure 3.6). Applying more Zn ($T_{20\text{-}Zn}$) did not further increase yields. The application of decomposed straw (TS) increased farmer yields by 60% to 5.3 t $ha^{-1}$. The application of Zn fertilizer increased $Zn_{STRAW}$ significantly ($p<0.01$). $Zn_{STRAW}$ was 13 mg $kg^{-1}$ in the TF and TS treatment and 30 mg $kg^{-1}$ in $T_{10\text{-}Zn}$ and $T_{20\text{-}Zn}$ treatments. Trends were similar for $Zn_{GRAIN}$ with small concentrations (9 mg $kg^{-1}$) for TS and TF and larger concentrations (16 mg $kg^{-1}$) for $T_{10\text{-}Zn}$ and $T_{20\text{-}Zn}$. P straw concentrations were significantly higher ($p<0.01$) for TF (1.0 g $kg^{-1}$) than for treatments TS (0.7 g $kg^{-1}$), $T_{10\text{-}Zn}$ and $T_{20\text{-}Zn}$ (0.6 g $kg^{-1}$). In the Zn treatments, P concentrations are close to deficiency (< 0.6 g $kg^{-1}$) (Kanareugsa, 1980). Nitrogen concentrations in the straw showed similar trends with significant differences ($p<0.001$) between TF (7.3 g $kg^{-1}$), TS (5.9 g $kg^{-1}$), and $T_{10\text{-}Zn}$ and $T_{20\text{-}Zn}$ (4.7 g $kg^{-1}$). The small plant N concentrations correspond to N dilution in the straw and Zn treatments (Figure 3.7: $T_{20\text{-}Zn}$ not represented, but similar to $T_{10\text{-}Zn}$) and plant N accumulation in farmer fields (TF).

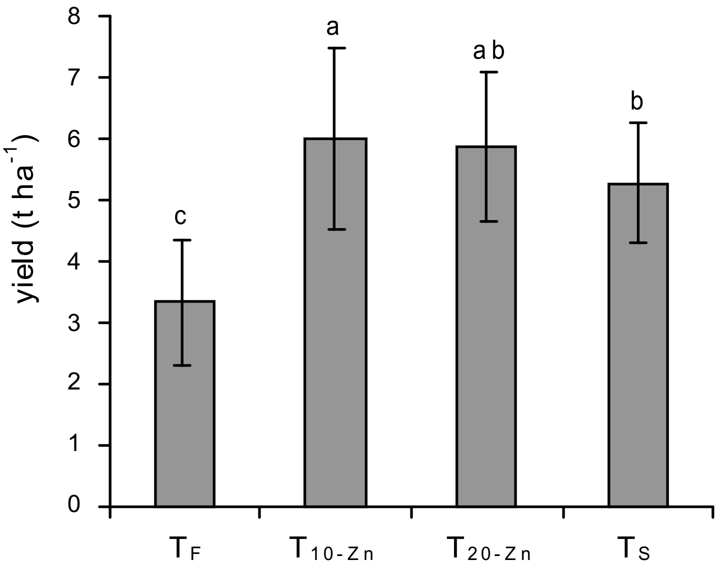

*Figure 3.6* *Average paddy yields ± standard deviation for the 2001 dry season farmer-managed trials ($T_F$ = control; $T_{10\text{-}Zn}$ = 10 kg Zn $ha^{-1}$; $T_{20\text{-}Zn}$ = 20 kg Zn $ha^{-1}$; $T_S$ = 5 t decomposed straw $ha^{-1}$). Letters represent differences ($p<0.05$) between treatments for LSD-test.*

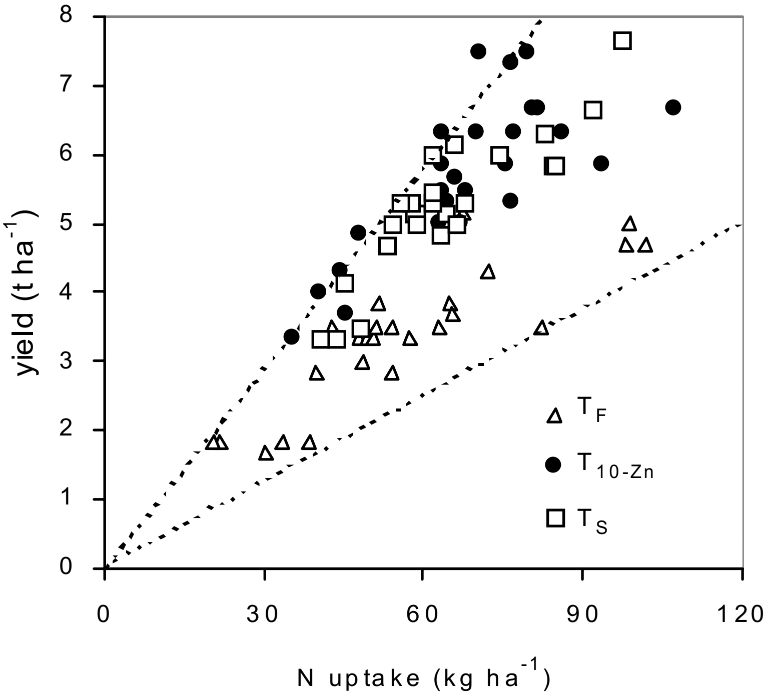

*Figure 3.7* *Grain yield as a function of N uptake in the total aboveground plant matter of the 2001 dry season farmer-managed trials. Slopes of the linear functions represent maximum dilution (upper line) and maximum accumulation (lower line) according to Witt et al. (1999)*

Evaluating the impact of earthworms on crop growth

Farmers correctly identified zones containing few and relatively large numbers of earthworms. Averaged over the two fields, 14 earthworms per sample were counted in the infested zones and zero earthworms in the non-infested zones. However, it appeared that areas that farmers rated 'earthworm infested' did not necessarily coincide with the presence of low productive spots. We found that plant height was similar in both fields and did not differ between infested and non-infested zones. Tiller number showed a positive linear relation ($R^2$ = 0.57) with the log-transformed earthworm number; i.e., tiller number increased with increasing amounts of earthworms, contrary to the framers' hypothesis.

## 3.4 Discussion

The impact and origin of the low productive spots

The yield decline observed by AMVS in the early to mid 1990s coincides with the appearance of low productive spots. Farmers estimated a yield reduction of 25 to 50%, which corresponds to the AMVS reported yield decline from 5.7 t ha$^{-1}$ in 1991 to yields between 2.2 t $ha^{-1}$ and 4.4 t $ha^{-1}$ from 1995 onward. Similar yield differences were observed in the 2001 dry season farmer-managed trials; i.e., with Zn fertilizer application yields were 6.0 t $ha^{-1}$ and without 3.4 t $ha^{-1}$. The spots occupy up to 70% of the surface area (see Figure 3.5) and grain yield of plants in the low productive spots is less then 50% (see Figure 3.3) of the grain yield observed outside the low productive spots.

We hypothesize that the low productive spots are the result of zinc deficiency. Low Zn availability on alkaline and calcareous soils is well known (e.g., Neue et al.; 1998, Dobermann and Fairhurst, 2000) and is related to the strong adsorption of Zn on carbonate minerals and/or the precipitation of ZnS in poorly-drained soils (Ponnamperuma, 1975). The average DTPA-extractable Zn content was 115 times lower than the total Zn, indicating that available Zn is only a small fraction of the total soil Zn content. The average DTPA-extractable Zn concentration (0.2 mg $kg^{-1}$) was well below the critical level (0.8 mg $kg^{-1}$) for Zn deficiency in lowland rice (Dobermann and Fairhurst, 2000). The observed range (0.08–0.46 mg $kg^{-1}$) at the study site was also low when compared to areas elsewhere in the world where Zn deficiency occurs; e.g., 0.08–49.4 mg $kg^{-1}$ in old rice soils of the Cauvery Delta in India (Savithri et al., 1999), 0.9–3.0 mg $kg^{-1}$ in the Fars province of Iran (Karimian and Yasrebi, 1995), 0.4–9.8 mg $kg^{-1}$ in Ontario Canada (Shang and Bates, 1987), 0.3–4.9 mg $kg^{-1}$ in Minnisota US (Moraghan et al, 1999). Contrary to what we would expect, we found no significant differences in soil characteristics or DTPA-extractable Zn content outside and inside the spots. However, uneven plant growth and patches of poorly established hills in the field are typical for zinc deficient soils in irrigated rice (Dobermann and Fairhurst, 2000). Since Zn availability is largely determined by soil carbonate content and redox potential, we assume that minor (undetectable) differences in these parameters at short distances can cause minor differences in Zn availability, triggering Zn deficiency in some areas, while other areas seem unaffected.

The results of the farmer-managed trials and the detailed monitoring of the low productive spots strengthen the hypothesis that the presence of the spots is related to Zn deficiency. The relative low yields of plots that received no Zn fertilizer, the observed prolongation of the vegetative stage, the appearance of chlorotic leaf midribs, and the brown coloration of older leaves (Neue et al., 1998) all indicate that the origin of the low productive spots was related to Zn deficiency. The delay in crop development resulted in a prolonged growing cycle, late harvest and often late application of urea fertilizer, when compared to local recommendations (Table 3.1). Zn concentrations in rice shoots (15.7 mg $kg^{-1}$) and straw (11.8 mg $kg^{-1}$) were low, confirming that Zn deficiency was plausible (Yoshida, 1981). However, plant Zn concentrations inside and outside the spots did not significantly differ. We suspect that increased plant growth by plants outside the spots was achieved by diluting Zn in the plant to a maximum. Zn concentrations in the straw and grain of TF and TS plots were about half the concentrations found in $T_{10\text{-}Zn}$ and $T_{20\text{-}Zn}$. The basal application of 10 or 20 kg Zn $ha^{-1}$ (as $ZnSO_4.7H_2O$) completely eradicated the spots. In plots that received Zn fertilizer, plants no longer showed a prolongation of the vegetative growth, and flowering and maturity were homogeneous throughout the plot. Moderate to high N and P concentrations in straw of TF are signs of N and P accumulation in the plant (see also Figure 3.7), which proves that other factors than N or P are limiting growth when neither Zn fertilizer nor decomposed straw are applied. Although diseases were present, they were not specific to the low productive spots and often appeared at growth stages when the spots were already clearly visible in the field. Although farmers rated the presence of 'excessive' numbers of earthworms as a production constraint, high earthworm numbers did not coincide with the appearance of low productive spots, nor did earthworms influence plant growth negatively. On the contrary, plant growth was positively correlated to size of the earthworm population.

Solutions and recommendations

Application of zinc fertilizer is certainly the most convenient and rapid solution for increasing yields. Further study will be necessary to determine the optimum zinc fertilizer dose. Most likely, zinc fertilizer dose can be lowered, as recommendations for lowland rice is generally below 6 kg Zn ha$^{-1}$ (Dobermann and Fairhurst, 2000; Savithri et al., 1999).

Zinc fertilizer is currently not available in Burkina Faso and little is known about its future price. Zinc fertilizer used in the trials was imported from Ivory Coast. Farmer cooperations and AMVS are currently trying to convince fertilizer companies to import zinc fertilizer. For the time being, the application of organic amendments (i.e., manure, compost or decomposed straw) seems the only readily available alternative to increase yields by 1.5 to 2.0 t ha$^{-1}$. The application of organic amendments is likely to slightly improve Zn availability, although Zn concentrations in straw and grain of straw amended plots remained at Zn deficient levels (13 mg kg$^{-1}$ and 9 mg kg$^{-1}$, respectively); i.e., the application of organic amendments increased Zn uptake, but Zn concentrations remained at the deficiency level, indicating that application of Zn fertilizer could further increase yield. The positive effect of organic matter amendments is probably related to dissolution of carbonate-bound Zn. Increased dissolution of native carbonate salts upon organic matter application has been observed in other Sahelian irrigation schemes (Chapter 6). The decrease in the surface area of the low productive spots during the growing season (Figure 3.5) is probably related to crop recovery at later growth stages, as often observed on zinc deficient soils (Dobermann and Fairhurst, 2000).

At present, farmers apply 200 kg ha$^{-1}$ of NPK fertilizer (12 24 12) and 180 kg urea ha$^{-1}$, corresponding to 106 kg N ha$^{-1}$ and 21 kg P ha$^{-1}$. This P dose is relatively large and N dose relatively small when compared to other Sahelian sites with similar yield potential (Wopereis et al., 1999; Haefele et al., 2001). However, P-Olson and P-Bray1 were both low (Dobermann and Fairhurst, 2000) and P concentrations in the straw decreased to near deficiency levels in the high-yielding Zn plots. This indicates that the current P fertilizer dose is needed when yield levels are high (>5 t ha$^{-1}$). However, at yield levels of 3 to 4 t $ha^{-1}$, the current P fertilizer dose is large and does not only result in a poor cost-benefit ratio, but is likely to decrease Zn availability (Dobermann and Fairhurst, 2000). When Zn fertilizer was applied, yields nearly doubled, but N was diluted to the maximum (see Figure 3.7). This indicates that plants in the Zn treated plots were most likely N deficient. Hence, if Zn fertilizer is applied farmers can further improve yields by increasing urea fertilizer applications.

Farmer knowledge and practices

Farmers were keen participants during all phases of the research project. Farmers made a good quantitative estimate of the yield losses as a result of the presence of low productive spots. Farmers were correct in presuming a relationship between the calcareous nature of the soil (i.e., nodules and white efflorescence on the soil surface) and the presence of the low productive spots. Some farmers mentioned poor drainage as a cause for the low productive spots. Poor drainage can indeed contribute to a further lowering of zinc availability (Ponnamperuma, 1975). Farmers correctly mentioned that the low productive spots were related to a soil-born problem. However, their perception about the relation between low productivity spots and earthworms could not be confirmed. It would be interesting to try to better understand farmers' experiences in this respect. In general, their observations have increased our understanding of the nature and origin of the low productive spots.

Low doses and late timing of N and P fertilizer, in combination with insufficient weeding have often been considered the main cropping constraints in many Sahelian schemes (Wopereis et al., 1999; Haefele et al., 2001 and 2002). However, not sub-optimal N and P fertilizer and weed management, but Zn deficiency appeared to be the main constraint limiting yield at the study site; application of Zn fertilizer nearly doubled yield, while fertilizer and weed management remained unchanged. This corresponds to our general impression that most cropping practices were close to the local recommendations. The only exception was NPK fertilizer dose, which farmers applied in lower quantities (200 kg $ha^{-1}$) than what AMVS recommended (300 kg $ha^{-1}$). Note, however, that a lowering in NPK dose would even be recommended at current low yield levels (3 to 4 t $ha^{-1}$) and in view of the negative effect of P on Zn availability (Dobermann and Fairhurst, 2000). In other words, current farmer fertilizer management is more profitable than what is recommended by the AMVS at present.

The application of organic amendments was, according to farmers, the only potential solution to the problem. Indeed, the application of 5 t $ha^{-1}$ manure, compost or decomposed rice straw did prove to be very beneficial. However, application of organic resources can only partly solve the problem. Its application is labor intensive, which is a constraint for many farmers that have a small family and/or limited financial resources. The organic matter amendment doses used in the trials are slightly higher than the average straw yield, which is approximately equal to grain yield. Vegetable cropping is an important activity in the Sourou Valley, so rice cropping is likely to compete for the limited quantity of organic amendments available, especially manure and compost. Furthermore, yields may continue to decline with organic amendments, as the soil Zn stock might be further depleted.

Both researchers and farmers appreciated the pre-testing of Zn fertilizer applications in two farmer fields in the 2000 wet season (Section 3.2 - farmer-managed trials). The positive visual effect of Zn fertilizer application did not only convince researchers to pursue their research on Zn deficiency, but also motivated farmers to participate in the 2001 farmer-managed trials. Farmers were eager to find a solution rapidly and the pre-testing method allowed the identification and dissemination of promising techniques, without spending years of conducting capital and labor intensive trials at a research station.

## 3.5 Conclusions

We conclude that the appearance of low productive spots in the Sourou irrigation scheme and the subsequent yield decline in the early mid-nineties was caused by Zn deficiency. Yield losses due to Zn deficiency are between 25–50%. The large heterogeneity in plant growth at short distances in the field and the small (undetectable) differences in soil properties suggest that rice plants are currently around the break-even point of Zn deficiency-sufficiency. Hence, a further minor decrease in Zn availability could have a devastating impact on future rice yields. Although it is commonly accepted that large quantities of carbonate salts suppress Zn availability, it will be important to better identify the mechanism that led to Zn deficiency at the study site, as total soil Zn content in the 0–0.2 m root zone is over 100 times larger than DTPA-extractable Zn and over 50 times larger than a Zn fertilizer dose of 10 kg ha$^{-1}$. So far, little is known about importance of Zn deficiency in irrigated rice cropping in the Sahel. Most of the Sahelian rice soils have an alkaline-calcareous character, as found at the studied site. Thus, Zn deficiency could possibly become an important cropping constraint for other Sahelian irrigation schemes in the near future.

Farmers were able to correctly relate the calcareous nature of the soil to the appearance of the low productive spots. Farmers identified the application of decomposed rice straw as a possible solution. Although application of Zn fertilizer is less labor extensive and more effective than use of organic amendments, it is not yet available in Burkina Faso. Despite efforts by AMVS and farmer cooperations to obtain Zn fertilizer, the application of decomposed rice straw seems the only solution available to farmers at present. Despite the relative recent introduction (± 15 years ago) of irrigated rice cropping, most farmers proved to have good understanding of cropping constraints and possible solutions. This study shows that farmer knowledge can be used to guide research on rice cropping constraints in the Sahel, for the mutual benefit of both farmers and researchers.

# 4 THE EFFECT OF STRAW APPLICATION ON RICE YIELDS AND NUTRIENT AVAILABILITY ON FARMER-IDENTIFIED DEGRADED AND NON-DEGRADED SOILS IN A SAHELIAN IRRIGATION SCHEME

*P.J.A. van Asten, L.M. Mulder, P.M. van Bodegom, M.J. Kropff*

Like elsewhere in the Sahel, actual rice yields (3–5 t $ha^{-1}$) in an irrigation scheme in central southern Mauritania are far below yield potential (± 8 t $ha^{-1}$). Earlier studies showed that N and P deficiency were the main agronomic constraints contributing to the small yields. We investigated the potential of rice straw application as a means to improve yields and fertilizer efficiency on an alkaline calcareous soil (pH 8.2) and a neutral soil (pH 6.2). Farmers at the study site classified the alkaline soil as 'degraded' (DG) and the neutral soil as 'non-degraded' (NDG). Application of 5 t straw $ha^{-1}$ increased yields by 1.1 t $ha^{-1}$ on average, independent of soil type and fertilizer dose. Only at near-potential yields (> 7 t $ha^{-1}$) was the positive effect of straw application no longer significant. Straw application improved N availability, but not P availability. The improved N availability was attributed to N mineralized from the straw, from increased mineralization of soil organic matter (SOM) with a low C:N ratio (< 7.2) and from increased recovery efficiency of applied mineral fertilizer N (urea). We deduced that improved N fertilizer recovery upon straw application was due to reduced nitrification-denitrification losses. The low N fertilizer recovery on the alkaline DG soil compared to the pH neutral NDG soil was attributed to $NH_3$ volatilization losses. Straw application did not affect $NH_3$ volatilization. Similar studies in Asia showed little short-term effects of straw on yield and N uptake. We hypothesize that the positive effect of straw application at our study site is related to the soils' low C content (< 4.3 g $kg^{-1}$) and low C:N ratio when compared to most lowland rice soils in Asia. Straw is a low-cost alternative to improve yield and fertilizer recovery efficiency at the study site.

**Keywords**: *Oryza sativa* L. N availability, P availability, volatilization, nitrification-denitrification, crop residue management.

## 4.1 Introduction

The irrigation scheme of Foum Gleita in southern central Mauritania is one of the many typical large Sahelian irrigation schemes that were developed to improve food security after the devastating droughts in the 1970s and 1980s. Rice (*Oryza sativa* L.) is the dominant crop in these irrigation schemes. Actual yields are often low (3–5 t ha$^{-1}$) and far from potential (7–10 t ha$^{-1}$), which raises questions about the economic viability of the costly irrigation schemes in this region (Bélières et al., 1995). There is an urgent need to improve productivity while keeping input costs low. Mineral fertilizers make up about 20% of the total production costs for rice farmers in the Sahel (Donovan et al., 1999). In Chapter 2, we concluded that mineral fertilizer management (composition, dose and timing) in Foum Gleita is often far from optimal, contributing largely (25–50%) to the observed yield gap (potential minus actual yield). Yield levels are also largely related to soil type in Foum Gleita. Productivity problems are more pronounced on farmer-identified 'degraded' (DG) soils than on the so-called 'non-degraded' (NDG) soils. The DG soils are calcareous (pH 7–8.5) while the NDG soils are not calcareous (pH 6–7.5). In Chapter 2 we observed that soil N and P supply and N and P fertilizer recovery efficiency (REN, REP) were much lower on the DG soils (REN = 0.26; REP = 0.13) than on NDG soils (REN = 0.40; REP = 0.22). We hypothesized that low REN and REP on the DG soils were partly due to N volatilization and P immobilization; processes that become more important with increasing carbonate levels. An expensive measure to improve nutrient availability, especially on the DG soils, would be to increase mineral fertilizer dose. Alternatively, methods could be developed that improve the low recovery efficiencies of the applied mineral fertilizer dose, while keeping labor requirements at an acceptable level. Rice farmers in Asia have experimented for a long time with the use of straw as a low-cost source of nutrients and as a way to improve soil quality (Ponnamperuma, 1984). Most rice farmers in Foum Gleita currently burn their straw, although some straw is used at cattle fodder at the end of the dry season (DS). The effect of rice straw incorporation on soil quality, nutrient uptake and rice yields has been studied in a wide range of soil and climatic conditions. Ponnamperuma (1984) stated that the yield advantage due to straw incorporation over straw burning or removal is about 0.4 t ha$^{-1}$, and it increases with time as soil fertility builds up. Dobermann and Fairhurst (2000) stated that there is little short-term effect of straw incorporation on rice yield, but that long-term benefits are significant. However, the majority of the studies, on which the above authors have based their conclusions, were conducted at neutral to acidic lowland soils in Asia. Ponnamperuma (1984) cited Chatterjee et al. (1979) who found that, averaged for three nitrogen levels and two seasons, incorporation of 10 t ha$^{-1}$ of fresh straw increased yields by 1.8 t ha$^{-1}$ to 5.2 t ha$^{-1}$ on an alkaline clay loam soil in India.

Apart from being a nitrogen source, straw application might improve the recovery efficiency of applied mineral N fertilizer. Microbial organisms that decompose the straw can act as a N sink (immobilization), when straw is incorporated shortly before transplanting in farmers fields (Witt et al., 2000). However this effect is temporary and a few weeks to months later, microbial organisms will act as a nutrient source (mineralization) (Yoneyama and Yoshida, 1977; Ponnamperuma, 1984; Witt et al., 2000). Olk et al. (2000) concluded from a literature review that the process of immobilization-mineralization buffers soil inorganic N at levels conducive to adequate plant growth while reducing excessive vegetative growth early in the season, leaching, and large denitrification losses. In addition to preventing excessive leaching and denitrification losses, it well possible that this N buffering effect also decreases the high volatilization losses on the DG soils through temporary immobilization of some of the Urea-$NH_4^+$.

Straw application may also influence phosphorus availability. Straw is a source of P and upon decomposition part of this P may become available to plants. However, microbial organisms that decompose organic matter can also (temporarily) immobilize P, as is the case with N. The availability of P increases upon flooding, mainly because of increased solubility of Fe-bound P and increased solubility of Ca-bound P (Dobermann and Fairhurst, 2000). The release of Fe-bound P largely depends on the soil's redox level (Eh), while the dissolution of Ca-bound P depends on the soil's pH and $pCO_2$. The application of fresh organic matter enhances the decrease in both Eh and pH of submerged calcareous-alkaline soils (Chorom and Rengasamy, 1997). Hence, straw can also indirectly improve P availability through solubilization of Fe- and Ca-bound P. Therefore, we hypothesize that plant available P increases directly and indirectly when straw is applied.

From the above it follows that the straw amendments can have direct and indirect beneficial effects on N and P availability. However, the extent of these beneficial effects and their impact on yield will depend largely on the importance and duration of microbial N and P immobilization. In order to verify whether straw can be used as a low cost amendment for the improvement of yields in Foum Gleita, we conducted a series of field trials with straw on both DG and NDG soils. In addition, on-station pot trials were carried out to further examine the effect of straw amendments on processes that determine N and P availability. Hereby, special attention was given to the identification of processes that affect REN and REP on the alkaline DG soils.

## 4.2 Materials and methods

### Site description

Foum Gleita (16°08'N, 12°46'W) is situated in central southern Mauritania. The climate in Foum Gleita is typically Sahelian with erratic rainfall (250 mm $yr^{-1}$) between July and October, followed by a short cool period (November–February) with minimum air temperatures as low as 10 °C and a hot dry season (March–June) with maximum air temperatures up to 46 °C. The Foum Gleita scheme was built in 1984 and a large dam allows for gravimetric irrigation throughout the year. The irrigation water quality varies throughout the year (pH 7.5–8.3 and EC 0.10–0.25 dS $m^{-1}$) as a function of rainfall and evaporation.

The DG soils are found on the upper and middle slopes and have formed *in situ* from the schist parent material (< 0.8m). The soil contains very little phosphorus ($P_{Bray1}$ 2.6 mg $kg^{-1}$). The NDG soils (>1.2m) are found further down slope on the lower slopes, river banks, and depressions. These soils have a (partly) alluvial origin and contain more phosphorus ($P_{Bray1}$ > 4.4 mg $kg^{-1}$) (Chapter 2). In both soils organic carbon % and C:N ratio are low (Table 4.1).

*Table 4.1: Soil characteristics of the top horizon (0–20cm) and average straw nutrient content in the straw trails on the 'degraded' (DG) and 'non–degraded' (NDG) soil.*

| | DG | NDG |
|---|---|---|
| Texture class[1] | SiCL | L |
| $pH_{1:2.5}$ | 8.2 | 6.2 |
| $EC_{1:5}$ dS $m^{-1}$ | 0.17 | 0.06 |
| CaCO3 [g $kg^{-1}$] | 4.0 | <0.5 |
| CEC [$cmol_c kg^{-1}$] | 14.8 | 11.0 |
| ESP [%] | 18.0 | 1.5 |
| C [g $kg^{-1}$] | 4.3 | 4.0 |
| N total [g $kg^{-1}$] | 0.6 | 0.7 |
| C:N ratio | 7.2 | 5.7 |
| $N_{STRAW}$ [g $kg^{-1}$] | 4.4 | 5.4 |
| $P_{STRAW}$ [g $kg^{-1}$] | 0.4 | 1.0 |
| N in 5 t straw [kg] | 22 | 27 |
| P in 5 t straw [kg] | 2 | 5 |

[1] FAO (1990)

Field trials

Researcher-managed straw trials were conducted in the 2000 and 2001 dry seasons (DS) on both a DG and NDG soil. Topsoil pH on the DG site ($pH_{1:2.5}$ = 8.2) was higher than on the NDG site ($pH_{1:2.5}$ = 6.2). Rice variety IR-13240-108-2-2-3, in Mauritania known as Sahel 108, was used. Four levels of fertilizer dose (NP) and two levels of straw application (S) resulted in the following eight treatments: T1 = control; T2 = N; T3 = N + ½P; T4 = N + P; T5 = control + S; T6 = N + S; T7 = N + ½P + S; T8 = N + P +S. Treatments were repeated three times in a randomized block design. The total N fertilizer (urea) dose was 175 kg $ha^{-1}$ divided in three split applications (40% three weeks after transplanting, 40% at panicle initiation and 20% at heading). The P fertilizer was 26 kg/ha and the ½P dose was 13 kg $ha^{-1}$. All P fertilizer was applied before transplanting (basal application) in the form of triple super phosphate (TSP). The straw applied was fresh at a rate of 5 t dry matter $ha^{-1}$. The straw was incorporated loosely into the topsoil 3 days before transplanting, which coincided with soil tillage practices.

Individual plot size was 5 m × 5 m. Paddy yields were estimated from a 6 $m^2$ harvest area in the center of the plot. Grain moisture content was determined from a 12-hill sub sample. Grain yields were corrected to 14% moisture content. Harvest index was determined from oven-dry (3% moisture content) straw and grain weight of the 12-hill sub sample. Straw yield was derived from the harvest index and the 6 $m^2$ grain yield. Concentrations of N in grain and straw at maturity were determined using the Micro-Kjeldahl method (Bremner, 1996). Plant phosphorus concentrations were measured using the method of Yoshida et al. (1976). Total N and P uptake were estimated from the

N and P concentrations of straw ($N_{STRAW}$, $P_{STRAW}$) and grain ($N_{GRAIN}$, $P_{GRAIN}$), and straw and grain yield. Soil N supply was estimated from total N uptake in T1 and soil P supply followed from the total P uptake in T2. Straw N supply was estimated as the difference in N uptake between T5 and T1, and straw P supply was similarly calculated using the difference in P uptake between T6 and T2, respectively. REN and REP were calculated as the additional nutrient uptake (total nutrient uptake minus soil and straw nutrient supply) following fertilizer application divided by the inorganic fertilizer dose.

Pot trials

A large quantity of topsoil (0–0.3m) was sampled in a rice field bordering the field trials at the degraded soil ($pH_{1:2.5} = 8.2$). The sample was brought to the WARDA station in Saint Louis, air-dried and homogenized, before being transferred to plastic 10 liter polypropylene buckets (Ø 25cm). The trial consisted of 14 treatments, varying in fertilizer application (NP), straw application (S) and the presence of a plastic cover (C) (Table 4.2). Each treatment was replicated 3 times, resulting in a total of 42 pots, which were distributed randomly over two large concrete basins. Pots were saturated with water 5 days before transplanting. Three thirty-day-old rice seedlings of IR-12340-108-2-2-3 (Sahel 108) were transplanted into each pot to the soil micro-environment of irrigated rice. Space between the pots was filled with earth and a border of rice plants was transplanted around the pots to mimic light competition. A water layer of about 3 cm was maintained in the basins to irrigate the border rice seedlings and to ensure the same soil and water temperatures (± 30 °C) for all pots. Total N dose (urea) was 0.86 g N pot$^{-1}$ (~175 kg N ha$^{-1}$) and ½N dose was 0.43 g N pot$^{-1}$, divided in three split applications (40%, 40%, and 20% at early tillering, panicle initiation, and flowering). Urea was dissolved in irrigation water prior to application to ensure an even distribution over the soil. Straw dose was 24.5 g pot$^{-1}$ (~5 t ha$^{-1}$) and P dose was 0.65 g $P_2O_5$ pot$^{-1}$ (~26 kg P ha$^{-1}$). Straw was mixed with the wet topsoil three days before transplanting. TSP granules were supplied simultaneously. The C treatment pots were covered with transparent plastic directly after the first N application, in order to suppress $NH_3$ volatilization losses. In the middle of the covered pots a 10 cm high PVC tube (Ø 12.5 cm) was inserted into the soil (2 cm deep), through which the plants could grow. The floodwater inside the PVC tubes was covered with a layer of small polystyrene foam balls in order to diminish gas exchange between the water surface and the atmosphere. Similar PVC tubes were

*Table 4.2: The treatments of the pot trials.*

| Treatments | |
|---|---|
| P | P S |
| N P | N P S |
| N | N S |
| ½N P | ½N P S |
| P C | P S C |
| N P C | N P S C |
| ½N P C | ½N P S C |

P = Phosphorus application of 26 kg P ha$^{-1}$
N = Nitrogen application of 175 kg N ha$^{-1}$
½N= Nitrogen application of 87,5 kg N ha$^{-1}$
S = Straw application of 5 t ha$^{-1}$ and
C = Pot cover with transparent plastic and acidification of the floodwater to a pH ≤ 7.4

also used in non-covered pots to eradicate bias effects. In order to allow the monitoring of the flood water quality, a round hole (Ø 1 cm) was made in the plastic cover. The hole was closed with a rubber stopper. Furthermore the floodwater pH in the C treatments was maintained low ($pH < 7.0$), as an additional means to decrease volatilization, which is very low when $pH < 7.0$ (Mikkelsen, 1987). Daily acidification of the floodwater of C treatments started directly after the first N application using 0.1 M HCl. Irrigation water originated from the Senegal River. Its alkalinity was increased up to 1.5 mmol $l^{-1}$, using $Na_2CO_3$, in order to mimic average irrigation water quality in Foum Gleita. Pots were irrigated daily to maintain constant water levels. In order to avoid excessive salt stress, the floodwater in the pots was renewed at 2, 25 and 45 days after transplanting (DAT). The flood water pH, EC and temperature were measured daily (at 9.00 am and at 3.00 pm) in all pots. Concentrations of $NH_4^+$ in the floodwater of all treatments were monitored at 1, 3, 5 and 7 days after N application. The $NH_4^+$ samples were taken at 9.00 am and stored at 4°C in air-tight polypropylene bottles (20 ml), after acidification to $pH < 2.0$ with concentrated HCl. Concentration of $NH_4^+$ was determined with the salicylate method (Nelson, 1983). Floodwater $NO_3^-$ concentrations of treatments N and NS treatments were monitored after the 2nd N application using a Skalar (SA-40) continuous-flow analyzer. Plant available P in the soil was monitored using resin capsules (UNIBEST, Inc., Bozeman MT). Each capsule contained 2.2 mmol$_c$ of cation + anion exchange capacity and had a total surface area of 11.4 $cm^2$. The process of absorption by the resins is considered to mimic important exchange, solubilization, and transport processes occurring in the rice rhizopshere (Dobermann et al., 1997). Soil samples of the N, NP, NS and NPS treatments were taken at 0, 32 and 92 days after transplanting (DAT). Each sample was split into three sub-samples and transferred into airtight polypropylene bottles. A resin capsule was inserted into each sub-sample and the bottles were stored for incubation at a dark place. Resin capsules were removed from a first series of sub-samples after 1 day of incubation. The same procedure was repeated after 7 and 14 days of incubation. P was extracted from the resin capsules using HCl as an extractant (Dobermann et al., 1997). The *in situ* soil pH at 5 cm depth was measured weekly, using pH penetration electrodes. Harvest was done at maturity and yield and yield components were determined. Plant samples were oven-dried (80°C). Plant N, P and K concentrations, nutrient uptake, and fertilizer recovery rates were determined as in the straw field trials.

### Statistical analyses

Statistical analyses were conducted using the software package SPSS for Windows (Version 10.0). Significance of factors and interactions on yield and plant nutrient concentrations from the field trials were analyzed for each season using ANOVA. Means for yields were compared using least square difference (LSD) test. Means for $P_{RESIN}$ of different treatments were compared with the LSD test. Significance of factors and interactions on $NH_4^+$ peak concentrations of floodwater in the pot trials after the 2nd and 3rd urea application were analyzed using ANOVA. A one-tailed student t-test was used to compare $NO_3^-$ concentrations in floodwater of the pot trials.

## 4.3 Results

### Yield, REN and REP in the field trials

Yields are shown for each soil type × season combination in Figure 4.1. The trial at the DG soil suffered from excessive bird damage during the 2001 DS and no proper yield data were obtained. However, plant measurements (height, tiller number) at mid-season showed that plant growth trends were similar to what was found in the 2000 DS (data not shown). The positive effect of straw on rice growth was already noticeable at early tillering stage. Both fertilizer dose (NP) and straw application (S) showed significant effects ($p < 0.001$) on yield at both sites in the 2000 DS, but the straw effect was not significant ($p = 0.09$) in the 2001 DS. There was no significant NP × S interaction in any of the trials, nor was there any S × soil type interaction in the 2000 DS trials; i.e.,

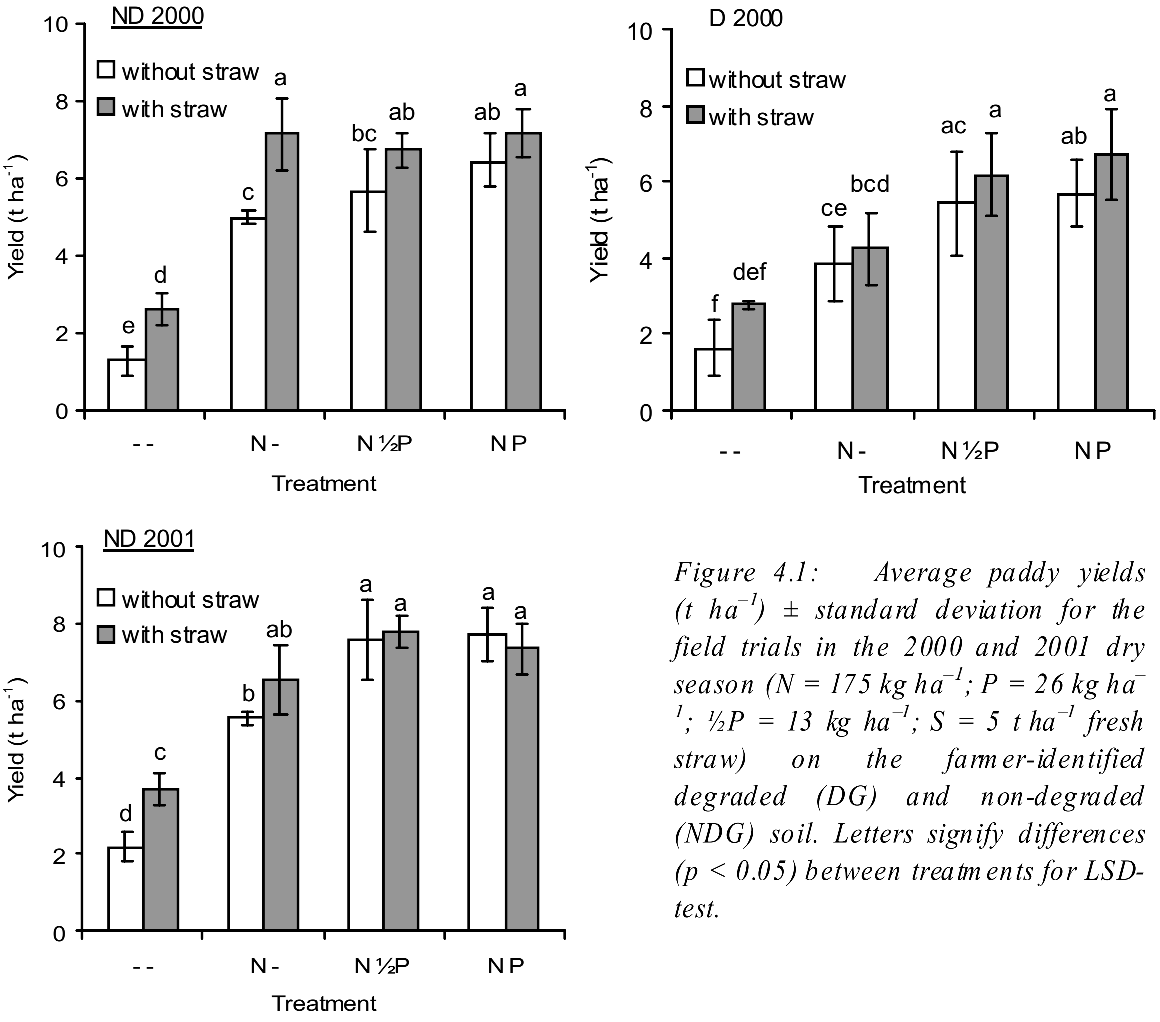

*Figure 4.1: Average paddy yields ($t\ ha^{-1}$) ± standard deviation for the field trials in the 2000 and 2001 dry season ($N = 175\ kg\ ha^{-1}$; $P = 26\ kg\ ha^{-1}$; $½P = 13\ kg\ ha^{-1}$; $S = 5\ t\ ha^{-1}$ fresh straw) on the farmer-identified degraded (DG) and non-degraded (NDG) soil. Letters signify differences ($p < 0.05$) between treatments for LSD-test.*

Table 4.3: *Average N uptake (kg ha$^{-1}$) and recovery efficiency of applied Urea-N (kg kg$^{-1}$) for the field trials in the 2000 and 2001 dry season (DS). (N = 175 kg ha$^{-1}$; P = 26 kg ha$^{-1}$; ½P = 13 kg ha$^{-1}$; S = 5 t ha$^{-1}$ fresh straw).*

| | T1 | T2 | T3 | T4 | T5 | T6 | T7 | T8 |
|---|---|---|---|---|---|---|---|---|
| | – – – | N – – | N½P – | N P – | – – S | N – S | N½P S | N P S |
| *Dry season 2000* | | | | | | | | |
| Non-degraded soil | | | | | | | | |
| Uptake | 21 | 78 | 94 | 94 | 39 | 106 | 109 | 130 |
| Recovery efficiency | – | 0.33 | 0.42 | 0.42 | – | 0.38 | 0.40 | 0.52 |
| Degraded soil | | | | | | | | |
| Uptake | 20 | 55 | 75 | 66 | 33 | 63 | 86 | 107 |
| Recovery efficiency | – | 0.20 | 0.32 | 0.26 | – | 0.17 | 0.30 | 0.42 |
| *Dry season 2001* | | | | | | | | |
| Non-degraded soil | | | | | | | | |
| Uptake | 27 | 84 | 103 | 112 | 36 | 120 | 134 | 140 |
| Recovery efficiency | – | 0.32 | 0.43 | 0.49 | – | 0.48 | 0.56 | 0.59 |

Table 4.4: *Average P uptake (kg ha$^{-1}$) and recovery efficiency of applied TSP-P (kg kg$^{-1}$) for the field trials in the 2000 and 2001 dry season (DS). (N = 175 kg ha$^{-1}$; P = 26 kg ha$^{-1}$; ½P = 13 kg ha$^{-1}$; S = 5 t ha$^{-1}$ fresh straw).*

| | T1 | T2 | T3 | T4 | T5 | T6 | T7 | T8 |
|---|---|---|---|---|---|---|---|---|
| | – – – | N – – | N½P – | N P – | – – S | N – S | N½P S | N P S |
| *Dry season 2000* | | | | | | | | |
| Non–degraded soil | | | | | | | | |
| Uptake | 6 | 18 | 22 | 24 | 10 | 22 | 22 | 28 |
| Recovery efficiency | – | – | 0.29 | 0.21 | – | – | 0.05 | 0.25 |
| Degraded soil | | | | | | | | |
| Uptake | 4 | 8 | 11 | 11 | 6 | 8 | 13 | 17 |
| Recovery efficiency | – | – | 0.22 | 0.10 | – | – | 0.40 | 0.35 |
| *Dry season 2001* | | | | | | | | |
| Non–degraded soil | | | | | | | | |
| Uptake | 6 | 18 | 27 | 30 | 11 | 21 | 26 | 31 |
| Recovery efficiency | – | – | 0.67 | 0.45 | – | – | 0.39 | 0.37 |

the yield increasing effect of straw was independent of fertilizer dose and soil type. Straw application (S) had a significant positive effect on $N_{STRAW}$ and $N_{GRAIN}$ concentrations ($p<0.05$) in all trials. Fertilizer dose (NP) also had a significant ($p<0.05$) effect on $N_{GRAIN}$ in all trials. At the NDG soil in the 2001 DS trial NP and NP x S interaction had significant effect ($p<0.05$) on $N_{STRAW}$. The $N_{STRAW}$ and $N_{GRAIN}$ were significantly ($p<0.001$) lower at the DG soils, with values ranging from 0.38–0.57

g kg$^{-1}$ and 0.71–0.98 g kg$^{-1}$ respectively on the DG soil and from 0.42–0.76 g kg$^{-1}$ and 0.80–1.23 g kg$^{-1}$ respectively on the NDG soil. Soil type × S and soil type × NP interactions for $N_{STRAW}$ and $N_{GRAIN}$ were not significant. Nitrogen uptake and REN are shown in Table 4.3. REN was on average 0.10–0.31 kg kg$^{-1}$ higher on the NDG soils, when compared to similar treatments on the DG soils. On both soils, both the applications of P and straw improved REN values. Straw application had no significant effect ($p>0.05$) on $P_{STRAW}$ at both soils, but fertilizer dose had ($p<0.05$). $P_{STRAW}$ on the DG soil was 0.02–0.03 mg kg$^{-1}$ in treatments that received N in combination with no or half the P dose, and 0.04–0.06 mg kg$^{-1}$ in treatments that received full P dose. Trends were similar on the NDG soil, but $P_{STRAW}$ was distinctly higher (0.07–0.13 mg kg$^{-1}$). P uptake and REP for all field trials are presented in Table 4.4. When straw was applied, REP increased on the DG soil but decreased on the NDG soil. When no straw was applied in the 2000 DS trials, REP values were distinctly higher on the NDG soils, when compared to the DG soils. On the NDG soil, REP was distinctly higher in the 2001 DS, when compared to the 2000 DS, because residual effect of P application was not taken into account in the calculation of the recovery fraction.

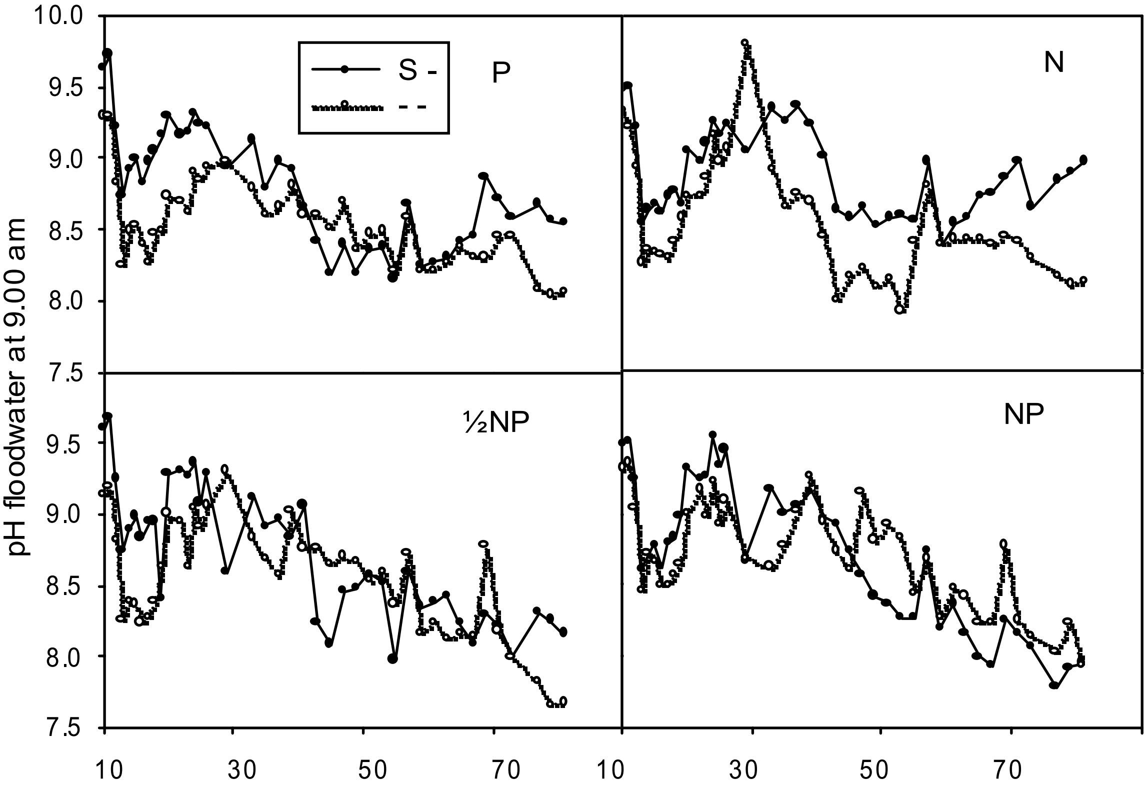

*Figure 4.2: Evolution of floodwater pH of non–covered treatments in the pot trials: S ~ 5 t straw ha$^{-1}$; N~175 kg ha$^{-1}$; ½N~87.5 kg ha$^{-1}$; P~26 kg ha$^{-1}$.*

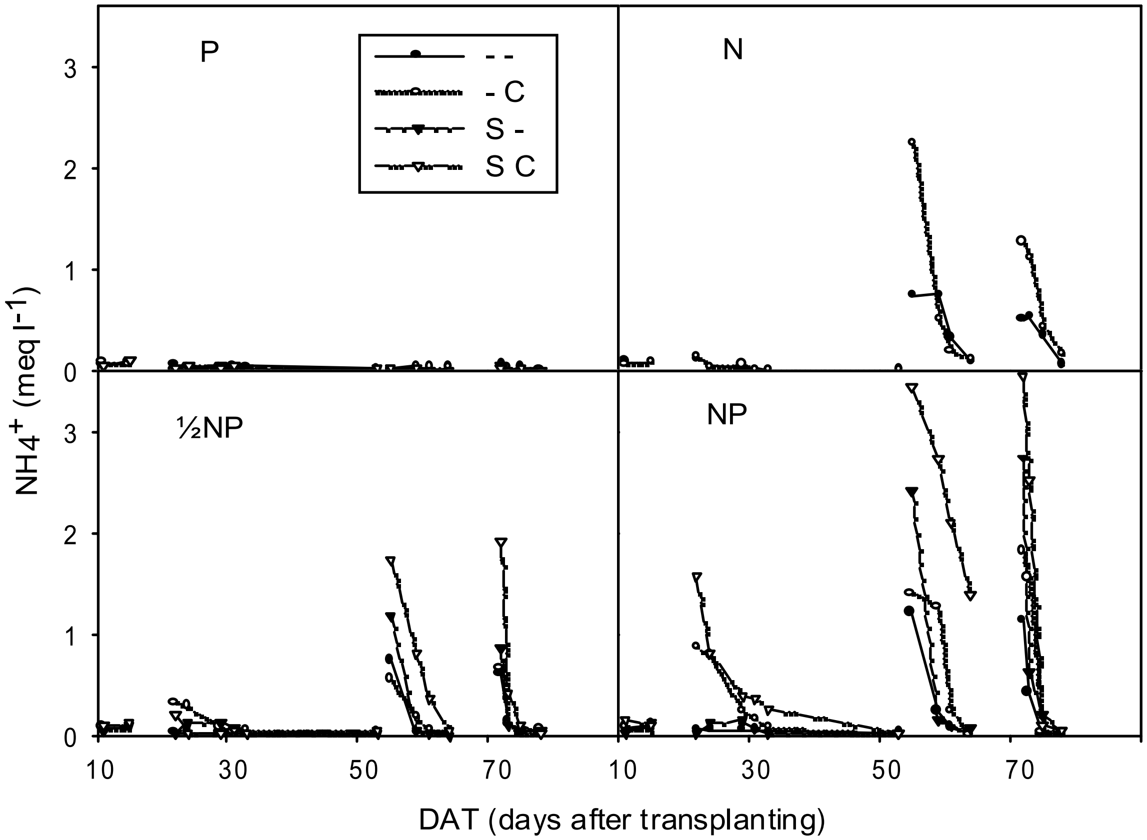

*Figure 4.3: Floodwater $NH_4^+$ concentrations for treatments in the pot trials; S ~5 t straw $ha^{-1}$; C = cover, N ~175 kg $ha^{-1}$; ½N ~87.5 kg $ha^{-1}$; P ~26 kg $ha^{-1}$.*

Monitoring soil and water chemistry changes in the pot trial

The results of the morning (9.00 am) floodwater pH measurements ($pH_{FW}$) are shown in Figure 4.2. The results of the afternoon (3.00 pm) measurements showed a very similar pattern, but pH values were about 1 pH unit higher for treatments with P fertilizer application and 0.3 pH unit higher for treatments without P fertilizer application (not shown). Straw amendments had little effect on the floodwater pH and pH values in all treatments were high enough to support substantial volatilization.

The changes of floodwater $NH_4^+$ concentrations can be observed in Figure 4.3. The peak $NH_4^+$ concentrations after the second and third application showed very similar trends; factors N, C, S were all significantly ($p<0.01$) contributing to the $NH_4^+$ concentrations and there was significant ($p<0.05$) interaction of N × C, N × S and C × S after the second N application. $NH_4^+$ peak concentrations in treatments that received N fertilizer decreased in the following order: SC > S- > -C > --. $NH_4^+$ concentrations after the 1st urea application were only measured from day 5 onward, due to technical problems. On day 5 after the 1st N application, the C treatments had distinctly higher $NH_4^+$ concentrations.

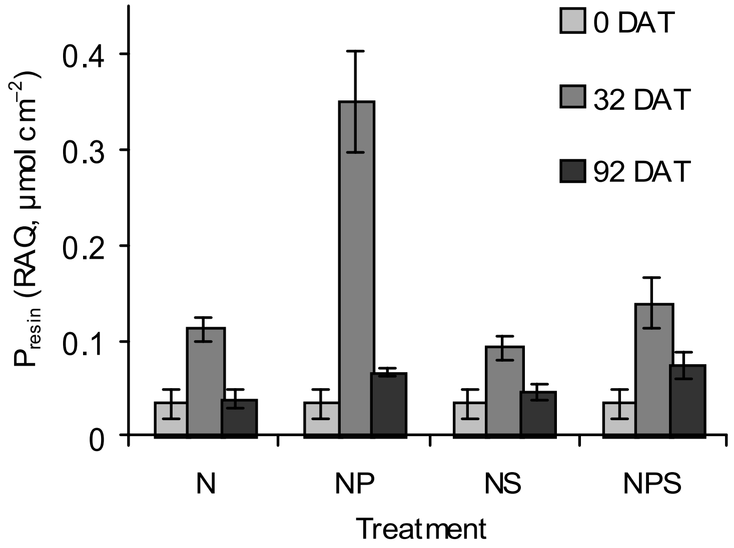

*Figure 4.4: Mean $P_{RESIN}$ ± standard deviation of the pot trials at 0, 32 and 92 days after transplantation and 7 days incubation period.*

Floodwater $NO_3^-$ concentrations for the treatments N and NS varied little during the first 15 days after the second N application, but average concentration in the N treatment (0.063 mmol $NO_3^-$ $l^{-1}$) was significantly higher ($p<0.05$) than in the NS treatment (0.026 mmol $NO_3^-$ $l^{-1}$).

The incubation time (0, 7, and 14 days) had no significant effect on the P absorbed at the resin capsules ($P_{RESIN}$). In Figure 4.4, $P_{RESIN}$ values are shown for samples from 0, 32, and 92 DAT and 7 days incubation. At 0 DAT, no differences between the treatments were found. At 32 DAT, $P_{RESIN}$ in the NP treatments was significantly higher ($p < 0.001$) than in the N, NS and NPS treatment. At 92 DAT, $P_{RESIN}$ in the NP and NPS treatments were significantly higher ($p < 0.05$) than treatments N and NS.

## 4.4 Discussion

In the 2000 DS field trials, the application of straw increased yields by 1.1 t $ha^{-1}$ on average independent of soil type or fertilizer dose. In the 2001 DS, a similar yield increase (1.3 t $ha^{-1}$) could be observed, except for the treatments that received both N and P fertilizer on the NDG soil. The yields of the latter treatments were close to yield potential (± 8 t $ha^{-1}$) (Chapter 2), so no further yield increase could be expected.

On both soils, application of 175 kg $ha^{-1}$ N significantly increased yields. Adding P fertilizer further increased yields at both soils, indicating the occurrence of N-P co-limitation. In the 2000 DS, yield levels were similar at both soil types for all treatments, except for the treatments that received N fertilizer but no P fertilizer. Yields for the latter treatments were lower at the DG soil than on the NDG soil, indicating that P deficiency was more severe on the DG soils. The plant P concentrations and P uptake confirm that P deficiency is more important on the DG soil; $P_{STRAW}$ on the DG soil was below the deficiency level (0.6 mg kg$^{-1}$) (Dobermann and Fairhurst, 2000) and particularly low (0.02–0.03 mg kg$^{-1}$) for treatments that received no P fertilizer. The outcome of the field trials was similar to findings in Chapter 2, where we concluded that P deficiency was a major constraint in Foum Gleita, especially on the DG soils when N, but no P fertilizer is applied.

In P deficient conditions (application of N, but no P fertilizer), P uptake did not or hardly increase when straw was applied on both soils. Hence, we conclude that straw has little direct effect on P availability and, as such, cannot be considered an important P source. Neither were there any signs that straw increased P availability by solubilizing part of the Fe or Ca-bound P in the soil. The effect of straw on REP was negative for the NDG soils, but slightly positive for the DG soil. However, P resin capsule measurements in the pot trials suggested negative effects of straw application on P availability in the DG soil. During the vegetative growth period (32 DAT), $P_{RESIN}$ in treatments that received P fertilizer was markedly lower when combined with straw application. A decrease in P availability during the first weeks after straw application is likely due to microbial immobilization. We conclude that P deficiency is an important yield-limiting factor, especially on the DG soils. However, there is little evidence that indicates that the application of straw improves P availability on either of the studied soils.

Knowing that straw application had little positive effect on P availability, while at the same time its application increased yields significantly, we have all the more reason to closely examine the effect of straw application on N availability on both soils. In treatments that received no fertilizer, straw application increased yield by 1.3 t ha$^{-1}$ on average and N uptake by 13 kg ha$^{-1}$ on average for both soil types. This equals about half the N applied through straw application. This is relatively high when compared to literature values on decomposition and nutrient release of rice straw under the prevailing conditions (e.g., Villegas-Pangga et al., 2000). Therefore, we assume that the positive effect of straw on N uptake in the non-fertilized plots is partly due to an additional release of soil N. The C:N ratio (< 7.2) of the Foum Gleita soils is low and in the range commonly found for soil microbiota (Reichardt et al., 2000). This indicates that microbial breakdown of soil organic matter (SOM) is primarily carbon limited. The application of crop residues with a high C:N ratio would provide soil microbes the necessary energy to mineralize part of the N-rich SOM. Hence, besides its direct effect (i.e., straw as an N-source), straw may indirectly improve N availability through mineralization of N-rich SOM.

Yield levels for treatments that received both N and P fertilizer were similar at both soils, but plant N concentrations, N uptake and REN were all much lower on the DG soils, when compared to the NDG soils. However, the increase of yield, N uptake and REN upon straw application was very similar on both soils. Hence, the straw effect was independent of soil type. In treatments that received the full N and P dose, straw application increased N uptake by 35 kg ha$^{-1}$ on average, which largely exceeds the N content of the applied 5 t straw ha$^{-1}$. The increased N uptake was also expressed in the REN, which increased by 0.10–0.16 kg kg$^{-1}$ for NP treatments at both soils.

Volatilization losses are likely to be high on the DG soil due to its high pH and calcareous character (Singh and Nye, 1986); floodwater pH in the pot trials (pH 7.5–10.5) was high enough to support substantial $NH_3$ volatilization losses (Reddy and Patrick, 1984). Chen et al. (1998) observed higher $NH_4^+$ concentrations when floodwater was acidified and attributed the phenomenon to decreased $NH_3$ volatilization. The consistently higher $NH_4^+$ concentrations in the floodwater of C treatments correspond to Chen's (1998) observations and are in line with the assumption that volatilization losses are important on the DG soils. In our introduction we hypothesized that the application of straw could decrease volatilization losses through temporal microbial immobilization of N. If so, this N buffering effect of straw should be highest on the DG soils and would lead to higher increases in REN than on the NDG soil. However, we did not observe this. Thus, the field trials provided no evidence that supported the hypothesis of decreased volatilization due to temporal microbial N-immobilization. Floodwater $NH_4^+$ measurements in the pots neither provided evidence for reduced volatilization when straw was applied. On the contrary, application of straw increased $NH_4^+$ in the floodwater, while floodwater pH in non-covered straw treatments remained as high as in non-straw treatments. This could even result in increased $NH_3$ volatilization rate in straw treatments. Boulden et al. (1991) already reported that increased urea hydrolysis, resulted in increased floodwater $NH_4^+$ concentrations, which enhanced $NH_3$ volatilization losses. Furthermore, if volatilization decreased as a result of straw application, we should have observed negative interaction of the factors C x S on $NH_4^+$ peak concentrations, but the increase in $NH_4^+$ peak concentrations upon straw application was equal or higher in C treatments when compared to the no C treatments. Therefore, we reject the hypothesis that the application of straw improves N availability through a decrease in $NH_3$ volatilization losses. This conclusion is in line with studies by Tian et al. (2001) and Gill et al. (1999) who found that application of rice straw had respectively no effect and an increasing effect on NH3 volatilization losses.

If straw application does not decrease volatilization losses, then what process improved REN on both soils? The answer may be found in the floodwater $NH_4^+$ measurements of the pot trial. The changes of $NH_4^+$ concentrations in the floodwater after the 2nd and 3rd N application showed similar patterns; i.e., both straw and cover significantly increased peak $NH_4^+$ concentrations. At 3–5 days after the 2nd and 3rd N application, $NH_4^+$ concentration in S treatments were no longer higher than those in treatments that received no S. We attribute the higher $NH_4^+$ peak concentrations in the S treatments to increased hydrolysis of the applied urea. This positive effect of organic matter application on urea hydrolysis was found earlier by several authors (Pattnaik et al, 1999;

Sahrawat, 1983). Gill et al. (1999) found in incubation trials that about 90% of the applied urea hydrolyzed within 2 days in wheat straw and green manure amended soil, compared to 5 days for the unamended soil. Hence, depletion of the (applied) urea stock was much more rapid in rice straw amended soil. A more rapid hydrolysis would lead to higher $NH_4^+$ peak concentrations initially, but would leave less urea for conversion to $NH_4^+$ later on (i.e., day 3–5). When we translate this to the straw and no straw treatments, it would mean that we expected $NH_4^+$ peak concentrations to be higher for the straw treatments, but the peak would be of shorter duration when compared to the no straw treatments. In other words, floodwater $NH_4^+$ concentrations should initially be lower, but later on be higher in the no straw treatments when compared to the straw treatments. However, after the initial $NH_4^+$ peak concentration (day 1 to 3), floodwater $NH_4^+$ in the straw treatments decreased to levels equivalent to, and not lower than, the $NH_4^+$ concentrations in the non-straw treatments (day 5–7). A plausible explanation is that the floodwater $NH_4^+$ concentration in the straw treatments remained relatively high due to decreased nitrification-denitrification losses.

It is generally agreed that the rate of denitrification is controlled by the rate of nitrification in flooded soils (e.g., Rao et al., 1984). Nitrification-denitrification is an important N fertilizer loss mechanism in irrigated rice; although estimates vary widely, most authors find losses of 10–60 % of applied N (Aulakh et al., 2001; Reddy et al., 1990; Reddy and Patrick, 1984). We have good reasons to believe that nitrification-denitrification losses are very high in Foum Gleita. Firstly, low to moderate REN indicates that substantial losses of applied N occur at both DG and NDG soil. Secondly, both soils contain little organic carbon (< 4.3 mg $kg^{-1}$) in combination with a low C:N ratio (< 7.2). Microbial activity is, therefore, C-limited. In incubation trials, $CO_2^-$ production rate was 4–5 times lower on the Foum Gleita DG soil when compared to some of Asia's most-studied rice soils (Mahaas, Gapan, Bugallon, Luisiana, and Pila) (van Bodegom, unpublished results). As a result, nitrifying bacteria would suffer little from oxygen competition with microbiota that decompose organic matter. Therefore, high nitrification rates could be sustained in the no-straw treatments. However, application of fresh organic matter likely increased competition for oxygen. Bacteria that aerobically breakdown organic matter outcompete the nitrifying bacteria for the limited amount of oxygen in the flooded soil (Focht and Verstraete, 1977). Increased oxygen competition would lead to decreased nitrification rate, and consequently decreased nitrification-denitrification losses. Adhya et al. (1996) showed that nitrification potential of samples from green-manure amended plots was distinctly less than that of samples from control plots in a rice soil. The lower floodwater $NO_3^-$ concentrations in S treatments are in line with this hypothesis, although the latter could also be attributed to higher denitrification rates as a result of rice straw application (Rochester and Constable, 2000). Both soils have similar %C and C:N ratios and we assume that these comparable characteristics explain why the positive effects of straw on N availability and REN are very similar on both soils.

## 4.5 Conclusions

In Foum Gleita, the application of rice straw has a strong positive effect (≈ 1.1 t $ha^{-1}$) on rice yields, independent of fertilizer dose and soil type. This is in contrast to most Asian rice soils that show little short-term effects of rice straw application on yield. The yield increase can be attributed to increased availability of N, not P. Increased N availability is likely due to N mineralized from the straw and N mineralized from the SOM, which has a low C:N ratio. Furthermore, the application of straw increased recovery efficiency of applied Urea-N. The improved REN could not be attributed to a decrease in volatilization losses, although we found substantial evidence that indicate that $NH_3$ volatilization losses play a major role on the more alkaline calcareous DG soil. We attributed the improved REN to reduced nitrification-denitrification losses. Nitrification is expected to play an important role in these soils. Compared to most of Asia's major rice soils, the soils have a low %C and low C:N ratio and relatively little SOM is broken down when soils are incubated. We estimate that nitrifying bacteria experience little competition for oxygen, which results in conditions that favor large nitrification-denitrification losses. Much more than in most Asian rice soils, application of fresh straw will lead to a relative large increase of the soil's %C and C:N ratio. Straw amendments will stimulate microbiota activity and increase oxygen competition. A decrease in available oxygen will slow down nitrification and subsequently limit nitrification-denitrification losses. We hypothesize that rice straw has similar effects on yield and REN on other rice soils with similar low %C and C:N ratio. To verify whether the positive effect of straw on N availability is related to the low %C and low C:N ratio of the soil, further research should be conducted using $^{15}N$-labeled urea. Farmers in Foum Gleita can use rice straw as a cheap alternative to increase yields and profitability on the short term, independent of their mineral fertilizer management and soil type.

# 5 ACTUAL AND POTENTIAL SALT-RELATED SOIL DEGRADATION IN AN IRRIGATED RICE SCHEME IN THE SAHELIAN ZONE OF MAURITANIA

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Salt-related soil degradation due to irrigation activities is considered a major threat to the sustainability of rice cropping under semi-arid conditions in West Africa. Rice productivity problems related to soil salinity, alkalinity and topographic position were observed in an irrigated rice scheme in southern central Mauritania. Detailed study of soils in a toposequence revealed that highest topsoil salinity and alkalinity were found at the shallow soils (< 1.2m) of the middle and upper slopes. Here, soils have formed *in situ* from the schist parent rock, which releases carbonate rich salts upon weathering. Within these soils large differences in salinity and alkalinity level occur at short distances, indicating minimal groundwater flow and a strong variation in the geochemical composition of the vertically positioned bedrock. Further down slope, soils have a (partly) colluvio-alluvial origin. Here, sedimentation during annual floods increased soil depth (> 2.5m) and salinity levels remained low due to leaching. Foum Gleita's irrigation water used is amongst the most alkaline in the Sahel. However, no clear indications of secondary salinization or alkalinization due to irrigation activities were observed. A comparison of historical data revealed no significant changes of topsoil salinity and pH over the last thirty years. The PHREEQC 2.0 model was used to study actual and potential development of soil salinity and alkalinity problems, by simulating excessive concentration of the irrigation water through evaporation. The changes into a strongly sodic alkaline solution due to precipitation of Mg-calcite and Mg silicate minerals did not fit with current composition of ground and surface water, which showed geochemical control of alkalinity at high concentrations. Incorporation of cation exchange processes, using a small (1.0 $\text{mmol}_c$ 100 g dry $\text{soil}^{-1}$) but calcium saturated CEC, resulted in a better fit with field data. Results indicate that the soil's buffer capacity to counteract alkalinization processes is large. However, the soil water and salt balance needs to be quantified in order to determine development rate and equilibrium levels of soil salinity and alkalinity for different soil type x water management combinations. This study does neither reject the hypothesis that salt-related soil degradation jeopardizes the sustainability of rice cropping in the Sahel, nor does it provide evidence for its verification. However, our results are in line with other studies in West Africa, in that current salt-related production problems are inherited, rather than being induced by irrigated rice cropping.

**Keywords**: Alkalinization, *Oryza sativa* L., toposequence, geochemical modeling

## 5.1 Introduction

In response to the droughts, which devastated crops and livestock in the Sahel in the 1970s and 1980s, massive investments were made by international donors and Sahelian countries to establish large irrigation schemes that would improve food security. Irrigated rice (*Oryza sativa* L.) was introduced as the main crop in these schemes. Rice cropping in the Sahel requires large amounts of water due to the high evaporative demand of the hot and dry climate. Although most irrigation waters in the Sahel are of good quality (i.e., low mineralized water), excessive concentration through evaporation can become hazardous as these waters often posses a positive Calcite Residual Alkalinity ($RA_{calcite}$ = Alkalinity – $Ca^{2+}$ in $mol_c\ l^{-1}$) (Valles et al., 1991; Bertrand et al., 1993). Soil degradation through salinization and alkalinization is considered one of the most important threats jeopardizing sustainable irrigated rice cropping in the Sahel (Bertrand et al., 1993, Boivin, 1995, Ceuppens et al., 1997, Boivin et al., 2002). Given the high investment costs of irrigated agriculture and the high costs of reversing alkalinization processes, precaution has to be taken when salt-related production problems are found in these environments. Crop production problems related to soil salinity and alkalinity have been reported throughout the Sahelian zone, i.e., the Senegal River delta (Wopereis et al., 1998), Office du Niger in Mali (Bertrand et al., 1993), Sourou Valley in Burkina Faso (Barro et al., 2000), Lossa in Niger (Marlet et al., 1998a) and Foum Gleita in Mauritania (Chapter 2). However, the results of soil studies at these sites were not always in line with the hypothesis that irrigated rice cropping increases salinization or alkalinization in the Sahel. On the contrary, Ceuppens and Wopereis (1999) showed that soil salinity in the Senegal River delta, originating from marine deposits, progressively decreased as a function of rice cropping intensity. In the Office du Niger, rice yields increased significantly over the last 10 years as a function of improved management practices, while soil alkalinity decreased slightly on the clayey soils used for rice cropping, but increased on the more sandy soils where vegetable cropping prevailed (Marlet, 1999a). In the Sourou Valley zinc deficiency in rice was found, which seemed more related to the calcareous origin of the parent material than to active alkalinization induced by irrigation (Barro et al., 2000). In the Lossa irrigation scheme, Barbiéro and Van Vliet-Lanoe (1998) found that soil alkalinization was no longer occurring and Barbiéro et al. (2001) observed that alkaline soils in Lossa de-alkalinized more rapid when cultivating the local fodder crop 'Bourgi' (*Echinochloa stagnina*) under submerged conditions, similar to irrigated rice cropping. From the above studies it follows that salt-related soil degradation in irrigated rice schemes in the Sahel needs careful study before drawing conclusions about its importance, its source and its (potential) changes.

In this study, we focus on the irrigation scheme of Foum Gleita (16°08'N, 12°46'W), southern central Mauritania (Figure 2.1). Constructed between 1985 and 1989, with a surface area of 1950 ha, it is one of the many recent and typically large irrigation schemes in the Sahel. Plans to extend the irrigation scheme to 3600 hectares have so far not been materialized, partly due to productivity problems. Both yield levels and cropped area started to decline a few years after installation of the scheme (SONADER, 1998). In addition, farmers increasingly complained about salinity problems and by 1993 about 12% (237 ha) of the area had been abandoned. Farmers and extension workers in the area fear that salt- related soil degradation threatens the existence of the irrigation scheme. In Chapter 2 we showed that productivity problems in Foum Gleita were the result of both soil quality problems and sub-optimal crop management. Rice yields increased and the percentage of abandoned land declined going from shallow (< 1.2 m to schist parent rock) soils upslope to deeper soils further down slope. The topsoil pH and EC values of shallow soils were significantly higher than for deeper soils, but they could not be classified as saline nor sodic following USDA classification. Furthermore, the $RA_{calcite}$ of the irrigation water varied between 0.5 and 1.2 mmol $l^{-1}$ (Chapter 2), which is up to 3 times higher than concentrations reported by Bertrand et al. (1993), Marlet et al. (1998b) and Boivin et al. (2002) for the Niger and Senegal River. This makes Foum Gleita irrigation water potentially more dangerous, with respect to alkalinization hazard, than the waters of the two major Sahelian rivers. We hypothesize that soil alkalinization will develop more rapidly in Foum Gleita than elsewhere in the Sahel. Hence, the site could act as an early warning system.

The objectives of this study were: (i) to characterize the distribution of alkaline salts in Foum Gleita, thereby focusing on both the (potential) role of the schist parent rock and the irrigation water as sources of alkaline salts, and (ii) to create insight into the dynamics of the soil degradation, by looking both backward (i.e., comparing actual to historical soil data) and forward (i.e., using geochemical simulation tools) in time, in order to obtain a semi-quantitative idea on the changes of these soils under the current irrigation practices.

## 5.2 Materials and methods

### The research site

The climate in Foum Gleita is typically Sahelian with erratic rainfall (250 mm $yr^{-1}$) between July and October, followed by a short cool period (November–February) with minimum air temperatures as low as 10 °C and a hot dry season (March–June) with maximum air temperatures up to 46 °C. Reference evapotranspiration is 2700 mm $yr^{-1}$.

The Gorgol Noire river watershed upstream of Foum Gleita is located on the ‘Mauritanides’ geological region, consisting mostly of Precambrian and Primary metamorphosed rock, which was folded and lifted in the Appalachian era (Carité, 1989). The soils have formed from a parent rock observed at a depth ranging from 0 m upslope to 4 m down slope, and consisting mostly of chloritoschists (green schist), calc-chloritoschists, micaschists, and quartz. In the schist, pyrite and iron oxide minerals are also frequently observed (Chiron, 1973). The vertically positioned schist has a north-south orientation. Sporadically some Secondary dolerite intrusions can be observed in the form of small rock outcrops (BCEOM, 1986). The landscape is characterized by

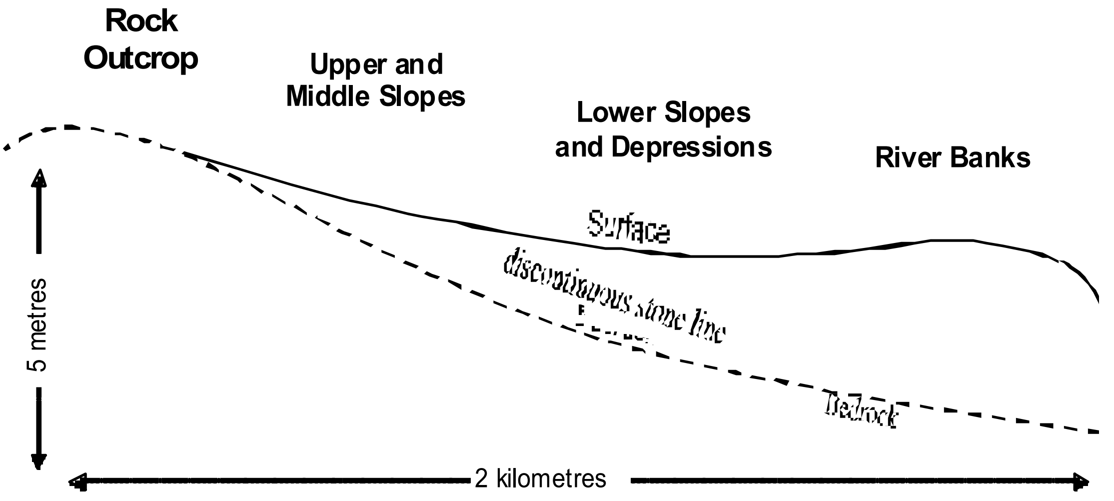

*Figure 5.1: Schematic cross section and corresponding geomorphological units of the Foum Gleita landscape.*

large slightly sloping (1–2%) barren plains, interrupted by rock outcrops and valley bottoms that are generally marked by the presence of some shrubs and small trees. Four major geomorphological units can be distinguished in the Foum Gleita irrigation scheme: (i) rock outcrops, (ii) the upper and middle slopes, (iii) lower slopes and depressions, and (iv) river banks (Figure 5.1). Soils of the landscape are shallow (< 1.2 m) and have formed *in situ* from the weathered parent rock. Further down slope, these soils are covered with local colluvial and alluvial deposits, which increases soil depth up to 3.5 m. Soils at the riverbanks consist of alternating sandy and clayey deposits parallel to the (former) river course and soils are up to 4 m deep (BCEOM, 1986).

The Gorgol river is a tributary to the Senegal River. Originally the river regime was intermittent with peak floods during rain events. The construction of the dam, blocking the river's narrow passage through the Oua-Oua mountain chain, reduced peak floods and assured a minimum discharge flow in the dry season. Water from a 8950 km$^2$ large watershed now accumulates in a shallow (3–4 m) but large artificial lake (25–170 km$^2$). The normal retention capacity of the dam is large (500 Mm$^3$) compared to simulated needs, but irrigation water is excessively used which sometimes leads to depletion of stocks down to the minimum storage capacity (100 Mm$^3$) required to ensure complete irrigation of the command area (SONADER, 1992). The general situation in Foum Gleita is one of excessive water use, poor canal maintenance, excessive weed growth, non-application of drainage practices and non-functional drains; conditions that are increasing the risk of alkalinization. Evaporative demand is very high and accounts for 60–70% of total water losses from the dam (SONADER, 1992). As a result, irrigation water quality varies throughout the year; i.e., pH = 7.5 and EC = 0.10 dS m$^{-1}$ just after the wet season and increasing to pH = 8.3 and EC = 0.25 dS m$^{-1}$ at the end of the dry season (Van Asten, unpublished).

### Detailed study of soils in a toposequence

The distribution pattern of (alkaline) salts was studied in a toposequence, in order to create further insight into the origin and changes of alkalinity in Foum Gleita. All soil samplings occurred between January 1999 and October 2000. Based on the BCEOM (1986) soil map and statements of farmers and extension workers, a 532 m long toposequence was selected for detailed study in the northern part of the irrigation scheme (irrigation block S4). The toposequence covered both the geomorphological units 'upper and middle slope', as well as the 'lower slope and depression' and can be considered representative for the majority of the Foum Gleita rice soils. The toposequence included four irrigation blocks (blocks I to IV) with an average width of 130 m (Figure 5.2). Each irrigation block was delimited by an irrigation canal upslope and a drainage canal down slope. Due to poor maintenance, drainage canals were shallow (< 60 cm), heavily weed infested and several contained water throughout the year, even during fallow periods. Farmers abandoned rice cultivation in the upper-slope irrigation block (block I), only a few years after construction of the scheme. According to farmers, soil quality was poor and the topsoil too stony.

In each irrigation block, 6 sample sites were chosen at evenly spaced intervals (20–25 m), resulting in a total of 24 sample points, covering the complete toposequence. A total of 158 samples was taken at 0.2 m depth interval up to the parent rock, using a hand auger. Samples were oven-dried (80 °C) and ground before analyzing pH in a 1:2.5 paste and EC in a 1:5 paste. Results of these analyses were interpolated in order to obtain cross-section maps. Soil pits were dug down to the parent rock at three different sites in the toposequence (Figures 5.2 and 5.3). The soil profiles were described following the FAO guidelines for soil profile description (FAO, 1990b) and soil samples were taken of each horizon for analysis. Samples were analyzed for pH and pH-KCl in a 1:2.5 paste and electrical conductivity (EC) in a 1:5 paste. Exchangeable bases ($Ca^{2+}$, $Mg^{2+}$, $K^{+}$, $Na^{+}$) were determined using an AAS after extraction with ammonium chloride. Cation exchange capacity (CEC) of the samples was determined as described by Chapman (1965). Soil texture was analyzed using the pipette method and classified following the FAO guidelines (FAO, 1990b). In 1997, eight piezometers were installed along the toposequence, covering irrigation blocks II, III and IV of the toposequence (Figures 5.2 and 5.3). Piezometers reached down to the parent rock or to hard quartz layers. In August 2000 all piezometers contained water, which allowed for simultaneous comparison of groundwater quality along the toposequence. Water samples were taken at each piezometer and filtered (0.45 μm) after on site (i.e., field) determination of pH, EC and alkalinity (Gran, 1952). Filtered sub-samples were acidified (pH<2.0), using concentrated $HNO_3$, and stored in polypropylene bottles for laboratory analysis. Cations were determined using an AAS, $Cl^{-}$ was analyzed colorimetrically using mercury(II)thyiocyanate (Fixen et al., 1988), $SO4^{2-}$ was determined colorimetrically using BaCl and methyl blue, and Si concentrations were determined following the

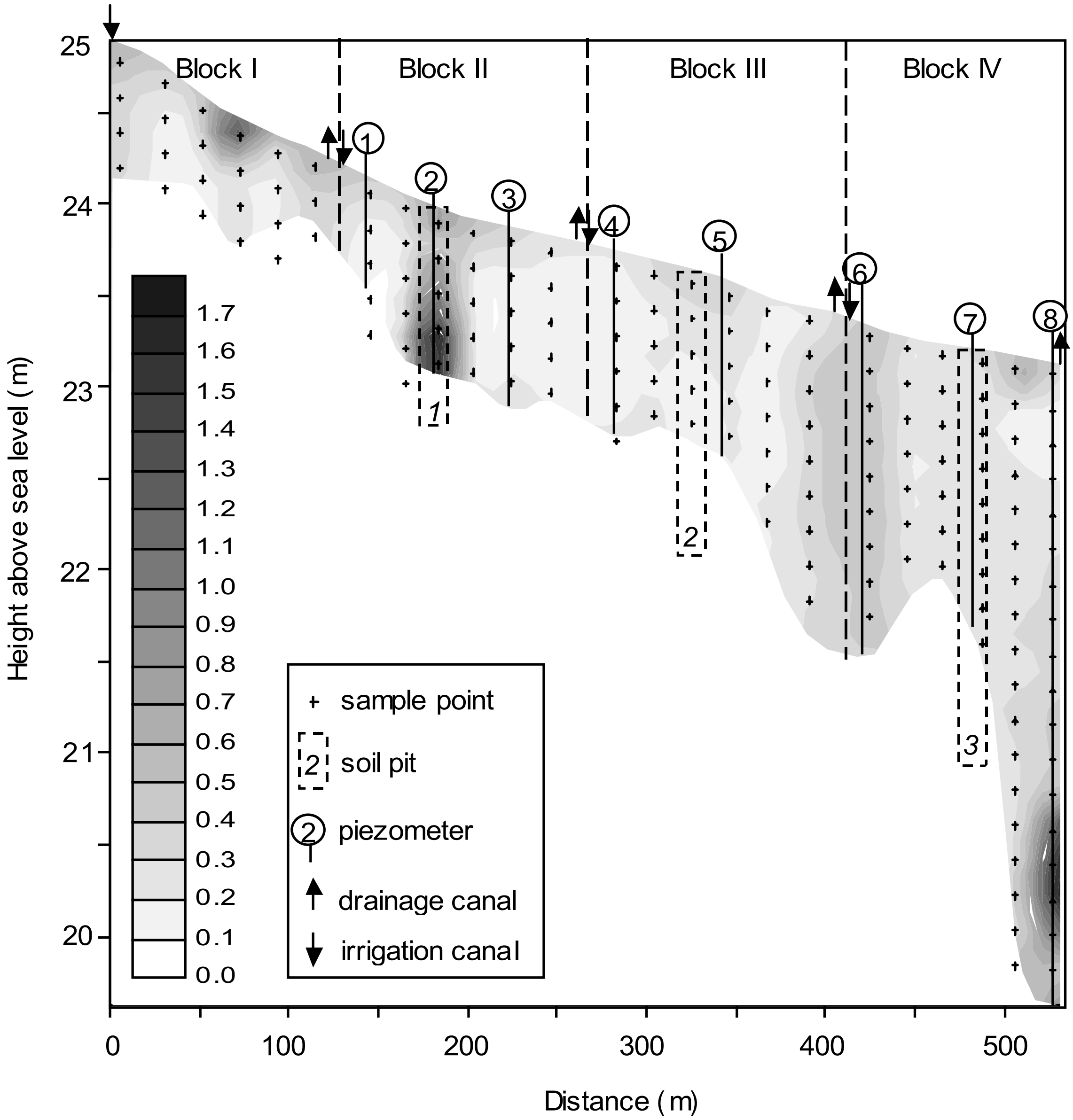

*Figure 5.2: Cross-section map of the toposequence showing EC (1:5 paste in dS $m^{-1}$), soil depth, the location of piezometers, irrigation and drainage canals, sample points, soil pits, and irrigation and drainage canals.*

silicomolybdic acid procedure (Jones and Dreher, 1996). Saturation indices (SI) for minerals defined in the WATEQ4 database were calculated using the PHREEQC 2.0 geochemical simulation model (Parkhurst and Appelo, 1999). This allowed for the assessment of minerals that could potentially precipitate in this environment, thereby altering the soil solution composition.

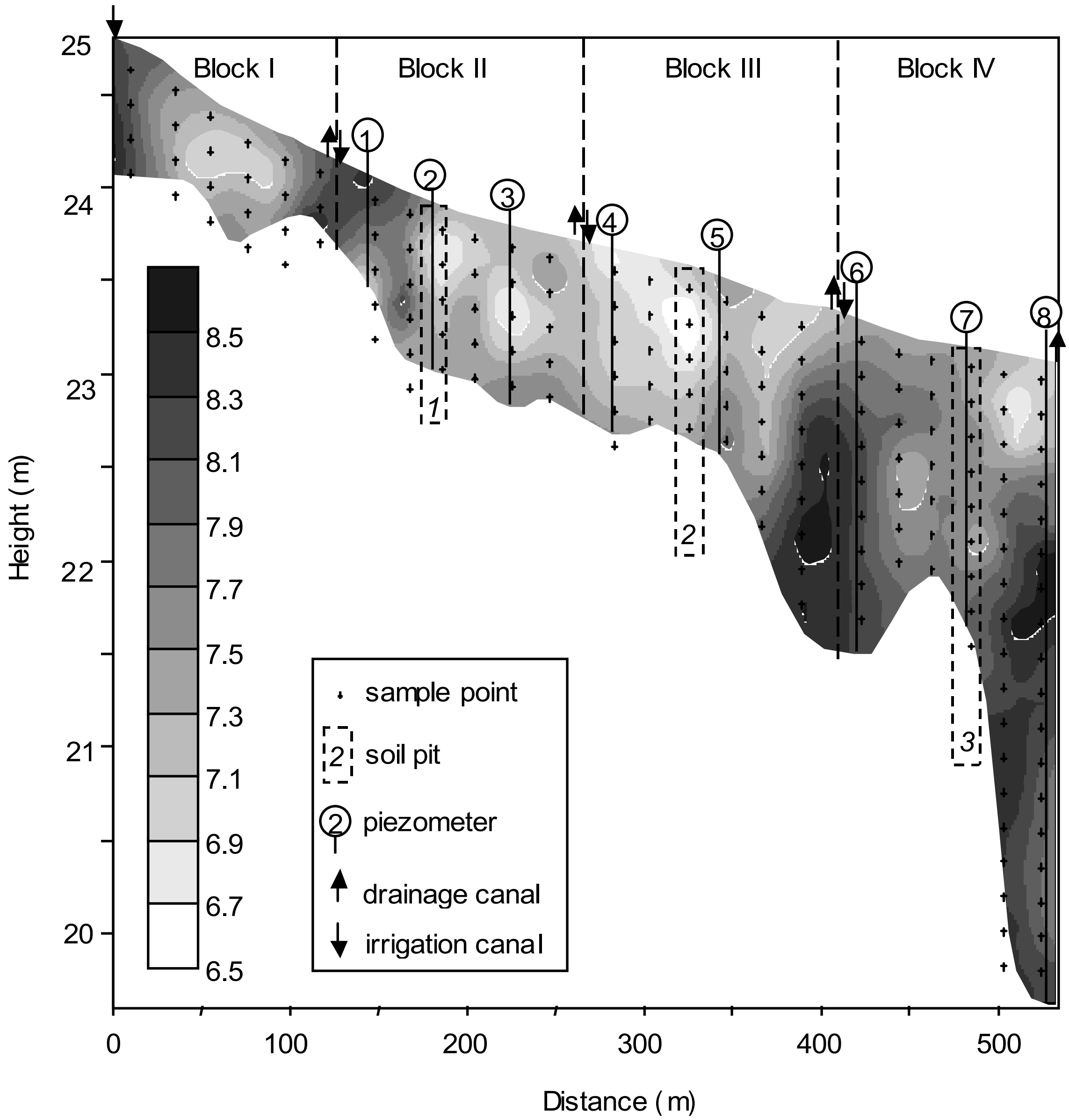

*Figure 5.3: Cross-section map of the toposequence showing pH (1:2.5 paste), soil depth, the location of piezometers, irrigation and drainage canals, sample points, soil pits, and irrigation and drainage canals.*

## Historical analysis of soil data

Historical soil data were compared to the results of recent soil studies in order to verify whether soil quality decreased since irrigation activities started. The area bordering the Gorgol Noir River downstream of the Oua-Oua mountain chain has been the subject of several soil studies over the last 30 years. The first study, investigating the soil's potential to sustain irrigated agriculture, was carried out by the UNDP (1970). It was a reconnaissance study (1:50.000), identifying the major soil types between the future dam location and Lexceiba, 40 km further downstream. About 45 samples of topsoil horizons, varying in depth from 0.15 to 0.45 m, were taken and EC and pH were measured in the saturated paste extract. A second more detailed study was carried out by Il Nuovo Castoro (1977), focusing on 6850 ha potential irrigable land just downstream of the current dam, including the actual 1950 ha Foum Gleita irrigation scheme. EC and pH were determined in a 1:2 water extract for all topsoil horizons of 266 soil pits covering the total area. In 1986, a third soil study was conducted by the French 'Bureau Central d'Etudes pour les Equipements d'Outre-Mer' (BCEOM), focusing only on the 1950 ha of the current scheme. Some 114 soil pits throughout the scheme were studied and sampled. Soil samples from the top horizon (average 0–0.23 m depth) were analyzed for pH and EC in a 1:5 extract. A fourth soil study (unpublished) was carried out in 1993, by the Mauritanian 'Laboratoire Nationale des Sols' (LANASOLS) to investigate soil degradation problems in Foum Gleita. By that time, 12% of the irrigation scheme's land had already been abandoned. Topsoil horizons (0–0.2 m) of all abandoned fields were sampled and pH and EC were analyzed in a 1:5 paste. The most recent soil samples were taken for this study by WARDA at the onset of the 1998 wet season and the 1999 wet season. Topsoil samples (0–0.2 m) were taken in 100 farmer fields throughout the irrigation scheme, and included both cultivated and uncultivated fields. The samples were analyzed for pH in a 1:2.5 paste and EC in a 1:5 paste. Means for topsoil EC from the BCEOM (1986) and WARDA (1998–1999) soil studies were compared with the Newman-Keuls test using the STATISTICA 5.5 software. Results from other soil studies were compared qualitatively as methodological differences did not allow for statistical comparisons (i.e., different sample area and extraction methods).

### The composition and changes of surface and groundwaters

Throughout the year 2000, irrigation, drainage and groundwater samples were taken (if present) at various sites within the irrigation scheme at 2–3 months intervals. Samples were treated and analyzed as described in the detailed study of soils in a toposequence.

The changes in irrigation water composition upon concentration through evaporation were modeled using the PHREEQC 2.0 hydro-geochemical simulation model and the WATEQ4 database (Parkhurst and Appelo, 1999). The initial irrigation water composition used for modeling was the average of values measured in 2000. Aluminum concentration was calculated, assuming equilibrium with kaolinite. For the model exercise, we selected those minerals that were likely to precipitate in natural soil environments within the observed salinity range; i.e., Mg-Calcite, sepiolite, illite, gypsum. Precipitation of pure Calcite was not allowed. Chemical analysis of carbonate nodules sampled during the detailed toposequence study revealed that these contain on average 2% of $MgCO_3$, which is similar to findings of Suarez and Rhoades (1982). The precipitation of a Mg-calcite ($Ca_{0.98}Mg_{0.02}CO_3$) solid solution was allowed, using the equilibrium constant of Calcite [$\log(k) = -8.48$]. Several authors - Gac (1980) for Lake Cad, Guedarri (1984) for Chott el Djerid, Barbiéro (1995) for Niger irrigation water, and Condom et al. (1999) for Punjab irrigation waters - suggested control of silica and magnesium through formation of sepiolite, although they were unable to give evidence for the presence of these minerals in the soils. However, precipitation of sepiolite mimics well the precipitation of more complex Mg-montmorillonite minerals that can only be modeled if Al complexing is taken into account (Valles et al., 1989). Gac et al. (1977) and Barbiéro (1995) observed that the changes of Mg concentrations in the soil solution could not be explained by simply concentrating irrigation water. Mg in the soil solution was much more controlled (i.e., decreased more rapidly) than what could be expected from the model simulations. They hypothesized that existing Si-rich minerals in the soil act as a Si buffer, providing the necessary source material for the formation of Mg-rich montmorillonite clays. We introduced this soil's Si buffer function by allowing dissolution of quartz (SI = 0.6) from an infinite stock, the moment Si concentrations in the soil solution reach those of the groundwater samples. PHREEQC allows the user to specify the SI value at which precipitation of a specific mineral occurs, in order to account for the occurrence of supersaturation (Appelo and Postma, 1996). SI values for all minerals that could potentially precipitate were set zero, except for Mg-Calcite which precipitated at SI = 0.9. The $SI_{Mg\text{-}calcite}$ was based on the (near) maximum value of the August 2000 groundwater samples at $pCO_2 = 10^{-1.8}$ atm. All simulations were done at a constant $pCO_2$ of $10^{-1.8}$ atm, which corresponds to the average $pCO_2$ of tropical soil environments (Brook et al., 1983). Temperature was maintained at a constant 30 °C. Concentration of irrigation water by evaporation was simulated by extracting pure water from the initial solution. At each simulation step, the water content of the solution was decreased by half (0.50 kg). The mass of concentrated solution was than doubled; i.e., after each simulation cycle the initial amount of water was restored (1.00 kg). Each concentration step was followed by precipitation of minerals for which the given saturation index had been exceeded. This simulation cycle was repeated 10 times, resulting in a final concentration factor of 1024. The above simulation procedure was performed a second time, but now cation exchange processes were included. Equilibrium with the exchange complex was calculated after each concentration-precipitation cycle. The initial composition of the exchange complex was calculated assuming equilibrium with the irrigation water. In PHREEQC 2.0 the exchange complex was defined as the number of exchange sites per kg water. Simulations were conducted with CEC values varying between 0.015 M $kg^{-1}$ water and 1.200 M $kg^{-1}$ water (i.e., 0.25 $mmol_c$ 100 g dry $soil^{-1}$ and 20.00 $mmol_c$ 100g dry $soil^{-1}$, respectively, when soil bulk density equals 1.8 kg $l^{-1}$ and water content equals 0.3 kg water $l^{-1}$).

## 5.3 Results

### Analysis of soil properties in a toposequence

Results of the toposequence sampling in relation to the location of irrigation blocks, soil pits and piezometers are shown in Figures 5.2 and 5.3. Soils were shallow (< 0.8 m) in irrigation block I and relatively deep (1.4–3.6 m) in block IV. Highest topsoil pH and EC values were observed in the upper part of the toposequence. However, variability was large both horizontally as vertically and the cross section maps did not show a clear

*Table 5.1: Texture class and basic soil chemical parameters for soil pits of the detailed toposequence study at irrigation block S4 (see Figure 5.2).*

| Pit nr. | Depth (m) | $pH_{1:2.5}$ water | Texture Class[1] | Ca | Mg | K | Na | CEC | ESP (%) | $EC_{1:5}$ ($dS\ m^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | ($mmol_c$ 100g dry $soil^{-1}$) | | | | | | |
| 1 | 0.00 – 0.20 | 8.3 | SiL | 12.63 | 3.50 | 0.35 | 2.34 | 10.74 | 21.79 | 0.52 |
| 1 | 0.20 – 0.35 | 8.0 | SiCL | 14.50 | 3.88 | 0.34 | 4.89 | 13.25 | 36.91 | 0.69 |
| 1 | 0.35 – 0.80 | 8.3 | SiCL | 18.50 | 3.13 | 0.29 | 5.45 | 14.39 | 37.87 | 0.79 |
| 1 | 0.80 – 1.00 | 8.5 | CL | 23.88 | 2.63 | 0.19 | 4.76 | 13.31 | 35.73 | 1.32 |
| 1 | 1.00 – 1.15 | 8.5 | SiL | 23.25 | 2.00 | 0.21 | 5.38 | 8.23 | 65.31 | 1.03 |
| 2 | 0.00 – 0.20 | 7.1 | SiCL | 12.50 | 4.38 | 0.35 | 0.68 | 13.93 | 4.85 | 0.12 |
| 2 | 0.20 – 0.60 | 6.6 | SiCL | 11.85 | 4.38 | 0.23 | 0.53 | 17.15 | 3.06 | 0.13 |
| 2 | 0.60 – 1.15 | 7.1 | SiCL | 15.50 | 4.50 | 0.19 | 0.49 | 16.73 | 2.90 | 0.09 |
| 2 | 1.15 – 1.40 | 7.3 | SiCL | 20.88 | 4.50 | 0.28 | 0.54 | 18.47 | 2.92 | 0.16 |
| 2 | 1.40 – 1.55 | 7.6 | SiL | 35.63 | 2.88 | 0.17 | 0.43 | 13.17 | 3.23 | 0.12 |
| 3 | 0.00 – 0.20 | 7.3 | SiCL | 11.63 | 5.00 | 0.31 | 0.86 | 13.93 | 6.17 | 0.22 |
| 3 | 0.20 – 0.60 | 6.9 | SiCL | 11.25 | 3.88 | 0.19 | 0.87 | 13.81 | 6.26 | 0.15 |
| 3 | 0.60 – 1.30 | 7.3 | SiCL | 12.13 | 3.63 | 0.17 | 1.05 | 14.01 | 7.46 | 0.25 |
| 3 | 1.30 – 2.10 | 8.4 | CL | 29.25 | 4.38 | 0.15 | 1.80 | 13.71 | 13.13 | 0.37 |
| 3 | 2.10 – 2.15 | 8.4 | SiCL | 29.13 | 5.88 | 0.18 | 2.66 | 16.06 | 16.56 | 0.47 |
| 3 | 2.15 – 2.25 | 8.5 | SiL | 30.00 | 3.88 | 0.07 | 2.08 | 8.37 | 24.85 | 0.47 |

[1] Texture classes according to FAO guidelines for soil description (1990b).

*Table 5.2: Chemical characteristics of Foum Gleita irrigation water (average of the year 2000) and of groundwater (August 2000) in the toposequence.*

| | Irrigation water | Piezometers | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| pH | 7.54 | 8.3 | 8.0 | 8.0 | 7.7 | 7.3 | 7.9 | 7.6 | 7.3 |
| EC ($dS\ m^{-1}$) | 0.16 | 0.66 | 9.03 | 0.72 | 1.16 | 1.11 | 2.65 | 1.24 | 0.76 |
| $Ca^{2+}$ ($mmol_c\ l^{-1}$) | 0.78 | 1.42 | 7.78 | 3.64 | 6.29 | 6.19 | 1.92 | 6.29 | 2.42 |
| $Mg^{2+}$ ($mmol_c\ l^{-1}$) | 0.38 | 0.77 | 3.99 | 1.09 | 1.81 | 1.89 | 3.87 | 2.88 | 1.00 |
| $K^{+}$ ($mmol_c\ l^{-1}$) | 0.12 | 0.06 | 0.06 | 0.03 | 0.02 | 0.12 | 0.27 | 0.07 | 0.39 |
| $Na^{+}$ ($mmol_c\ l^{-1}$) | 0.32 | 5.05 | 83.74 | 2.61 | 5.05 | 4.87 | 22.8 | 5.74 | 2.96 |
| Alk ($mmol_c\ l^{-1}$) | 1.40 | 6.67 | 6.94 | 5.84 | 9.16 | 9.92 | 23.5 | 9.89 | 8.07 |
| $Cl^{-}$ ($mmol_c\ l^{-1}$) | 0.11 | 0.18 | 35.89 | 0.74 | 2.55 | 1.57 | 6.14 | 1.00 | 0.33 |
| $SO_4^{2-}$ ($mmol_c\ l^{-1}$) | 0.09 | 0.32 | 52.39 | 0.71 | 0.57 | 0.35 | 0.29 | 1.65 | 0.08 |
| Si ($mmol\ l^{-1}$) | 0. 12 | 0.48 | 0.42 | 0.52 | 0.60 | 0.52 | 0.45 | 0.42 | 0.42 |
| $RA_{Calcite}$ ($mmol_c\ l^{-1}$) | 0.62 | 5.3 | −0.8 | 2.2 | 2.9 | 3.7 | 21.5 | 3.6 | 5.7 |
| SAR[1] | 0.42 | 4,8 | 34,5 | 1,7 | 2,5 | 2,4 | 13,4 | 2,7 | 2,3 |
| $SI_{Calcite}$[2] | −1.39 | 0.07 | 0.11 | 0.35 | 0.89 | 0.95 | 1.04 | 0.93 | 0.46 |
| $SI_{Quartz}$[2] | −0.01 | 0.58 | 0.55 | 0.63 | 0.69 | 0.63 | 0.56 | 0.53 | 0.53 |

[1] Sodium Adsorptio Ration = $(Na^{+}) / ((Ca^{++} + Mg^{++})/2)^{0.5}$, concentrations in $mmol_c\ l^{-1}$

[2] at $pCO_2 = 10^{-1.8}$ atm.

pH and EC gradient as a function of topography. A slight increase in pH, and to a lesser extent EC, was observed near most irrigation and drainage canals.

The third soil pit (PIT-3) is part of the 'lower slope and depressions' mapping unit. Results of chemical and soil texture analysis are shown in Table 5.1. Soil texture varied little between soil pits (average 29% clay, 53% silt, and 18% sand) and was classified as silt loam, silty clay loam and clay loam. A horizon with abundant angular medium to coarse quartz fragments was found overlying the schist parent rock in PIT-1 and PIT-2. Its thickness varied strongly at short distances (0.05–0.35 m). In PIT-3, many fine angular quartz fragments were found in a thin layer at 2.15 m depth just above the weathered schist, and some rounded medium-sized quartz fragments were observed between 0.60 m and 2.00 m depth. Very few fine hard calcareous nodules were observed in PIT-1 at 0.35–0.80 m depth and none in PIT-2. In both pits, precipitation of carbonate minerals was observed in the partly weathered parent rock, i.e., in between the schist platelets. Furthermore, soil and salt deposits in the weathered parent rock had a very talc-like structure. In PIT-3, the presence and size of calcareous nodules increased rapidly from 1.30 m depth onwards. From 1.60 m onwards, calcareous nodules were hard in the center with a softer powdery exterior cementing the nodules up to 10 cm diameter at 2.00 m depth. The soils had a moderate to strong structure, being sub-angular blocky in PIT-1 and PIT-2, and more prismatic in PIT-3. The latter pit showed vertic properties in the upper horizons. The porosity throughout the toposequence was generally medium to high, but was distinctly lower near the soil surface. No evidence of degradation of the soil structure by sodication could be found. Biological activity observed in all pits was important, with termite nests and channels being the main features. The topsoil (0–0.2 m) of all pits showed actual hydro-morphological features with grayish-brown matrix colors and iron oxidation colors around (former) root channels. PIT-1 and PIT-2 seemed well drained with no actual hydromorphic features below 0.2m and only few iron-manganese mottling and nodules in the deeper horizons of the profile. In PIT-3, some soft iron-manganese concretions could be found at shallow depth (0.2–0.6 m) and iron mottling was abundantly present from 0.6 m onwards, with the appearance of grayish-blue reduction colors at 2.15 m depth. In the 1999 and 2000 wet season this soil was temporarily inundated during floods of the Gorgol Noire river. Results of the August 2000 groundwater sampling are given in Table 5.2. Groundwater from all piezometers, were classified as sodic-alkaline waters according to Valles et al. (1991), except for piezometer 2, which was classified 'sulphatic saline'. Saturation indices indicated supersaturation (SI 0.07–1.04) of the groundwater with respect to calcite at $pCO_2 = 10^{-1.8}$ atm.

Analysis of historical soil data

Analytical methods, sampling depth, and the number and location of sampling points varied strongly amongst the studies. A summary of basic statistics on pH and EC and the sampling and extraction method are given in Table 5.3. Soil pH and EC values of the 1986 study did not differ significantly from the soil samples taken in 1998/99.

*Table 5.3: EC (dS m$^{-1}$) and pH measurements of topsoil samples from different soil studies in the Foum Gleita area.*

| Source | UNDP | | Il N. Castoro | | BCEOM | | LANASOLS | | WARDA | |
|---|---|---|---|---|---|---|---|---|---|---|
| Year | 1970 | | 1977 | | 1986 | | 1993 | | 1998–1999 | |
| No. Obs. | 46 | | 266 | | 114 | | 331 | | 100 | |
| EC method | sat. paste | | 1 :2 extract | | 1 :5 extract | | 1 :5 extract | | 1 :5 extract | |
| pH method | sat. paste | | 1 :2 extract | | 1:5 extract | | 1 :5 extract | | 1:2.5 extract | |
| | EC | pH | EC | pH | EC | pH | EC | pH | EC | pH |
| Average | 0.49 | 7.2 | 0.24 | 6.9 | 0.12 | 7.1 | 0.16 | 7.4 | 0.13 | 7.4 |
| Median | 0.27 | 7.2 | 0.13 | 7.0 | 0.08 | 7.0 | 0.14 | 7.4 | 0.12 | 7.1 |
| Min | 0.15 | 6.0 | 0.02 | 5.5 | 0.03 | 5.7 | 0.04 | 6.9 | 0.03 | 5.3 |
| Max | 3.21 | 8.4 | 2.20 | 8.5 | 1.20 | 8.7 | 1.11 | 8.3 | 0.55 | 8.2 |
| Sample area and strategy | Includes samples outside the irrigation scheme | | Regular grid, covering the initially planned 3600 ha. | | Random sampling within the current irrigation scheme | | Only fields that had been abandoned by 1993 | | Random sampling within the current irrigation scheme | |

## The composition and changes of surface and groundwaters

Irrigation, drainage and groundwater samples taken in Foum Gleita were classified as sodic-alkaline waters according to Valles et al. (1991). The results of the chemical analysis of all irrigation, drainage, and groundwater sampled in the year 2000, are presented in the concentration diagrams of Figure 5.4. Electrical conductivity was taken as a tracer for concentration processes, because chloride concentrations were relatively low and showed large scatter. The average irrigation water composition is given in Table 5.2. The changes of the solution composition upon concentration can be observed in Figure 5.4. Small amounts of illite precipitate at concentration factor (CF) = 4 (EC~0.6 dS m$^{-1}$), but sepiolite is quantitatively the dominant Mg silicate mineral and precipitates from CF = 32 onwards (EC ~ 2.2 dS m$^{-1}$). A large part of the Si that precipitates with Mg is released by dissolution of quartz. This Si buffer maintains Si concentrations in the soil solution at ~ 0.5 mmol l$^{-1}$. Mg-calcite precipitates from CF = 16 (EC ~ 1.1 dS m$^{-1}$) onwards. When only taking into account concentration processes, the precipitation of Mg-calcite, sepiolite and illite results in a decrease of Mg and Ca concentrations in the soil solution at EC > 1–2 dS m$^{-1}$. Alkalinity concentration continues to increase, which is in line with the RA$_{calcite}$ concept. Likewise, the pH increases up to 8.9 (data not shown) upon concentration. Including exchange processes into the simulation of concentration processes drastically altered the changes of the

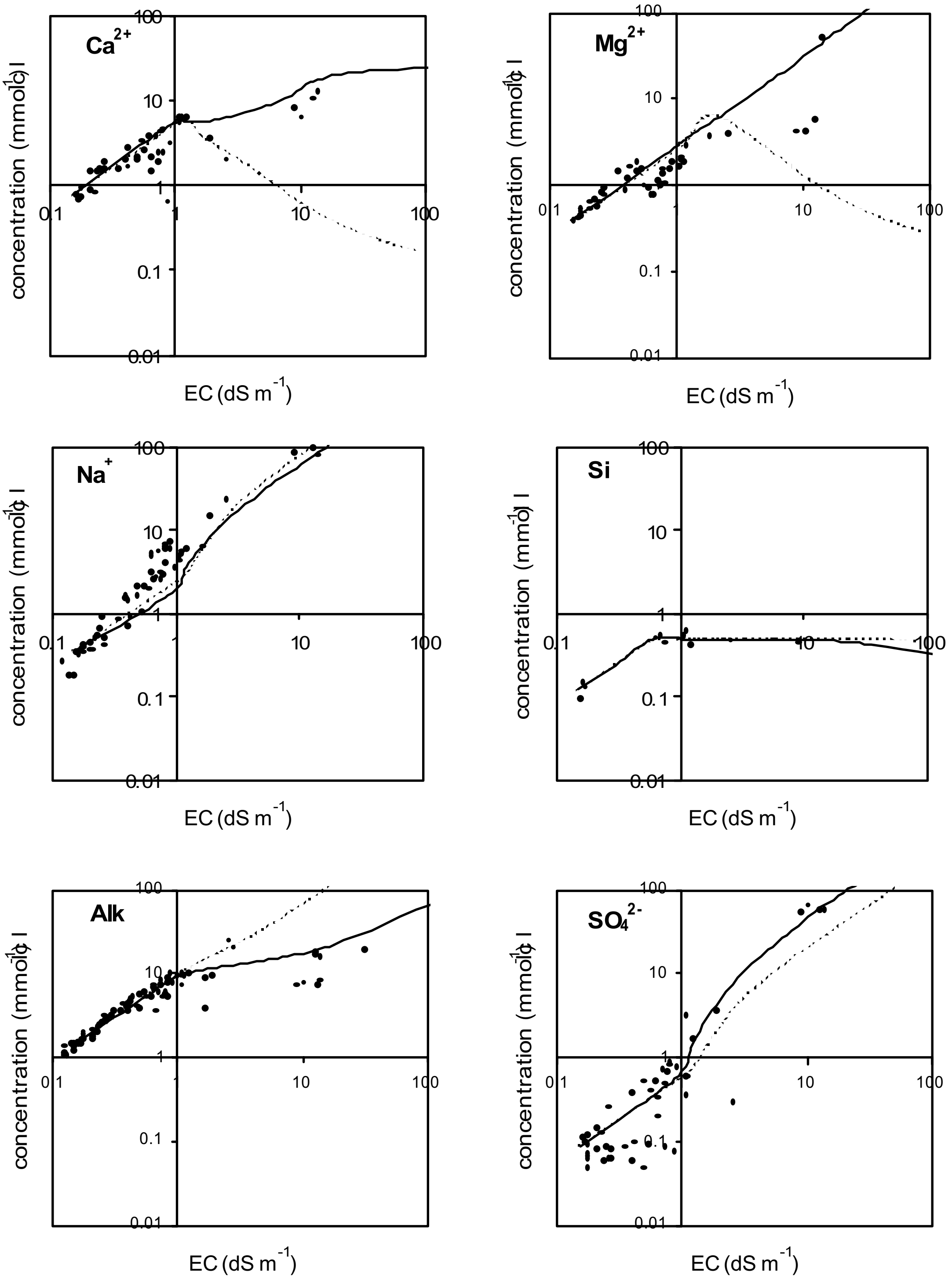

*Figure 5.4:* *Concentration diagrams showing field data [dots], simulated changes of the irrigation water upon concentration [dotted line], and simulated changes of the irrigation water upon concentration when exchange processes (CEC = 1.0 mmol$_c$100 g dry soil$^{-1}$) are included [solid line].*

solution composition. In equilibrium with the irrigation water, the percentages of Ca, Mg and Na adsorbed at the CEC are 75, 23, and 1, respectively. Using a CEC equivalent to 20.00 mmol$_c$ 100g dry soil$^{-1}$, the quantity of calcium released from the exchange complex upon concentration was so important, that the RA$_{calcite}$ became negative, resulting in a sulphatic saline solution. Only when the CEC was reduced to the equivalent of 1.0 mmol$_c$ 100 g dry soil$^{-1}$, the alkalinity of the solution remained stable at high EC values (> 2.0 dS m$^{-1}$) and was balanced by Ca, as observed in the field data. With increasing concentrations, the pH of the soil solution initially increases but than stabilizes around 7.5 (data not shown). Simulation exercises with slightly smaller (0.05 mmol$_c$ 100g dry soil$^{-1}$) or higher (1.5 mmol$_c$ 100 g dry soil$^{-1}$) CEC values lead to completely opposite changes of the solution composition; i.e., into a strong alkaline sodic solution and into a sulphatic saline solution respectively.

## 5.4 Discussion

### The distribution and origin of soil salinity and alkalinity

Highest topsoil pH and EC values were found on the highest positioned soils in the toposequence, which is in line with observations in Chapter 2, where we found that topsoil pH and EC increased when moving from the river banks and lower slopes to the middle and upper slopes. However, pH and EC showed strong horizontal variation, which seems to suggest that salt distribution through horizontal groundwater movement is minimal. The groundwater samples showed a heterogeneous pattern similar to that of the soil EC and pH shown on the cross-section maps. Although all groundwater samples, except for piezometer 2, were classified as sodic-alkaline, the composition of the groundwater varied distinctly, suggesting differences in geochemical origin.

The soil texture analysis of the soil pit samples did not reveal any differences in the origin of the parent material. Indications on the origin of the parent material could be obtained from the quartz fragments observations. In PIT-1 and PIT-2, angular quartz fragments had accumulated in a horizon (stone line) that varied strongly in thickness, overlying the schist weathering front. BCEOM (1986) hypothesized that this stone line separated *in situ* soil material from colluvio-alluvial deposits. However, the angular shape of the fragments and the irregular thickness of the horizon leave us to believe that that the stone line is the result of accumulation of coarse fragments at the base of the bioturbated horizon; a classical phenomenon under more humid climate (Boulet et al., 1995). This implies that soils at the upper part of the toposequence have formed from *in situ* weathering of the schist parent rock. In combination with our assumption that salt distribution through horizontal groundwater flow is minimal, this suggests that (alkaline) salts in PIT-1 and PIT-2 originate from the parent rock. The presence of precipitated carbonate minerals in between the schist platelets and increasing salinity and alkalinity levels near the parent rock are in line with this hypothesis. The presence of carbonate minerals in the lower horizons is also reflected in the high exchangeable Ca values compared to the CEC. Overestimation of exchangeable cations is largely due to the dissolution of (Ca-Mg-carbonate) salts when extracting with ammonium chloride. The similarities between PIT-1 and PIT-2 do not hold with respect to salinity and alkalinity levels. Both the soil analysis and the groundwater sample of piezometer 2 show high salinity levels near PIT-1, with sulfate as the major anion. The striking differences between PIT-1 and PIT-2 can only be explained by differences in the geochemical composition of the underlying parent rock. The presence of pyrite could be a possible explanation for the high sulfate concentrations and lower pH of the groundwater at piezometer 2. The north-south orientation (perpendicular to the slope) and the vertical position of the schist parent rock provide the ideal conditions needed to obtain large geochemical heterogeneity at short distances.

The presence of rounded quartz fragments in PIT-3 at 0.6–1.95 m depth suggests that this soil partly has a colluvio-alluvial origin. Only at a depth of 2.15 m, some angular quartz fragments were observed. The alluvial origin of the upper horizons of PIT-3 is also reflected in its vertic properties. Although the Foum Gleita dam reduced peak floods, these soils are regularly flooded even after installation of the irrigation scheme. These floods allow for deposition and neo-formation of swelling clays, and the leaching of easily soluble salts from the upper horizons (0–1.3 m). The grayish-blue reduction colors at 2.15 m depth and the presence of abundant iron mottling below 0.6m suggest that the groundwater level shows large annual fluctuations. We conclude that the accumulation of calcareous nodules (salts) at 1.3–2.0 m depth is related to the alluvial character of this soil and the alternating wetting-drying conditions (accumulation-precipitation) that result from occasional flooding and a fluctuating groundwater table.

## The recent and potential changes of alkalinity problems in Foum Gleita

Although methods to measure EC and pH in 1970, 1977, 1986, 1993 and 1998 sometimes differed, soil salinity and pH levels have not significantly evolved over the last thirty years. This is in line with results of the detailed toposequence study, in that soil salinity/alkalinity problems originate from the parent rock and not from the irrigation water. No clear symptoms of secondary alkalinization/salinization were observed, although pH values tend to slightly increase near irrigation and drainage canals. In combination with observations made by Van Asten et al. (Chapter 2), the increasing productivity problems observed in Foum Gleita seem more the result of soil nutrient mining practices (i.e., non-application of phosphorus fertilizer) on soils that already had a low nutrient status, than the result of recent soil salinization or alkalinization.

Both soil and groundwater analyses showed that pH increased with salinity (EC) level. However, at high salinity levels, pH values tended to stabilize or even decrease, which is in contrast to normal alkalinization processes, where pH values continue to increase.

In the concentration diagrams (Figure 5.4) alkalinity levels of water samples initially increased with EC, but eventually stabilized or decreased above EC values of 1–2 dS $m^{-1}$. Results of PHREEQC simulations using Foum Gleita irrigation water (dotted line in Figure 5.4) showed that the Foum Gleita irrigation water evolves towards a strongly alkaline sodic solution when excessively concentrated. This type of concentrated solution eventually leads to physical and chemical soil degradation.

The geochemical composition of most groundwater samples that have an EC higher than 1–2 dS $m^{-1}$ cannot be derived simply by concentrating of irrigation water, i.e., $RA_{calcite}$ is not conservative, but decreases upon concentration. The detailed toposequence study revealed that the contrasting geochemical composition of groundwaters could well be due to differences in geochemical background. Release of $Ca^{2+}$ from the cation exchange complex upon concentration can also (partly) explain the seemingly contrasting geochemical composition of groundwaters. PHREEQC simulation exercises including cation exchange processes yielded concentration diagrams that fitted well with field observations and that explain a decrease in $RA_{calcite}$ with concentration. Calcium release from the exchange complex upon increasing concentrations of the soil solution was so important that alkalinity could not further increase due to the precipitation of carbonate minerals. Including exchange processes did not improve simulation of $Mg^{2+}$ concentrations due to the increased solubility of sepiolite that resulted from the lower pH (7.5). The simulation of Mg-silicate precipitation needs further study but is of limited relevance to the understanding of alkalinization processes in Foum Gleita, as control of alkalinity by Mg is limited. The number of water samples with an EC > 1–2 dS $m^{-1}$ is too limited to conclude with certainty that decreasing alkalinity at high salinity levels is due to exchange processes. However, the CEC value that yielded the best fit with $Ca^{2+}$ and alkalinity concentrations observed in the field was very small (1.0 $mmol_c$ 100 g dry $soil^{-1}$). This suggests that the soil's cation exchange capacity contributes substantially to the buffering of alkalinization processes. Nonetheless, the soil's buffering capacity might eventually run out and the changes and rate of alkalinization processes in Foum Gleita can only be determined with detailed studies on the soil's salt and water balance.

## 5.5 Conclusions

Topsoil salinity and alkalinity levels are highest on the shallow soils of the upper slope. Here soils have formed *in situ* from the schist parent rock, which releases alkaline salts upon weathering. Soils in the lower part of the landscape have a (partly) colluvio-alluvial origin. The topsoil contains less salt due to regular flooding, which led, in combination with an alternating groundwater table, to the accumulation of carbonate minerals below the root zone (> 1.3 m). The differences in the origin of the parent material, and the vertical position and north-south orientation of the schist parent rock, perpendicular to the sampled toposequence, led to large differences in the geochemical composition of the soil and groundwater at short distances. The salt distribution pattern did not show clear signs of horizontal groundwater flow, nor of secondary salinization due to irrigation activities. Soil salinity and alkalinity are inherited from the parent rock. A comparison of soil studies over the last 30 years showed no clear changes of Foum Gleita's salinity and alkalinity levels.

Alkalinity and pH of groundwater samples decreased at higher salinity levels (EC > 2 dS $m^{-1}$) on Foum Gleita's most saline soils, suggesting that their geochemical origin differs from the majority of the soils. Their composition could not be derived from concentration of the irrigation water only. Simulation exercises using the PHREEQC2.0 geochemical model showed that most groundwater samples in Foum Gleita are supersaturated with respect to Mg-calcite at $pCO_2 = 10^{-1.8}$ atm. Concentration of Foum Gleita's irrigation water will lead to the precipitation of this mineral, resulting in a highly alkaline and sodic solution that eventually may lead to the formation of sodic alkaline soils. Model simulations that incorporated soil exchange processes showed drastically altered changes of Foum Gleita's irrigation water upon concentration. The release of exchangeable Ca from a small (CEC = 1.0 $mmol_c$ 100 g dry $soil^{-1}$) but calcium dominated soil complex led to the control of alkalinity in the soil solution. Inclusion of exchange processes in the simulations resulted in a good fit with field data. Changes of Mg concentrations could not be modeled well due to insufficient knowledge on the type of Mg-silicates that play key role in Foum Gleita. We concluded that exchange processes have (partly) resulted in the seemingly contrasting composition of Foum Gleita's most saline groundwaters. Moreover, the model simulations show that the soil's exchange complex forms an important buffer against alkalinization processes. The comparison of model simulations with concentration diagrams of field measurements created a good insight into the potential for soil alkalinization in Foum Gleita. However, quantitative studies on the water and salt balance at field level will be needed to determine development rate and equilibrium levels of soil salinity and alkalinity given soil types and current water management practices. Our results are in line with other studies focusing on salt related soil degradation in Sahelian irrigation schemes, in that no signs were found of secondary salinization or alkalinization in irrigated rice fields.

# 6 THE EFFECT OF IRRIGATED RICE CROPPING ON THE ALKALINITY OF TWO ALKALINE RICE SOILS IN THE SAHEL

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Irrigated rice cropping is practiced to reclaim alkaline-sodic soils in many parts of the world. This practice is in apparent contrast with earlier studies in the Sahel, which suggests that irrigated rice cropping may lead to the formation of alkaline-sodic soils. Soil column experiments were done with some of the Sahel's most alkaline-sodic rice soils from the Office du Niger (Mali) and Foum Gleita (Mauritania). Soils were irrigated using non-saline carbonate-rich irrigation water typical for the Sahel and percolation was maintained at 3–4 mm day$^{-1}$. After one cropping season, soils had turned from sodic to non-sodic, and pH had dramatically decreased, most notably in the upper soil layers. The changes were most important in the Office du Niger soil, due to its small buffering capacity (small CEC and $CaCO_3$). Alkalinity consumed by above-ground matter of the rice plants (grain and straw) equaled or exceeded alkalinity added via irrigation in a zero-percolation scenario. Hence, for a climate and irrigation water that are typical for Sahel, removal of straw and grain prevents further alkalinization of the soils if percolation is absent. However, in case of some percolation, straw can best be incorporated in the topsoil of calcareous soils as it accelerates de-alkalinization and de-sodication through increased dissolution of calcite. No evidence was found indicating that ferrolysis altered the short-term alkalinity balance of the studied soils to any extent. Our results are in line with recent field studies, and suggest a de-alkalinization of sodic-alkaline flooded (rice) soils in the Sahel.

**Keywords**: Alkalinization, sodication, irrigated rice, Sahel, straw

## 6.1 Introduction

Salt-related soil degradation is considered one of the most important threats to the sustainability of irrigation schemes in the Sahel (Bertrand et al., 1993; Boivin, 1995; Ceuppens et al., 1997; Boivin et al., 2002). It is considered to affect more than 10 % of irrigated lands worldwide (Rhoades, 1997; Szabolcs, 1994). Rice (*Oryza sativa* L) is the most important crop in the Sahelian irrigation schemes and it requires large amounts of water due to the large evaporation in the hot and dry climate. Although most irrigation waters in the Sahel contain little dissolved salt, they often possess a positive calcite residual alkalinity ($RA_{calcite}$ = Alkalinity – Ca in $mol_c\ l^{-1}$) (Valles et al., 1991; Bertrand et al., 1993). Therefore, if these waters are concentrated in the soil root zone, this may lead to the formation of an alkaline (high pH) and sodic (high sodium content) soil. Such a soil is less productive because of the pH-induced low availability of several plant nutrients (e.g., N, P, Zn), and the poor physical properties of the sodic horizon (Abrol et al., 1988). Crop production problems attributed to soil alkalinity-sodicity have been reported throughout the Sahelian zone, e.g., for the regions Office du Niger in Mali (Bertrand et al., 1993), Sourou Valley in Burkina Faso (Barro et al., 2000), Lossa in Niger (Marlet et al., 1998a) and Foum Gleita in Mauritania (Chapter 2). However, recent soil studies (Chapter 5; Marlet, 1999a; Barbiéro and Van Vliet-Lanoe, 1998) suggest that current alkalinity and sodicity-related production problems were inherited from the parent rock or from prolonged cultivation of non-flooded crops, rather than caused by irrigated rice cropping. Hence, it is likely that current alkaline-sodic rice soils in West Africa are not in equilibrium with current land use. The question rises whether irrigated rice cropping would increase or decrease the alkalinity and sodicity of current alkaline-sodic soils in the Sahel. We decided to study the processes that may affect the alkalinity and sodicity of alkaline-sodic soils in irrigated rice schemes in the Sahel, with emphasis on possibilities for reclamation of such soils. The reclamation of sodic soils is based on the replacement of exchangeable sodium by calcium ions. Several chemical amendments, such as gypsum, calcium chloride, and acids, have proven to reclaim sodic soils effectively (Abrol et al., 1988). However, such a remediation is expensive and the high initial investment needed is often prohibitive (Qadir et al., 1996). This appears especially true for irrigated rice cropping in the Sahel, where profits are often small (Donovan et al., 1999) and chemical amendments not readily available. On sodic soils that contain calcite, the use of organic amendments can be used as a low-cost alternative (Abrol et al., 1988). Chorom and Rengasamy (1997) found that due to the decomposition of organic matter $pCO_2$ increases in the soil rooting zone and pH decreases, which results in calcite dissolution and larger $Ca^{2+}$ concentrations in the soil solution. By exchange with sorbed sodium, the composition of the cation exchange complex changes favorably. Use of organic amendments is especially useful for the reclamation of sodic soils, when combined with irrigated rice cropping. Rice is very tolerant to sodic soil conditions (Abrol and Bhumbla, 1979). Due to its shallow rooting zone, roots are less hampered by a sodic B-horizon. Furthermore, rice roots release organic compounds and complex energy sources (Dormaar, 1988), which increase partial $CO_2$ pressure (Robbins, 1986), as well as decrease soil pH through proton excretion. All these processes combined favor the increased dissolution of $CaCO_3$ in the soil and the decrease of soil alkalinity and sodicity as a function of time (Abrol et al., 1988; Ahmad et al., 1990). Chhabra and Abrol (1977) showed that rice cultivation improved percolation rates even in highly sodic soils, which enhances the leaching of exchanged sodium from the rooting zone. Condom (2000) showed that redox processes can also influence the alkalinity balance of alkaline-sodic irrigated rice soils in Mali, but did not provide a semi-quantitative estimate of these processes on the alkalinity balance of the root zone. Brinkman (1970) showed that ferrolysis causes the acidification of rice soils in South-East Asia and Japan. Ferrolysis occurs when iron-hydroxides are reduced in anaerobic soils. Although the pH of an alkaline rice soil decreases towards neutral values upon flooding (Ponnamperuma, 1972), the alkalinity (Alk) of the soil solution may temporarily increase, due to the reduction of iron-hydroxides (e.g., Equation 6.1):

$$CH_2O + 4\ Fe(OH)_3 + 8\ H^+ \leftrightarrow CO_2 + 4\ Fe_2^{+} + 11\ H_2O \qquad [6.1]$$

Part of the reduced iron ($Fe^{2+}$) exchanges with cations such as $Na^+$, $Ca^{2+}$ and $Mg^{2+}$. The displaced cations, together with anions (mainly bicarbonate) that are produced simultaneously with the dissolved $Fe^{2+}$ (van Breemen, 1987), can be transferred into the surface water or leached to groundwater. After discontinuation of flooding, soil oxidation results in acidification of the upper horizon and alkalinization further downward. It is unknown to what extent ferrolysis also plays a role in the alkalinity balance of irrigated rice soils in the Sahel and to what extent this process can be influenced by the amendment of rice straw.

The objectives of this study were (i) to quantify the effect of irrigated rice cropping on the alkalinity and sodicity of alkaline-sodic rice soils in the Sahel, (ii) to identify and assess the relative importance of processes that contribute to changes in the alkalinity and sodicity of these soils, and (iii) to investigate the potential of rice straw as a low-cost amendment for the de-alkalinization of these soils. We conducted on-station soil column tests using two of West Africa's most alkaline-sodic rice soils. Soil column tests allow detailed and controlled monitoring of the soil and have earlier been used to successfully study (de-)alkalinization and (de-)sodication processes elsewhere in the world (e.g., Chhabra and Abrol, 1977; Chaudhry et al., 1992; Frenkel et al, 1989; Nadler et al., 1996; Zahow and Amrhein, 1992).

## 6.2 Methods

### Site descriptions

The alkaline-sodic rice soils used in this study originated from the Foum Gleita irrigation scheme (16°08'N, 12°46'W) in Mauritania and from the Office du Niger irrigation scheme (14°18'N, 05°59'W) in Mali (Figure 1.1). At both sites, the climate is typically Sahelian with a short wet season (250–450 mm $yr^{-1}$) from July to October and a long dry season with minimum temperatures around 15 °C in January and maximum temperatures regularly exceeding 40 °C in April–May. Potential evapotranspiration is very large (>2500 mm $yr^{-1}$). Most farmers cultivate rice in the wet season and a minority (less than 15%) practices double cropping.

The Foum Gleita scheme was established between 1985 and 1989 and covers about 1950 ha. After initial good productivity, farmers experienced yield reductions, which they attributed to salt efflorescences. By 1992, some 12% of the scheme's land had been abandoned and wet season yields had decreased from on average 4.6 t $ha^{-1}$ (1985–1991) to 3.8 t $ha^{-1}$ (1992–1999). In Chapter 2 we showed that productivity problems were caused (partially) by alkalinity-related nutrient deficiencies (N, P), most notably on the shallow (< 1.2 m thick) soils at the upper slopes where soils had formed *in situ* from the schist parent material. Farmers classified these soils as 'degraded'.

In the inland delta of the Niger River, the construction of the 'Office du Niger' scheme started in the 1930's. Initially, cotton was the major crop grown, but its large-scale cultivation was abandoned in the 1970s (Barral, 1997). Currently 90% of the 60000 ha are used for rice cultivation. The scheme is the largest in the Sahel. Groundwater levels rose from 45 m depth to less than 3 m depth in about 40 years and caused alkalinization of the initially slightly acidic soils (Ndiaye, 1999b). In the early 1980's a large part of the scheme was restored and drainage facilities increased (Marlet, 1999a). As a result, alkalinity of the clayey soils used for rice cropping decreased slightly, but increased in the adjacent coarse-textured soils that were mostly used for vegetable cropping (Marlet, 1999a).

### Soil column tests

A large topsoil sample (0–30 cm) was taken in Foum Gleita (F) and in the Office du Niger (O). Both samples were transported to the WARDA research station in Saint Louis, Senegal. The soils sampled were subject of earlier research (Condom, 2000; Van Asten et al., 2003a). Both samples were air-dried, ground (aggregate size < 1 cm), homogenized, and then transferred to 20 PVC columns (2 soil types x 5 treatments x 2 repetitions). The soil was slightly compacted to obtain a pore volume fraction of approximately 0.5 and a bulk soil volume of 8.6 liters. The 40 cm high columns (Figure 6.1) were placed in a greenhouse and wrapped in aluminum foil to prevent heating by the sun. A thin (2.5 cm) layer of purified quartz sand was first placed at the bottom of the columns for drainage. Prior to irrigation, the soil columns were water-saturated from below to prevent air entrapment. The water used for saturation and irrigation was non-saline and carbonate-rich, which is typical for the Sahel (see Table 6.1). Both soils were subject to the following five treatments (in duplicate): no plants (-), rice plants (-R), rice plants and nutrients (-RN), rice plants and straw (-RS), rice plants, nutrients and straw (-RNS). In each column, two thirty day old rice seedlings (*Oryza sativa* L.) were transplanted after complete water-saturation of the soil. Rice straw was incorporated at

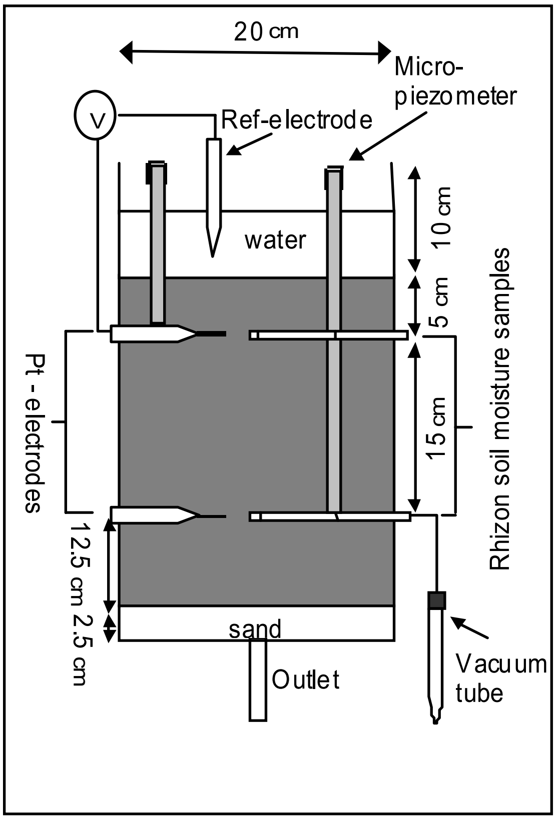

*Figure 6.1: Soil column setup*

an equivalent of 5 t dry matter ha$^{-1}$, shortly before saturation. Fertilization comprised basal application of 26 kg P ha$^{-1}$ (Triple Super Phosphate - TSP) and top-dressing of 150 kg N ha$^{-1}$ (Urea split application at 18, 42 and 67 days after transplanting). Irrigation started immediately after transplanting. A floodwater layer of approximately 5 cm was maintained by daily irrigation. By varying the height of the drain tube outlet, the hydraulic head could be adjusted to maintain percolation rates below 4 mm day$^{-1}$, which mimicked field conditions. The soil solution was sampled at 5 cm and 20 cm depth using small (Ø 2.5 mm) Rhizon soil moisture samplers having a hydrophilic porous polymer cup with a small dead volume (0.5 ml) and non-exchange properties (Rhizosphere Research Products, Wageningen). The samples were collected under vacuum using 10ml vacuum glass tubes at –0.5, 0, 0.5, 1, 1.5, 2, 4, 6, 8 and 11 weeks after the start of irrigation. In order to avoid pollution from previous samples, a small (1–2ml) sub sample was taken using a syringe, prior to connecting the vacuum glass tubes. Total alkalinity (Alk) of the soil solution samples was determined according to Gran (1952). Although phosphoric acid and other minor weak acids may

*Table 6.1: Water quality characteristics of different irrigation waters*

| | Column trial | Foum Gleita | Office du Niger |
|---|---|---|---|
| pH | 7.90 | 7.54 | 6.52 |
| EC (dS m$^{-1}$) | 0.13 | 0.16 | 0.05 |
| $Ca^{2+}$ (mmol$_c$ l$^{-1}$) | 0.47 | 0.78 | 0.11 |
| $Mg^{2+}$ (mmol$_c$ l$^{-1}$) | 0.22 | 0.38 | 0.10 |
| $K^{+}$ (mmol$_c$ l$^{-1}$) | 0.02 | 0.12 | 0.05 |
| $Na^{+}$ (mmol$_c$ l$^{-1}$) | 0.54 | 0.32 | 0.17 |
| Alk (mmol$_c$ l$^{-1}$) | 1.02 | 1.40 | 0.33 |
| $Cl^{-}$ (mmol$_c$ l$^{-1}$) | 0.21 | 0.11 | 0.08 |
| $SO_4^{2-}$ (mmol$_c$ l$^{-1}$) | 0.02 | 0.09 | 0.00 |
| Si (mmol l$^{-1}$) | 0.04 | 0.12 | 0.45 |
| RA$_{calcite}$ (mmol$_c$ l$^{-1}$) | 0.55 | 0.62 | 0.22 |

contribute to some extent, in practice only dissolved carbonic acid is of quantitative importance for the measured alkalinity (Appelo and Postma, 1996). Brackets in Equation 6.2 denote total concentrations in Mole-charge.

$$\mathrm{Alk} \approx (\mathrm{HCO_3}^-) + (\mathrm{CO_3}^{2-}) \qquad [6.2]$$

The remaining soil solution sample was acidified with nitric acid (pH < 2) and stored in a cool dark place before analysis of $Ca^{2+}$, $Mg^{2+}$, $Na^+$ and $Fe^{2+}$ using an atomic absorption spectrometer (AAS). Chloride was measured via colometric titration. Redox potential (Eh) was measured *in situ* using platinum electrodes at 5 cm and 20 cm depth. Soil pH at 5 cm and 20 cm depth was monitored using pH penetration electrodes and closable micro-piezometers. The geochemical simulation model PHREEQC 2.0 (Parkhurst and Appelo, 1999) was used to calculate saturation indices (SI) for minerals in the soil solution defined in the WATEQ4 database. This allowed us to assess the minerals that could potentially precipitate, thereby altering the soil solution composition. The $pCO_2$ of the soil solution was also calculated using PHREEQC 2.0, using the soil solution alkalinity as measured in the vacuum tube samples and the *in situ* pH as measured with the penetration electrodes.

Irrigation was discontinued 10 days before maturity of the rice grains. A sample of both soils was taken prior to filling the columns. Shortly after harvest, the soil of each column was sampled at 0–2.5, 2.5–7.5, 7.5–12.5, 12.5–17.5, 17.5–22.5 and 22.5–27.5 cm depth. All samples were oven-dried (80 °C), ground and analyzed for pH and EC in a 1:2.5 and 1:5 water-saturated paste respectively (i.e., $pH1_{:2.5}$ and $EC_{1:5}$). Furthermore, exchangeable bases of the original soils and the samples at 2.5–7.5 cm and 17.5–22.5 cm depth were determined using an AAS after extraction with ammonium chloride. Harvested plants were oven-dried (80 °C) and grain and straw weight were measured. Cations ($Ca^{2+}$, $Mg^{2+}$, $K^+$, $Na^+$) were analyzed using an AAS after extraction with a 1 N HCl solution (Yoshida et al., 1976). Concentration of N in grain and straw were determined using the Micro-Kjeldahl method (Bremner, 1996). Plant phosphorus concentrations were measured using the method described by Yoshida et al. (1976).

### Alkalinity balances

To examine the temporal development of the alkalinity of the soil root zone (0–20 cm) during the cropping season (0–11 weeks after transplanting), alkalinity balances were calculated for each soil column using the daily measurements of irrigated and percolated volumes and of the soil solute measurements at 0, 0.5, 1, 1.5, 2, 4, 6, 8 and 11 weeks after rice transplanting at 20 cm depth. Cumulative percolated volumes for the time intervals (i.e., 0–0.25, 0.25–0.75, 0.75–1.25, 1.25–1.75, 1.75–3, 3–5, 5–7, 7–9, 9–11 weeks after transplanting) were multiplied by the soil solution alkalinity of each corresponding time interval. The sum of the leached alkalinity of each time interval equaled the total alkalinity leached from the root zone of each column ($Alk_{LEACH}$). The alkalinity added with irrigation water ($Alk_{IRRI}$) was calculated as the total irrigated volume multiplied by the alkalinity of the irrigation water. This calculation was repeated, only the irrigated volume was limited to the evapotranspired volume ($Alk_{EVPT}$); i.e., the alkalinity added to each column if no percolation were to occur. The alkalinity that was removed from the column through harvest of the above-ground matter ($Alk_{PLANT}$) was calculated as a function of plant mineral content and biomass production, according to Van Beusichem (1984). Mineral concentrations of grain and straw were based on laboratory analysis of N, P, $K^+$, $Ca^{2+}$, $Mg^{2+}$ and $Na^+$, and literature values of $Cl^-$ and $SO_4^{2-}$ for modern *Oryza sativa* L. varieties (Boivin et al., 2002; De Datta, 1981; Dobermann and Fairhurst, 2000; Reuter et al., 1997); i.e., Cl = 0.75 % and S = 0.075 % for straw and Cl = 0.5 %, S = 0.1 % for grain. We assumed that plant N was taken up as $NH_4^+$ and plant P as $H_2PO_4^-$, where 40% of N uptake originated from urea and 20% of P uptake originated from TSP in the treatments that received fertilizer (Haefele, 2001; Chapter 2). Furthermore, we assumed that plant nutrient uptake was restricted to the 0–20 cm layer, which is generally considered to be the effective rooting depth of rice. The alkalinity added through straw application ($Alk_{STRAW}$) was calculated following the same methods and assumptions used for calculation of $Alk_{PLANT}$.

The effect of fertilizer application (i.e., urea and TSP) on the alkalinity balance of each column ($Alk_{NUTR}$) was calculated, disregarding N taken up by above-ground plant parts. We assumed that urea had no effect on the soil solution alkalinity; hydrolysis of urea consumes 1 proton per $NH_4^+$ ion, but an equivalent amount is released upon plant uptake, volatilization, and nitrification-denitrification. We assumed that upon dissolution of TSP ($Ca(H_2PO_4)_2$), half of the $H_2PO_4^-$ was converted to $HPO_4^{2-}$, considering the average *in situ* soil pH (7–7.5) at 5 cm depth in both soils.

Statistical analyses

Statistical analyses were conducted using the software package SPSS for Windows (Version 10.0). Treatment means for grain yield, plant biomass, irrigated volume, percolated volume, evapotranspired volume, and variables of the alkalinity balance were compared within each soil type, using least square difference (LSD) test after applying Levene's test of homogeneity of variances. Due to the low number of replications (i.e., two), the reader should focus more on soil quality changes when compared to the initial situation, than on significance of treatment differences

*Table 6.2: Soil conditions before the trial.*

| | Office du Niger (O) | Foum Gleita (F) |
|---|---|---|
| Texture class | SL | SCL |
| CEC ($cmol_c kg^{-1}$) | 4.5 | 15.0 |
| ESP (%) | 28 | 18 |
| $pH_{1:2.5}$ | 8.8 | 8.4 |
| $EC_{1:5}$ ($dS m^{-1}$) | 0.29 | 0.82 |
| $CaCO_3$ ($g kg^{-1}$) | < 1 | 4 |
| org. C ($g kg^{-1}$) | 2.7 | 4.3 |
| | *saturated paste* | |
| EC ($dS m^{-1}$) | 1.8 | 4.2 |
| $Na^+$ ($mmol_c l^{-1}$) | 20.5 | 43.0 |
| $Ca^{2+}$ ($mmol_c l^{-1}$) | 0.5 | 5.0 |
| $Mg^{2+}$ ($mmol_c l^{-1}$) | 0.2 | 3.2 |
| Alk ($mmol_c l^{-1}$) | 19.6 | 3.4 |
| SAR ($mmol l^{-½}$) | 17.2 | 15.0 |

## 6.3 Results

Changes in soil sodicity, pH and EC

Results of the analysis of the F and O soils (see Table 6.2) revealed that both soils were initially sodic (ESP>15) according to FAO classification (Abrol et al., 1988). The $EC_{1:5}$ was larger and $pH_{1:2.5}$ smaller in the F soil compared to the O soil. Unlike the O soil, the F soil contained some carbonate minerals (4 g $kg^{-1}$). The $pH_{1:2.5}$ and $EC_{1:5}$ profiles of both soils after the experiment for the different treatments are shown in Figure 6.2. In all columns, pH is lower near the soil surface. In both soils, largest pH decrease was found in treatments that received straw and/or nutrients. The pH decrease was most spectacular in the O soils, where pH dropped from an initial value of 8.8 to 7.0 or less near the soil surface. In both soils, the EC was largest near the soil surface, with highest values measured in treatments that received straw and nutrients. The ESP at a depth of 5 cm and 20 cm is shown in Figure 6.3. The largest decrease in ESP occurred in the O soil. In the F soil, the ESP at 5 cm depth decreased the most in treatments with good rice growth (FRNS, FRS, FRN).

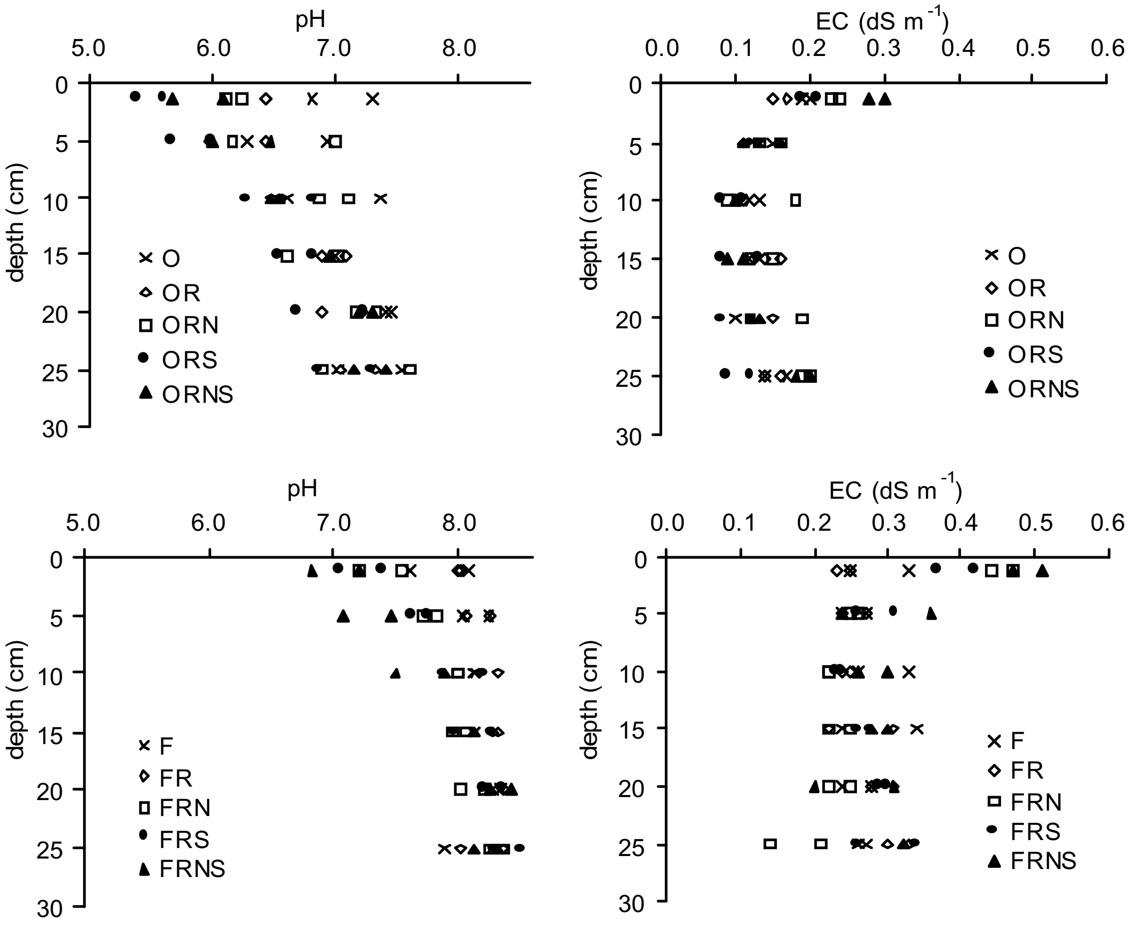

Figure 6.2: *The $pH_{1:2.5}$ and $EC_{1:5}$ profiles after 1 season of rice cropping for soils from Foum Gleita (F) and Office du Niger (O) for treatments with and without rice (R), nutrients (N) and straw (S) application.*

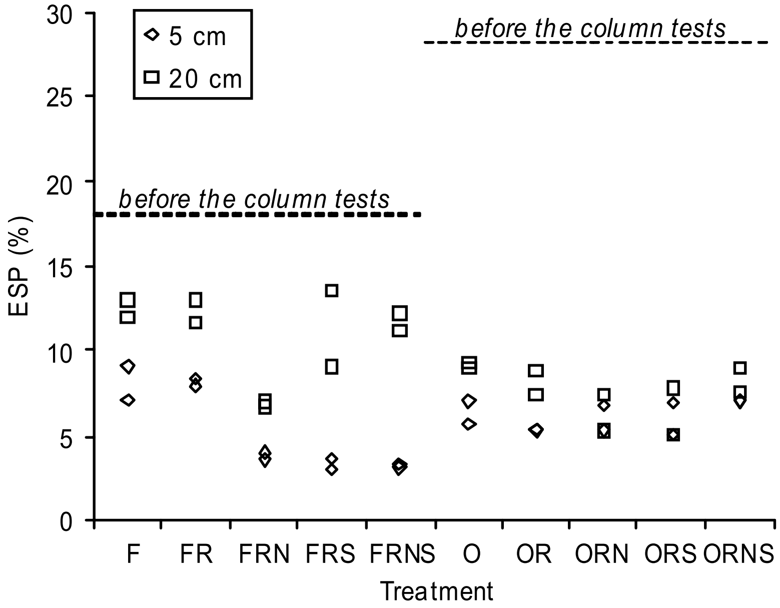

*Figure 6.3: The ESP at 5 cm and 20 cm depth before (dashed lines) and after (markers) the soil column tests for soils from Foum Gleita (F) and Office du Niger (O) for treatments without and with rice (R), nutrients (N) and straw (S) application.*

Water and salt movement

Soil columns filled with F soil wetted more rapidly (3–5 days) and homogeneously than columns filled with O soil (4–7 days). The soil solution appearing at the upper surface of the columns after complete saturation was clear for F columns but turbid for O columns, indicating clay or organic matter dispersion for the latter. The salts that had accumulated near the soil surface during wetting were transported downward with the irrigation water and these salt peaks (EC) at 5 cm and 20 cm can be observed in Figure 6.4. Although percolation rates were manually adjusted by varying the hydraulic head (i.e., height of the outlet), some differences in cumulative percolation were observed between the two soil types and different treatments (Table 6.3). Averaged for all treatments and times, percolation rates were 3.9 mm day$^{-1}$ and 3.0 mm day$^{-1}$ for the F and O columns, respectively. After 11 weeks, cumulative percolation was 9.5 ± 0.7 liters for the F columns and 7.2 ± 1.1 liters for the O columns. The large standard deviation for the cumulative percolated volume of the O columns was mainly due to large cumulative percolation (9.3 liters) measured in the ORS treatments. Unlike all other treatments, the FRN treatment received irrigation for another 4 weeks, because crop development was strongly delayed. Irrigation was only stopped after 15 weeks and cumulative percolated volume at maturity averaged 13.4 liters. Cumulative irrigation and evapotranspiration (Table 6.3) were positively related to crop growth; treatments with good plant growth had significant higher evapotranspiration rates than treatments with no or poor plant growth.

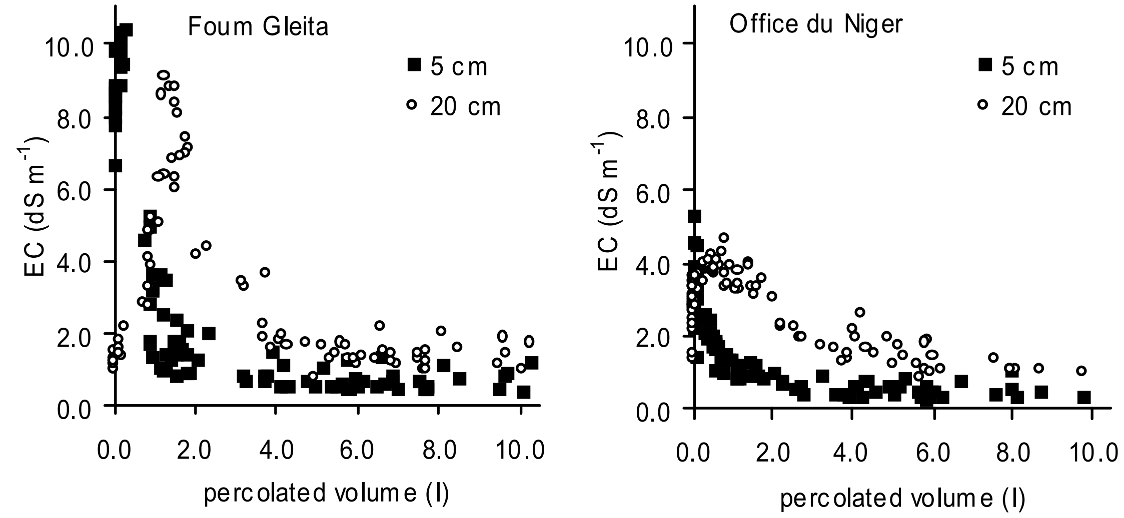

*Figure 6.4: Evolution of the electrical conductivity of the soil solution at 5 cm and 20 cm depth as a function of percolated volume measured at the outlet of the Foum Gleita and Office du Niger columns.*

### Plant growth

Yields were largest for treatments that received fertilizer (Table 6.3). Straw application had a strong positive effect on plant growth and yield for the F soil, but had no effect for the O soil. Rice plants in the FRN treatments showed stunted growth, brown coloration of the older leaves, and a prolonged vegetative growth period, which probably indicated zinc deficiency. Rice plants in the FR treatment showed almost no plant development after transplanting.

### Alkalinity balances

All treatments showed a negative alkalinity balance; i.e., alkalinity was lost from the root zone (Table 6.4). Largest alkalinity losses were observed for treatments that received nutrients and/or straw applications. Most alkalinity was lost through leaching. Plant uptake was also an important loss factor in treatments that had moderate to good rice growth. $\mathrm{Alk_{PLANT}}$ accounted for 8–18% of total alkalinity loss ($\mathrm{Alk_{TOTAL}}$) in the F columns (FRN, FRS, FRNS) and for 17–30% in the O columns (OR, ORN, ORS, ORNS). On average straw accounted for approximately 72 ± 10% and grain for 28 ± 10% of $\mathrm{Alk_{PLANT}}$. Plant mineral concentrations showed little variation between treatments and soils, and mean concentrations and standard deviation were 0.4 ± 0.04 % N, 0.06 ± 0.03 % P, 0.91 ± 0.25 % $K^+$, 0.37 ± 0.04 % $Ca^{2+}$, 0.24 ± 0.03 % $Mg^{2+}$, 0.92 ± 0.21 % $Na^+$ for straw and were 0.81 ± 0.09 % N, 0.23 ± 0.05 % P, 0.35 ± 0.09 % $K^+$, 0.05 ± 0.01 % $Ca^{2+}$, 0.10 ± 0.01 % $Mg^{2+}$, 0.010 ± 0.006 % $Na^+$ for grain. Application of nutrients had little direct effect on the alkalinity balance. Alkalinity added to the system in the zero-percolation scenario ($\mathrm{Alk_{EVPT}}$) was equal to or smaller than $\mathrm{Alk_{PLANT}}$. Straw application accounted for 26–35% of the total alkalinity added to the root zone in S treatments.

*Table 6.3: Average plant and water balance parameters (per column) for soils from Foum Gleita (F) and Office du Niger (O) for treatments without and with rice (R), nutrients (N) and straw (S) application.*

| | F | FR | FRN | FRS | FRNS | O | OR | ORN | ORS | ORNS |
|---|---|---|---|---|---|---|---|---|---|---|
| Grain (g) | – | – | 20a[5] | 10a | 26a | – | 22b | 41a | 22b | 37a |
| Plant (g) | – | –[4] | 52a | 18b | 56a | – | 40b | 72a | 42b | 77a |
| Leach[1] (l) | 9.0a | 9.0a | 10.3a[6] | 10.5a | 9.0a | 6.4a | 6.7a | 7.0a | 9.3a | 6.8a |
| Irri[2] (l) | 20.9c | 20.7c | 27.6b | 26.3b | 37.7a | 19.2c | 34.3b | 44.6a | 35.2b | 41.8ab |
| Evpt[3] (l) | 11.9c | 11.7c | 17.3b | 15.8b | 28.7a | 12.8c | 27.5b | 37.6a | 25.9b | 35.0a |

[1] total percolated volume after 11 weeks; [2] total irrigated volume after 11 weeks; [3] total evapotranspired volume after 11 weeks; [4] the mean above-ground biomass was less than 1 g and not included in the statistical analysis; [5] within each soil type, means in the same row followed by the same letter are not statistically different (LSD test; $p < 0.05$); [6] prolonged irrigation, resulting in 13.4 ± 0.2 liter percolation after 15 weeks

*Table 6.4: Average alkalinity balance parameters (mmol$_c$ column$^{-1}$) for soils from Foum Gleita (F) and Office du Niger (O) for treatments without and with rice (R), nutrients (N) and straw (S) application.*

| | F | FR | FRN | FRS | FRNS | O | OR | ORN | ORS | ORNS |
|---|---|---|---|---|---|---|---|---|---|---|
| $\text{Alk}_{\text{TOTAL}}$[1] | –119b[8] | –155ab | –189a | –180a | –195a | –119c | –127bc | –144bc | –183a | –156ab |
| $\text{Alk}_{\text{PLANT}}$[2] | – | – | –31b | –15a | –36b | – | –29c | –40b | –31c | –47a |
| $\text{Alk}_{\text{STRAW}}$[3] | 0 | 0 | 0 | 15 | 15 | 0 | 0 | 0 | 15 | 15 |
| $\text{Alk}_{\text{NUTR}}$[4] | 0 | 0 | –1 | 0 | –1 | 0 | 0 | –1 | 0 | –1 |
| $\text{Alk}_{\text{IRRI}}$[5] | 21c | 21c | 28b | 28b | 39a | 19c | 35b | 46a | 36b | 43ab |
| $\text{Alk}_{\text{EVPT}}$[6] | 12c | 12c | 18b | 16b | 29a | 13c | 28b | 38a | 26b | 36a |
| $\text{Alk}_{\text{LEACH}}$[7] | –140b | –176ab | –185a | –208a | –212a | –139b | –133b | –149b | –203a | –165ab |

[1] alkalinity accumulated in the root zone (0–20 cm) of each column; [2] alkalinity taken up by the plant (above-ground matter), assuming that nutrient uptake was restricted to the 0–20cm horizon; [3] alkalinity added with the application of 5 t ha$^{-1}$ of dry straw (97% dry matter); [4] alkalinity added with the application of nutrients (~326 kg Urea ha$^{-1}$; ~60 kg TSP ha$^{-1}$); [5] alkalinity added with the irrigation water; [6] alkalinity added if no percolation took place ~ evapotranspired volume × alkalinity irrigation water; [7] alkalinity leached from the root zone (0–20 cm); [8] within each soil type, treatment means in the same row followed by the same letter are not statistically different (LSD test; $p < 0.05$)

Changes in the soil solution

After saturation of the soil columns, pH at 5 cm depth *in situ* in the F soil stabilized within days to values of about 7.3 for S treatments and 7.6 for the other treatments. At 20 cm depth in the F soil, initial pH (7.7) steadily decreased during the first 4 weeks after saturation to a minimum of pH 6.9, followed by a slight increase to pH 7.0 for S treatments and pH 7.2 for the other treatments. In the O soil, pH development was similar at both depths with pH steadily declining from initial values of approximately 7.6 to pH values of 7.0, with no differences between S and no-S treatments.

*In situ* redox measurements revealed a rapid reduction of the soil environment after complete saturation of the soil columns. Redox potential at 5 cm depth in all columns dropped from pe > 1.0 to pe ± –4.0 within a week, except for the F columns without S, where pe reached this value only after 4 weeks. At 20 cm depth initial pe values varied around –3.0 for F columns and –4.5 for O columns, but stabilized at pe ± –4.0 in both soils after 6 weeks (pH and pe data not shown). Sodium was the dominant cation in the soil solution of both soils. However, its relative importance varied strongly in time. The Na:Ca ratio strongly decreased as the salt front passed at 5 and 20 cm depth. This effect was most pronounced at 20 cm depth and in the F soil (Figure 6.5). The soil solution alkalinity also showed important differences between soil types and as a function of time. In the O, soil alkalinity decreased linearly with the soil solution concentration and bicarbonate (at pH 7–7.5, ($HCO_3^-$) ≈ Alk) was the dominant anion. In the F soil, bicarbonate was the major anion at low solution concentration, but alkalinity was chemically controlled when the EC of the soil solution was higher than 2 dS $cm^{-1}$. In the O soil straw application had no distinct effect on the alkalinity of the soil solution. In the F soil, alkalinity increased after application of straw at 5 cm depth (Figure 6.7), but the effect was no longer visible at 20 cm depth. Soon after complete saturation of the

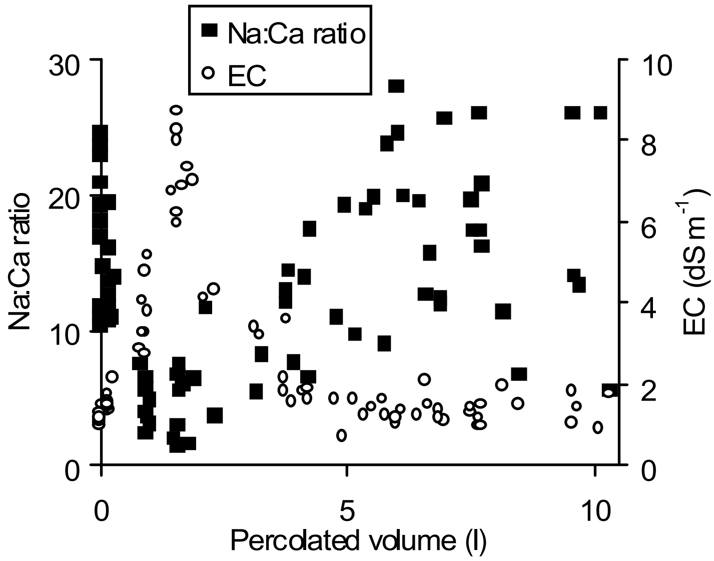

*Figure 6.5: Na:Ca ratio of the soil solution in the Foum Gleita columns at 20 cm depth as a function of percolated volume.*

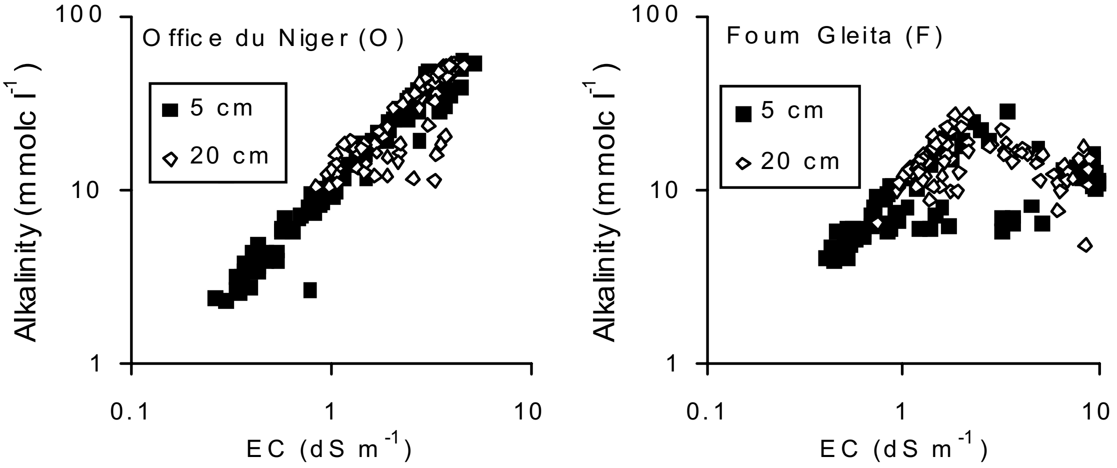

*Figure 6.6: Alkalinity as a function of EC in the soil solution of the Office du Niger and Foum Gleita.*

soil, $pCO_2$ was $10^{-1.5}$ atm for both soils and at both depths. At 5 cm depth, $pCO_2$ slowly decreased in time, to reach values around $10^{-1.8}$ atm in both soils, except for S treatments in the F soil, where a high $pCO_2$ ($10^{-1.5}$ atm) was maintained. At 20 cm depth, $pCO_2$ stabilized in both soils at around $10^{-1.3}$ atm. The soil solution of both soils at 5 cm depth showed supersaturation ($SI > 0$) with respect to calcite at the beginning of the trial. After 1–2 liters percolation, the salt peak was flushed downward and the saturation index (SI) of calcite rapidly declined to values between –0.5 and –1.0 for treatments without straw and to values of about zero for treatments with straw. These differences were best observed in the F soil (Figure 6.8). At 20 cm depth, SI-calcite also

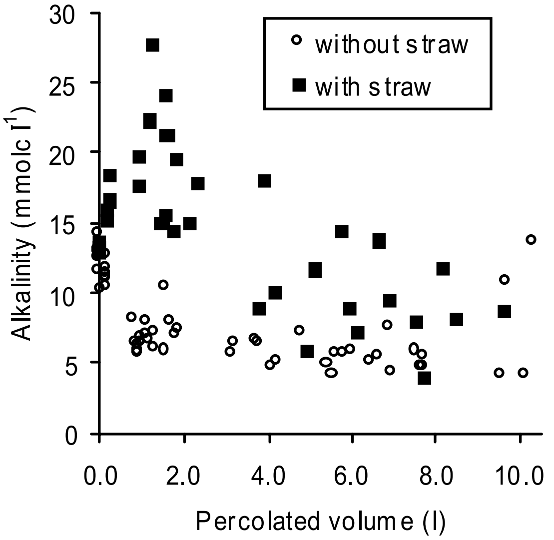

*Figure 6.7: Alkalinity of the soil solution for treatments with and without straw application at 5 cm depth in the Foum Gleita soil.*

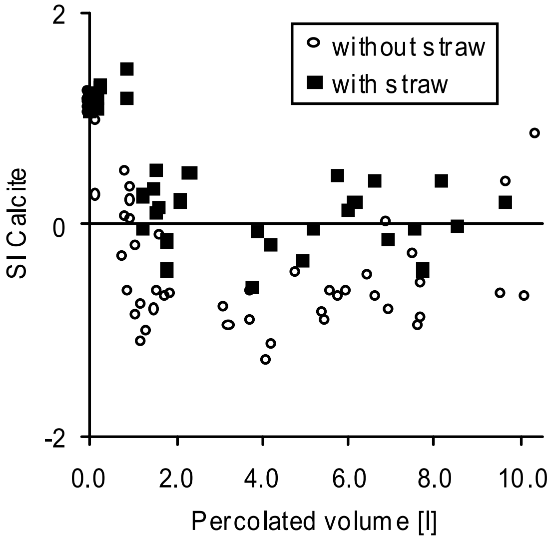

*Figure 6.8: The changes of the saturation index for calcite at 5 cm depth in the Foum Gleita soil, for treatments with and without straw application.*

decreased from an initial peak (1.8) to near-zero values after approximately 4 liters of percolation on both soils, with no differences between treatments with and without straw. Iron concentrations ($Fe^{2+}$) in the soil solution are shown in Figure 6.9. Iron concentrations for the O soil were distinctly larger than for the F soil. For the period of weeks 2 till 11, $Fe^{2+}$ concentrations in the O soil at 5 cm depth were stable, averaging 1.3 $mmol_c\ l^{-1}$ for S treatments and 0.5 $mmol_c\ l^{-1}$ for no S treatments. At 20 cm depth in the O soil, the effect of straw was less evident. Only from weeks 8 to 11, S treatments had larger $Fe^{2+}$ concentrations, similar to those at 5 cm depth. In the F columns, $Fe^{2+}$ concentrations were generally small (<0.3 $mmol_c\ l^{-1}$). Only in S treatments at 5 cm depth, $Fe^{2+}$ concentration steadily increased throughout the season to reach an average maximum of 0.6 $mmol_c\ l^{-1}$ at 11 weeks after transplanting. PHREEQC 2.0 simulations revealed that even at small concentrations of $Fe^{2+}$ (< 0.01 $mmol_c\ l^{-1}$), the solution was supersaturated with respect to siderite ($FeCO_3$) for both soils.

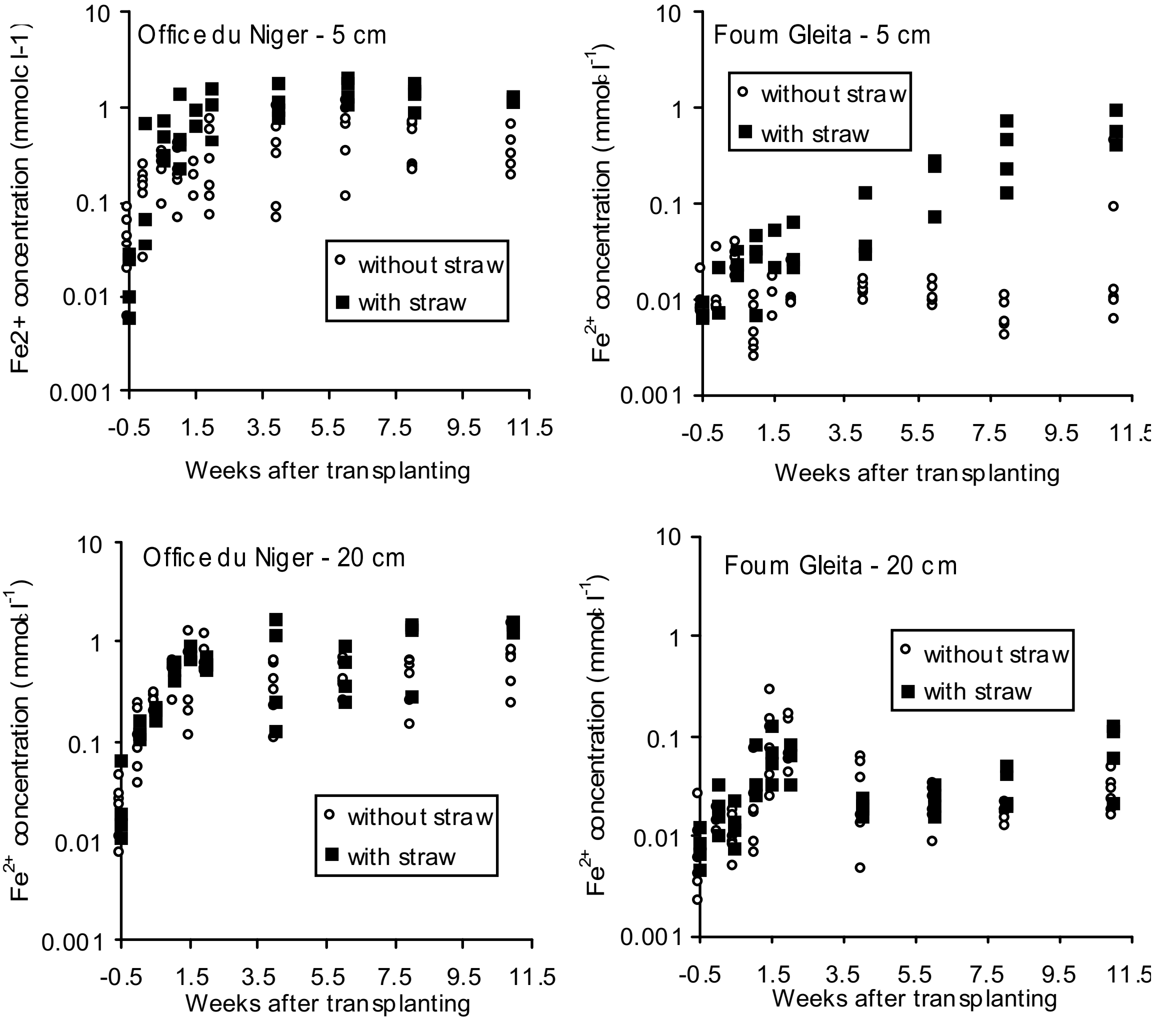

*Figure 6.9: Iron ($Fe^{2+}$) concentrations as measured in the vacuum tubes at 5 cm and 20 cm depth for the Office du Niger (O) and Foum Gleita (F) soil for treatments with and without straw application.*

## 6.4 Discussion

Transport and leaching processes

Average percolation rates (3–4 mm $day^{-1}$) correspond to maximum field rates for both soils (Condom, 2000; Van Asten, unpublished). However, percolation rates in the field are often sustained only during the first weeks after flooding, and can decrease to negligible values once groundwater levels have reached the surface (Condom, 2000).

The O soil showed signs of clay dispersion and behaved in a more heterogeneous way than the F soil; i.e., when compared to the F soil, the initial saturation of the O soil required more time, the wetting pattern was more irregular, and less irrigation water was needed (1.2 liter versus 1.6 liter) to flush the salt peak from 5 cm to 20 cm depth (Figure 6.4), which corresponds to a lower active pore volume (0.50 versus 0.67). Furthermore, the salt peak in the O soil showed stronger tailing, which agrees with larger dispersion and possibly bypass flow in this soil compared to the F soil. In the F soil, sodicity was somewhat lower and salinity of the soil solution higher, which opposes and in this case prevented clay dispersion. With the exception of treatment FRN and ORS, the cumulative percolated volume of treatments of the same soil type did not differ much (< 17%), which allows the interpretation of treatment effects on soil sodicity and alkalinity.

Changes in soil sodicity, alkalinity and salinity

Both soils showed a remarkable decrease in soil salinity (EC), sodicity (ESP) and pH. After one cropping season, the soils changed from sodic to non-sodic, with most dramatic changes in the O soil and near the soil surface. The trends observed in the alkalinity balances (Table 6.4) corresponded to those observed in the pH and ESP profiles after the experiment (Figures 6.2 and 6.3). Hence, we conclude that the soil solution and water balance measurements can generally be considered reliable and representative. The trend of decreasing alkalinity corresponds to field observations by Marlet (1999), who found that that soil pH had slightly decreased on the clayey soils in the ‘Office du Niger’ irrigation scheme during recent years of rice cropping.

The alkalinity balance calculations clearly revealed that leaching contributed most to the loss of soil alkalinity. Acidification of the soil by proton excretion of the rice crop was also an important factor, accounting for 8 to 30 % of the alkalinity losses. The proton excretion increased in treatments that received fertilizer. Hence, fertilizer application does not only increase yields and profit margins (Donovan et al., 1999), but also enhances acidification through plant proton excretion. When plant alkalinity uptake is converted to acidification rates per surface area, our findings (0.5–1.5 $mol_c\ m^{-1}$) were quite similar to the 1.3 $mol_c\ m^{-1}$ reported by Barbiéro et al. (2001), who cultivated the fodder crop Bourgi under flooded rice-like conditions with the aim to reclaim alkaline-sodic soils in the Lossa irrigation scheme in Niger. In case of zero-percolation (i.e., no leaching), treatments with proper rice growth (FRN, FRS, FRNS, OR, ORN, ORS, ORNS) would still have had a neutral to negative alkalinity balance, since $Alk_{PLANT} \geq Alk_{EVPT}$. Grain yield accounted for approximately 28 % of $Alk_{PLANT}$ and removal of grain only would not compensate the alkalinity added by irrigation in a zero-percolation system in the current trial setup. However, alkalinity and $RA_{calcite}$ of the irrigation water used in this trial are 2–3 times larger than values reported by Bertrand et al. (1993), Marlet et al. (1998) and Boivin et al. (2002) for the Niger and Senegal River. Hence, removal of grain only would compensate to a large extent for the alkalinity added during irrigation in a soil without natural or artificial drainage in most Sahelian irrigation schemes. Whether removal of straw should be recommended to farmers is questionable, since straw amendments help improve yield and long-term soil fertility (Ponnamperuma, 1984).

Application of straw initially increased the soil alkalinity with 15 $mmol_c$ per column, but this increase was completely compensated by increased $Alk_{LEACH}$ (Table 6.4), especially in the F columns. In the F columns, straw application also increased plant growth and, thus, the acidifying effect of plants ($Alk_{PLANT}$). The improved plant growth was attributed to increased N availability and increased Zn availability, something that was earlier observed in field trials in Sahelian irrigation schemes (Van Asten, unpublished). The higher $Alk_{LEACH}$ and $Alk_{PLANT}$ caused most S treatments to have a lower $Alk_{TOTAL}$ than their equivalent treatments without S. This is in agreement with the pH profiles (Figure 6.2) that showed lowest topsoil $pH_{1:2.5}$ in treatments that received straw. At the end of the trial, the $EC_{1:5}$ was higher in the surface horizon for all treatments, due to capillary rise that occurred between the moment that irrigation was discontinued and harvest. This effect was strongest in treatments with good plant growth.

Exchange processes and precipitation-dissolution of calcite

A decrease in soil sodicity implies a desorption of exchangeable $Na^+$, which is well observed in Figure 6.5. The Na:Ca ratio in the soil solution rapidly increased after the passage of the salt peak, which indicates the desorption of $Na^+$ from the exchange complex. Already in 1933, Gapon observed the dependence of exchange of monovalent and divalent cations on the ionic strength of the soil solution. This effect explains that soil sodicity decreases if the soil is leached with a low ionic strength solution that has a Na:Ca ratio similar to (or lower than) that of the original soil solution, as was the case in our trial. The drop in ESP was more pronounced and noticeable at greater depth in the O than in the F soil, due to its smaller CEC. Sodic soils with a small CEC will thus be easier to reclaim than soils with a large CEC. Conversely, soils with a small CEC will be more prone to sodication by capillary rise from saline groundwater or use of poor quality irrigation water.

In the F soil, the application of straw led to an increase in soil solution alkalinity (Figure 6.7), $Ca^{2+}$ concentration (data not shown) and $pCO_2$ at 5 cm depth. This effect can be attributed to the dissolution of native calcite (4 g $kg^{-1}$). This is visualized in Figure 6.8, where the SI calcite of the soil solution of S treatments remains close to zero (i.e., saturation), even when salinity levels drop. The hypothesis that application of straw would increase $pCO_2$, thereby dissolving native CaCO3, seems therefore correct. The O soil contained very little $CaCO_3$ (< 1 g $kg^{-1}$), so straw had little effect on the alkalinity of the soil solution. Precipitation and dissolution of calcite was controlling alkalinity of the soil solution of F columns, but not in the O columns. This is well illustrated in Figure 6.6, where we observe geochemical control of alkalinity at large concentrations in the F but not in the O soil. The soil solution had a positive $RA_{calcite}$ (results not shown) at small concentrations (EC < 2 dS $m^{-1}$), but a negative $RA_{calcite}$ and a lowering of solution alkalinity at larger concentrations (results not shown). This can be explained by desorption of exchangeable $Ca^{2+}$ with increasing solution concentration, which leads to calcite precipitation and a subsequent lowering of the soil solution alkalinity.

Redox processes

The rapid decrease in soil pe shortly after inundation was accompanied by an increase of $Fe^{2+}$ in the soil solution. The observed pe values were in the range that is commonly found for rice soils (Ponnamperuma, 1972). In both soils, clear differences in $Fe^{2+}$ concentrations between S and no-S treatments at 5 cm observed from week 2 onwards, appeared at 20 cm depth not earlier than 8 weeks after transplanting. The delay in $Fe^{2+}$ transport might be attributed to (i) adsorption of $Fe^{2+}$ at the cation exchange complex, which would lead to ferrolysis (Brinkman, 1970), or (ii) precipitation of secondary minerals such as siderite ($FeCO_3$). Siderite precipitation would lead to an equivalent lowering of $Fe^{2+}$ and alkalinity in the soil solution, so its precipitation would decrease the potential acidifying effect of ferrolysis. As in many field studies (Bruno et al., 1992), the soil solution of both soils and at both depth rapidly became supersaturated with respect to siderite. The current trial setup does not allow us to differentiate whether the delay in downward $Fe^{2+}$ transport can be attributed to adsorption at the exchange complex (~ferrolysis), or precipitation of secondary iron minerals. In the O soil, iron concentrations were distinctly higher (0.5–1.0 $mmol_c$ $l^{-1}$) when straw was applied (Figure 6.9), but remained low compared to the soil solution alkalinity (3–55 $mmol_c$ $l^{-1}$). This suggests that the potential effect of ferrolysis on the soil alkalinity balances in the current trial setup was very limited. However, $Fe^{2+}$ concentrations are still high enough to suspect significant long-term effects of ferrolysis on the alkalinity balances of both soils.

## 6.5 Conclusions

Irrigated rice cropping can potentially be used for the reclamation of two of West Africa's most alkaline-sodic soils; in one cropping season, the soils in the column experiments changed from sodic to non-sodic and pH decreased significantly. The loss of alkalinity and sodicity was predominantly the result of leaching with non-saline carbonate-rich irrigation water. The effect of leaching may be less dramatic in field conditions, where percolation rates can be lowered by subsoil conditions and increasing groundwater levels throughout the cropping season. Nevertheless, the trend of de-alkalinization observed in the soil columns corresponds to field observations of soils used for flooded crops elsewhere in the Sahel (Marlet, 1999; Barbiéro et al., 2001). Proton excretion by plants is an important factor responsible for 8–30% of the observed soil alkalinity decrease. Plant acidification rates per surface area correspond to field observations in Niger (Barbiéro et al., 2001) and equaled or exceeded alkalinity added via the irrigation water in a zero-percolation scenario. Although initially soil alkalinity increased slightly with rice straw application, its decomposition increased $pCO_2$ and caused dissolution of native calcite in the F soil. This resulted in increased leaching of alkalinity and a further lowering of the soil sodicitiy. Eventually this process may lead to a decalcification of the soil. Application of straw significantly increased iron reduction in the top layer (5 cm) of both soils. However, ferrolysis was of little importance to the short term changes of the soils' alkalinity balances, but might be importance for the long-term changes. Overall, we conclude that straw application accelerates a decrease of topsoil alkalinity and sodicity, provided that the soil contains some calcite and that downward percolation is assured. On non-calcareous alkaline-sodic soils with very low percolation rates, removal of straw may be the better option if decreasing the soil alkalinity is the primary objective. Fertilizer applications increase plant growth and enhance soil acidification through plant proton excretion. Compared to soils with a large CEC and $CaCO_3$ content, soils with a small CEC and $CaCO_3$ content have less buffer capacity and can be reclaimed rapidly. Under standard conditions of cultivation, farmers in Foum Gleita and the Office du Niger do not have to fear rapid alkalinization of their rice fields, provided that capillary rise during the fallow season is limited.

# 7 CONCLUSIONS

In the mid-1990's, declining rice yields and the observation of salt efflorescences at the soil surface worried both farmers and scientist and led to the general belief that the agricultural potential of Sahelian irrigation schemes was jeopardized by rapid salinization and alkalinization. This 'doom' scenario was further fueled by studies that showed that most Sahelian irrigation waters are relatively carbonate rich and might not be as safe as suggested by low SAR and EC values. In Senegal, Mali and Niger, several studies were conducted to quantify salinisation and alkalinization processes, but few scientists focused on the relationship between low and declining rice productivity and the supposed salt-related soil degradation problems. Hence, salt-related soil degradation became an important issue in Sahel irrigation schemes, without knowing much about what impact it could possibly have on rice productivity.

We took a close look at rice productivity problems in the irrigation schemes of Foum Gleita and the Sourou Valley and concluded that low yields were caused by nutrient deficiencies. N and P deficiency were identified as major cropping constraints in Foum Gleita, while Zn deficiency prevailed in the Sourou Valley. The large majority of the 'problem' soils at both sites contained little salt and little exchangeable sodium (ESP < 5%). Hence, the soils could neither be classified saline nor sodic according to USDA classification (Richards, 1954) and for neither sodicity nor salinity it is probable that they contributed to the observed nutrient deficiency problems. However, in Foum Gleita and the Sourou Valley, all soils where serious rice productivity problems were observed had an alkaline-calcareous character (pH 7.0 -8.5). The presence of alkaline salts may well have contributed to the low availability of N, P and Zn through gaseous losses (N) and adsorption onto, or precipitation in the form of carbonate minerals (P, Zn). Hence, the soils could not be classified degraded following international classification, but the alkalinity-induced soil fertility problems the farmers were facing were very real. As such, farmers in both schemes were correct in relating (alkaline) salt efflorescences to the productivity problems.

Most Sahelian farmers had no experience with rice cropping prior to the construction of the irrigation schemes 15-20 years ago. Therefore, it seemed little surprising that most studies on rice productivity problems in Sahelian irrigation schemes identified sub-optimal crop management as primary reason for the low yields. We monitored farmer practices in Foum Gleita and the Sourou Valley and found that farmers' crop management in both Foum Gleita and in the Sourou Valley generally deviated somewhat from local recommendations. However, not the non-compliance to local recommendations, but the inadequacy of local fertilizer recommendations was the main reason for the large yield gaps, i.e., the small N dose and zero P fertilizer dose recommendations in Foum Gleita and zero Zn fertilizer dose recommendation in the Sourou Valley. Both in Foum Gleita and in the Sourou Valley, yields could easily be increased from around 3–4 t $ha^{-1}$ to 5–6.5 t $ha^{-1}$ through application of ample N, P and Zn fertilizer. In Foum Gleita, however, N and P fertilizer requirements on the alkaline 'degraded' soils were much larger than on the pH neutral 'non-degraded' soils. For most farmers in the Sourou Valley and on the 'degraded' soils in Foum Gleita, the recommended fertilizer doses are either very expensive or not available on the local market. Hence, we tested the use of organic amendments as an alternative solution to improve nutrient availability, while maintaining production costs at an acceptable level.

The use of organic amendments proved very beneficial at both irrigation schemes. In Foum Gleita, application of 5 t rice straw ha$^{-1}$ increased yields by 1.1 t ha$^{-1}$ on average, independent of soil type and fertilizer dose. Straw application improved N availability, but we found no clear evidence of improved P availability. The improved N availability was attributed to N mineralized from the straw, from increased mineralization of soil organic matter (SOM) with a low C:N ratio ($\leq$ 7.2) and from increased recovery efficiency of applied mineral fertilizer N (urea). We hypothesized that improved N fertilizer recovery upon straw application was due to reduced nitrification-denitrification losses. In the Sourou Valley, the application of 5 t ha$^{-1}$ decomposed rice straw, compost, or cattle manure increased yields by 1.5 to 2.0 t ha$^{-1}$. The use of organic amendments improved Zn uptake, but did not eradicate Zn deficiency entirely. Overall, the use of (decomposed) straw amendments proved very beneficial at both sites. Most Asian studies on the use of rice straw in irrigated rice show little to no short-term yield increase (0-0.4 t ha$^{-1}$). Although we tried to explain how straw amendments influenced N and P availability in Foum Gleita (Chapter 4), more research is needed to fully understand and quantify the long-term role of organic matter amendments. In the mean time, farmers can apply (decomposed) rice straw to improve their yields. Straw is readily available, although it is occasionally used as cattle fodder in Foum Gleita. In the Sourou Valley organic amendments are also used for vegetable cropping. However, the main constraint for large-scale adoption of organic matter amendments by farmers may be the large labor requirements that are needed to incorporate organic amendments into the topsoil.

We found no evidence to support the hypothesis that alkalinization through excessive evapotranspiration of RA$_{calcite}$ positive irrigation water is an ongoing process in Foum Gleita and the Sourou Valley. Both in Foum Gleita and in the Sourou Valley, most field and groundwater was only 2–6 times more concentrated than irrigation water. Such small concentration factors indicate the absence of excessive concentration of irrigation waters at this point in time. In Foum Gleita, the alkaline salts in the so-called degraded soils originated from the schist parent rock at shallow depths (<1.2 m). A comparison of historical soil data revealed no significant changes of soil pH and EC over the last 30 years. Although Foum Gleita's irrigation water is amongst the most alkaline in the Sahel, the soils appear to have a substantial buffer capacity against alkalinization; despite the positive RA$_{calcite}$ of the soil and irrigation water, they do not develop into highly alkaline-sodic solutions upon concentration due to release of Ca$^{2+}$ from the exchange complex. Furthermore, proton excretion by plants largely compensates for the alkalinity that is added during irrigation when percolation is absent. This means that, even in schemes with limited drainage facilities, irrigated rice cropping is unlikely to contribute to a substantial build up of alkaline salts in the root zone during the growing season. Although we found no evidence of ongoing alkalinization in the Sahelian schemes, alkalinization can still occur when irrigation is halted and substantial capillary rise from a shallow groundwater table occurs. Moreover, substantial capillary rise can occur in fields that are left uncultivated, or in areas bordering an irrigated rice scheme. More research will be needed to further examine secondary salinization and alkalinization effects of irrigated rice cropping on non-flooded neighbouring areas (e.g., land used for vegetable cropping or fallow).

The existing alkaline-sodic soils in the Sahel can be reclaimed through irrigated rice cropping, provided some drainage to remove alkaline salts is possible. Most Sahelian irrigation waters contain little salt, and the presence of a pounded water layer enhances downward leaching of salts. The rice crop further enhances the reclamation of alkaline-sodic soils through proton excretion. Our results correspond to findings in Asia, where rice is often used to enhance reclamation of alkaline-sodic soils. If some (natural) drainage occurs and the soil contains some calcite, then straw can best be incorporated in the soil, as its anaerobic decomposition increases $pCO_2$ and $Ca^{2+}$ in the soil solution. The latter enhances desorption and leaching of exchangeable $Na^+$ and favours de-sodication and de-alkalinization of the soil. Thus, the application of organic amendments did not only improve nutrient availability in Foum Gleita, but also contributed to the reclamation of calcareous alkaline-sodic rice soils. In non-calcareous alkaline soils, removal of straw would be the better option, if the sole objective is to decrease soil alkalinity to a maximum. We found no evidence that ferrolysis affected the short term alkalinity balance of alkaline rice soils to any extent.

Overall, we conclude that there is little evidence that supports the hypothesis that alkalinization is an ongoing process in irrigated rice fields in the Sahel. On the contrary, irrigated rice cropping may well decrease the alkalinity and sodicity of alkaline-sodic rice soils in the Sahel. Nonetheless, alkalinity-induced nutrient deficiency problems have been found to occur in several of the Sahelian irrigation schemes. As such, alkalinity can be a real cropping constraint. Farmers were persistent in indicating that low yields were related to a salt-related problem, despite our primary interpretation that soil EC, pH and ESP were nothing to worry about according to international classifications. Very often, farmers not only proved right (e.g., by pointing to (alkaline) salts), but their participation in the research was instrumental for the identification of crop production constraints and potential solutions. We showed in farmer fields and research-managed trials that alkalinity-induced nutrient deficiencies can be overcome by the application of mineral fertilizers. However, the mineral fertilizer doses needed are large, or are not available on the local market. In both cases, farmers will not be able to adopt new fertilizer recommendations. Furthermore, if we do not better understand the mechanisms that reduce nutrient availability, fertilizer recommendations might have to increase or remain high in time. We showed that productivity problems can partially be overcome by application of organic amendments, but little is known about the long-term effects of organic matter applications in combination with (too) low mineral fertilizer doses. Thus, further research on processes that regulate availability of N, P and Zn on alkaline-calcareous rice soils is recommended. In addition, long term salt-related problems still deserve our attention in areas where groundwater is in contact with the root zone, in combination with limited (natural) possibilities to leach accumulated salts.

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# SUMMARY

In the Sahel, irrigated rice cropping has been introduced on a large-scale in the 1970's and 1980's, after droughts devastated crops and livestock. The massive investments in irrigation infrastructure were meant to improve food security, while generating income for the local farmers. Furthermore, rice demand in the Sahel was rapidly growing due to a steady increase of the urban population. The production of rice in Sahelian countries would decrease the need for expensive imports. The irrigation schemes were constructed along the major Sahelian rivers and their tributaries. In general, irrigation water is abundantly available along these rivers and the dry and sunny climate allows high potential yields in both dry and wet season; i.e., between 7 and 9 t $ha^{-1}$, with peaks up to 12 t $ha^{-1}$. However, actual yields vary between 4-6 t $ha^{-1}$ and cropping intensity is often low. Several researchers showed that a series of socio-economic constraints led to sub-optimal crop- and land management, with low fertilizer doses and late timing of fertilizer application and weeding as major yield limiting factors. In some irrigation schemes, yields started to decline to levels below 4 t $ha^{-1}$, only a few years after construction of the schemes. Both farmers and researchers feared that this yield decline was due to an accumulation of (alkaline) salts. Although most Sahelian irrigation waters contain little salt, they contain relative large amounts of (bi)carbonate ($RA_{calcite} > 0$). Excessive and continuous concentration of such waters can lead to the formation of an alkaline (high pH) and sodic (high sodium content) soil. Such a soil has a low agricultural potential and reclamation of alkaline-sodic soils is often time-consuming and expensive. In the early 1990's, the first signs of alkalinization were reported from the Sahel's oldest irrigation scheme in Mali and some salt efflorescences were observed in other Sahelian schemes. In the mid 1990's, the 'doom scenario' of human-induced degradation of the Sahel's most precious land rapidly gained popularity amongst scientist and extension workers active in the region. In this context, WARDA initiated research to investigate the causes of declining yields and the potential dangers of soil alkalinization. The results of this research form the basis of this thesis.

In Chapter 2 and 3, we investigated the causes of declining yields in the irrigation schemes of Foum Gleita in Mauritania and the Sourou Valley in Burkina Faso. In both schemes, yields had dropped from around 4.5-5.5 t $ha^{-1}$ to around 3-4 t $ha^{-1}$ some 5-10 years after construction. At both sites, we organized meetings with farmers to discuss possible causes and solutions for the rice productivity problems. Results of these meetings were used to setup farmer surveys, farmer-managed trials, and researcher-managed trials.

In Foum Gleita, low yields were caused by N and P deficiency. Yields were lowest on the upper and middle slopes, where soils are shallow (<1.2m). Farmers classified these soils as degraded. Although these 'degraded' soils were more alkaline and saline than soils further down slope, EC, pH and ESP values were generally too low to classify the soils as saline or sodic following international classifications. N and P deficiency on the degraded soils were caused by low soil N supply, low soil P supply, occasional low N

fertilizer dose, and not applying of P fertilizer. The alkaline-calcareous nature of the 'degraded' soils likely contributed to low N availability through volatilization and low P availability through adsorption on, or precipitation of carbonate minerals.

In the Sourou Valley, yield decline coincided with the appearance of low productive spots. These spots were caused by Zn deficiency, due to the soils' low DTPA-extractable Zn content, the alkaline-calcareous character of the soil, and the non-application of Zn fertilizer in combination with a relatively large P fertilizer dose. Zn deficiency is a known problem on alkaline-calcareous rice soils due to the soil's high carbonate concentrations. In the Sahel, many rice soils have an alkaline-calcareous character, and this study is one of the first to show that Zn deficiency can be a serious cropping constraint in Sahelian irrigation schemes.

Farmers' crop management in both Foum Gleita and in the Sourou Valley generally deviated somewhat from local recommendations. However, not complying to the local recommendations was not the main cause for low yields. Rather, the inadequacy of the local recommendations, i.e., small N fertilizer dose and zero P fertilizer dose recommendations in Foum Gleita and zero Zn fertilizer dose recommendation in the Sourou Valley contributed most to the observed productivity problems. Both in Foum Gleita and in the Sourou Valley, yields could easily be increased from around 3-4 t ha$^{-1}$ to 5-6.5 t ha$^{-1}$ through application of ample N, P and Zn fertilizer. However, the recommended fertilizer doses are either very costly or the fertilizer is not (sufficiently) available on the local markets. Therefore, we tested the application of organic amendments at a rate of 5 t ha$^{-1}$ dry matter as a means to improve soil fertility.

In the Sourou Valley, decomposed organic amendments increased yields by 1.5-2 t ha$^{-1}$. We found that the application of decomposed rice straw in 29 farmer fields increased both yield and plant Zn uptake, but Zn concentrations remained very low. This indicates that Zn deficiency was not fully eradicated. The positive effect of organic matter application on Zn uptake might be related to increased dissolution of carbonate-bound Zn. Increased dissolution of native carbonate salts upon application of organic matter was observed in a calcareous alkaline soil of Foum Gleita (Chapter 6). However, more research will be needed on the mechanisms that control Zn availability as total Zn content of the 0-0.2m root zone is over 50 times larger than the quantity applied with 10 kg Zn fertilizer ha$^{-1}$ and over 100 times larger than the DTPA-extractable Zn content.

In Chapter 4, we closer examined the effect of 'fresh' straw amendments on yields and N and P availability in Foum Gleita. Application of 5 t 'fresh' straw ha$^{-1}$ increased yields on average by 1.1 t ha$^{-1}$, independent of soil type or applied mineral fertilizer. Only if yields were close to potential, straw did not have an effect on yield. The positive effect of straw was attributed to improved N availability, but we found no evidence of improved P availability. Based on a field and pot trial, we concluded that the improved N availability was due to N mineralized from the straw, to increased mineralization of soil organic matter with a low C:N ratio ($\leq 7.2$), and to increased recovery efficiency of applied mineral fertilizer N (urea). We hypothesized that improved N fertilizer recovery upon straw application was due to reduced nitrification-denitrification losses. In general, we conclude that improved organic matter management can substantially improve yields, while maintaining fertilizer costs at an acceptable level. However, improved mineral fertilizer management will remain necessary for many farmers in Foum Gleita and the Sourou Valley, because (i) some nutrient pools (P, Zn) may still be further depleted, despite organic matter amendments, (ii) farmers may find the incorporation of organic amendments too labor intensive, and (iii) some organic matter sources (e.g., fresh straw) may be used as cattle fodder or will be used to fertilize other crops (e.g., vegetables).

In Chapter 5, we investigated actual and potential salt-related soil degradation in Foum Gleita. The irrigation water in Foum Gleita is one of the most alkaline ones used in the Sahel. Hence, if alkalinization in Sahelian irrigated rice schemes is an ongoing process, we would expect the highest alkalinization rates in Foum Gleita. As such, the Foum Gleita irrigation scheme could act as an early warning system for what might happen in other Sahelian schemes at a later stage. In Chapter 3, we already concluded that higher concentrations of alkaline salts on the ‘degraded’ soils likely contributed to low availability of N and P. In Chapter 5, we tried to explain how these salts were distributed and where they originated from. Detailed sampling of soils in a 532m long toposequence, combined with soil pit and groundwater analysis revealed that the ‘degraded’ soils, which are found on the upper section of the toposequence, originate from the schist parent rock that can be found at shallow depths (< 1.2m). Soils further down slope are thicker and consist (partly) of alluvial deposits. Annual floods leach the lower lying soils and prevent a build up of alkaline salts. Within the toposequence, large variations in soil salinity and alkalinity occur at short distances, indicating minimum horizontal groundwater flow and a strong variation in the geochemical composition of the vertically positioned bedrock. The distribution of the salts did not seem to be related to the presence of irrigation and drainage canals. Hence, we found no evidence that supports the hypothesis that irrigation activities increased soil alkalinity. Furthermore, a comparison of historical data revealed no significant changes of topsoil salinity and pH over the last 30 years. We concluded that current alkalinity problems in Foum Gleita were inherited from the parent rock and were not the result of human-induced alkalinization. We used the PHREEQC 2.0 model to simulate excessive concentrating of the irrigation water by evapotranspiration. The development over time into a strongly sodic-alkaline solution did not agree with field data, which showed geochemical control of alkalinity at high solution concentrations. Only when cation exchange processes were included, simulated changes with regard to $Ca^{2+}$ and Alkalinity of the soil solution agreed with field data. The best agreement with field data was obtained when modeling with a small (1 $mmol_c$ 100 g dry $soil^{-1}$) but calcium saturated CEC. The model simulations revealed that the soil’s capacity to counteract alkalinization is very large, though not infinite. The comparison of historical soil data, the detailed toposequence study and the simulation modeling exercise all suggest that rapid alkalinization is not to be expected in irrigated rice fields in Foum Gleita.

In Chapter 6, we studied the effect of irrigated rice cropping and organic matter management on two of the most alkaline-sodic rice soils in the Sahel: a 'degraded' soil from Foum Gleita and an alkaline-sodic soil from the Office du Niger (Mali). The soils were used to fill soil columns with treatments with and without rice, mineral fertilizer and rice straw amendments. The column tests were conducted at the WARDA research station in Senegal, using non-saline carbonate-rich irrigation water typical for the Sahel. Percolation was artificially maintained at 3–4 mm day$^{-1}$. Complete water and alkalinity balances were established for all columns and compared to soil analysis before and after one rice cropping season. For all treatments, soils had turned from sodic to non-sodic, and pH had dramatically decreased, most notably near the soil surface. The changes were largest in the Office du Niger soil due to its small buffering capacity (little $CaCO_3$ and small CEC). The large decrease in sodicity and alkalinity was mainly the result of leaching with non-saline water. Proton excretion by plants accounted for 8-30% of the alkalinity loss. Moreover, proton excretion equaled or exceeded alkalinity added via irrigation in a zero-percolation scenario. This means that removal of straw and grain would prevent further alkalinization of the soils if percolation is absent. However, removal of straw is mostly not recommended, as was shown in Chapters 3 and 4. Furthermore, in the Foum Gleita soil, straw application led to the dissolution of native calcite, due to an increase in $pCO_2$. The dissolution of calcite increased $Ca^{2+}$ of the soil solution and enhanced desorption of exchangeable $Na^+$. This process resulted in an accelerated de-alkalinization and de-sodication of the soil. The reduction of iron hydroxides could theoretically accelerate de-alkalinization of the upper soil layers. However, we found no evidence to indicate that ferrolysis altered the short-term alkalinity balance of the studied soils to any extent. Our results are in line with recent field studies, and suggest a de-alkalinization of sodic-alkaline flooded (rice) soils in the Sahel.

We showed that the small yields observed in some of the Sahelian irrigation schemes were related to inadequate or omitted application of mineral fertilizers (N, P, Zn), low recovery of applied fertilizers (N, P), and low plant available nutrient contents in the soil (N, P, Zn). Mineral fertilizers are costly or not available on the local markets, so many farmers will not be able to adopt improved mineral fertilizer recommendations. Improved organic matter management is one of the few means for farmers to improve their yields without substantially increasing costs. Organic amendments of 5 t ha$^{-1}$ can increase yields by 1-2 t ha$^{-1}$. Low plant available nutrient contents in the soil (N, P, Zn) were often related to the presence of carbonate salts. However, most soils could neither be classified saline nor sodic. Furthermore, the alkaline salts were in the studied soils before irrigated rice was introduced. Under standard conditions of cultivation, irrigated rice farmers in the Sahel do not have to anticipate rapid alkalinization of their rice fields. On the contrary, provided there is some (natural) drainage, rice cropping can be used to reclaim the current alkaline-sodic soils in the Sahel. Organic matter amendments can accelerate the reclamation of alkaline-sodic soils that contain native calcite.

# SAMENVATTING

Geïrrigeerde rijstbouw is op grote schaal geïntroduceerd in de Sahel in de jaren zeventig en tachtig als reactie op de droogtes die veestapels en oogsten hadden verwoest. De grote investeringen in irrigatie-infrastructuur hadden als doel de voedselzekerheid te verhogen en de boeren inkomstmogelijkheden te bieden. Verder nam de vraag naar en import van rijst gestaag toe door de groei van de stedelijke bevolking. De binnenlandse productie van rijst zou de dure import van rijst doen verminderen. De irrigatieschema's werden met name aangelegd langs de grote rivieren en hun zijarmen. Hier is voldoende water en het droge, zonnige klimaat garandeert hoge potentiële opbrengsten (7-9 t $ha^{-1}$ met uitschieters tot 12 t $ha^{-1}$) in het droge en natte seizoen. De huidige rijstoogsten bedragen echter zo'n 4 tot 6 t $ha^{-1}$ en veel land in de irrigatieschema's wordt niet of weinig benut. Verscheidene onderzoekers hebben aangetoond dat de tegenvallende opbrengsten het gevolg zijn van suboptimaal land- en gewasbeheer, met name gebrekkige bemesting- en onkruidbestrijdingtechnieken. Ongunstig sociaal-economische omstandigheden liggen echter aan de basis van de problematiek. In verschillende irrigatieschema's daalde de gewasopbrengst zelfs tot onder de 4 t $ha^{-1}$ enkele jaren na ingebruikname. Zowel boeren als onderzoekers vreesden dat deze afname het gevolg was van een ophoping van (alkalische) zouten. Alhoewel het meeste irrigatiewater in de Sahel weinig zout bevat, is dit water relatief rijk aan (bi)carbonaat ($RA_{calciet} > 0$). Voortdurende indamping (concentratie) van zulk water kan leiden tot de vorming van een alkalische natriumbodem (i.e., een bodem met een uitwisselbaar natriumgehalte van boven de 15% en met een basische pH). Dit type bodem heeft een laag landbouwpotentieel en het herstellen ervan is kapitaalintensief en tijdrovend. In het begin van de jaren negentig werden in Mali de eerste tekenen van de vorming van alkalische natriumbodems (i.e., alkalinisatie) waargenomen in het oudste grootschalige irrigatieschema van de Sahel. Gedurende de midden jaren negentig raakten meer en meer onderzoekers en landbouwvoorlichters ervan overtuigd dat deze door mensen veroorzaakte vorm van bodemdegradatie onvermijdelijk was. Het was in dit kader dat het West Afrikaanse Rijst Onderzoeksinstituut (WARDA) onderzoek verrichtte naar de oorzaken van de oogstproblemen en de mogelijke gevaren van de opeenhoping van (alkalische) zouten in de bodem. De resultaten van dit onderzoek vormen de basis van dit proefschrift.

In Hoofdstuk 2 en 3 worden de oorzaken van de afnemende rijstopbrengsten in twee irrigatieschema's in de Sahel (de Sourou vallei in Burkina Faso en Foum Gleita in Mauritanië) bestudeerd. Zo'n vijf tot tien jaar na de aanleg van beide irrigatieschema's daalden de gewasopbrengsten van 4.5–5.5 t $ha^{-1}$ naar 3–4 t $ha^{-1}$. Om mogelijke oorzaken van de lage gewasopbrengst te identificeren organiseerden we bijeenkomsten met de betrokken boeren. De resultaten van deze bijeenkomsten gebruikten we als leidraad voor het opzetten van enquêtes en proeven in boerenvelden. Sommige van deze proeven werden door boeren beheerd, en anderen door onderzoekers.

De lage opbrengsten in Foum Gleita blijken het gevolg te zijn van stikstof (N) en fosfor (P) gebrek. De laagste opbrengsten werden gemeten op ondiepe bodems (<1.2m) bovenin de toposequentie. Boeren classificeerden deze bodems als gedegradeerd. Alhoewel deze 'gedegradeerde' bodems meer alkalische zouten blijken te bevatten dan lagergelegen gronden, kunnen ze niet als zoute- of natriumbodem worden geclassificeerd volgens internationale standaarden. Het geconstateerd gebrek aan N en P in de plant wordt veroorzaakt doordat de bodem weinig N en P levert, de N kunstmestgift soms laag is, en er geen P kunstmest wordt toegediend. De kalkrijke alkalische aard van de 'gedegradeerde' bodems draagt waarschijnlijk bij aan een lage N beschikbaarheid door volatilisatie en een lage P beschikbaarheid door adsorptie aan, of precipitatie van carbonaatzouten.

In de Sourou vallei werden de afnemende oogsten veroorzaakt door de ontwikkeling van plekken van slechte rijstgroei in de velden. Ons onderzoek toont aan dat deze plekken het gevolg zijn van zink (Zn) gebrek in de rijstplant. De oorzaak van het Zn gebrek houdt verband met het geringe gehalte aan DTPA-extraheerbaar Zn en de kalkrijke alkalische aard van de bodem, in combinatie met het ontbreken van Zn kunstmestgiften en relatief grote P kunstmestgiften. Zn gebrek in rijstteelt op kalkrijke bodems is een bekend verschijnsel en is het gevolg van de hoge carbonaatconcentraties in de bodem. Veel van bodems waarop rijst wordt geteeld in de Sahel zijn kalkrijk. Dit is de eerste studie die aantoont dat Zn gebrek een serieuse belemmering voor de rijstteelt in de Sahel kan vormen.

Het gewasbeheer door de boeren in Foum Gleita en in de Sourou vallei week meestal enigszins af van de adviezen van de lokale landbouwvoorlichters. Dit was echter niet de belangrijkste oorzaak van de geringe gewasopbrengsten. Deze werden met name veroorzaakt door de ongeschiktheid van de lokale adviezen, zoals te lage N adviezen en een ontbrekend P advies in Foum Gleita en de afwezigheid van een Zn advies in de Sourou Vallei. Zowel in Foum Gleita als in de Sourou vallei nam de gewasopbrengst toe van 3–4 t $ha^{-1}$ naar 5–6.5 t $ha^{-1}$ wanneer voldoende N, P en/of Zn kunstmest werd toegediend. De aanbevolen kunstmesthoeveelheden zijn echter duur of niet beschikbaar op de lokale markten. Daarom hebben we getracht de bodemvruchtbaarheid te verbeteren met behulp van organische stof giften van 5 t droge stof $ha^{-1}$.

In de Sourou Vallei resulteerde de toediening van gedecomposteerd organisch materiaal in een opbrengstverhoging van 1.5–2 t $ha^{-1}$. Resultaten van 29 boerenvelden tonen aan dat hierbij de Zn opname door de plant toenam, maar dat Zn concentraties in de plant erg laag bleven, wat betekent dat het Zn gebrek niet volledig werd opgeheven. Het positieve effect van organische stof giften op Zn opname is waarschijnlijk gerelateerd aan het vrijkomen van carbonaat-gebonden Zn. Het oplossen van carbonaatzouten als gevolg van organische stof toediening wordt nader besproken in Hoofdstuk 6. Er is echter meer onderzoek nodig naar de mechanismen die de Zn beschikbaarheid in de bodem bepalen, aangezien de totale hoeveelheid Zn in de wortelzone (0 – 0.2 m) meer dan 50 keer groter is dan de hoeveelheid Zn toegediend in een 10 kg $ha^{-1}$ Zn kunstmestgift en meer dan 100 keer groter is dan het DTPA-extraheerbare Zn gehalte. Toediening van 5 t 'vers' stro $ha^{-1}$ op "gedegradeerde" en 'niet-gedegradeerde' bodems in Foum Gleita verhoogde de rijstopbrengst gemiddeld met 1.1 t $ha^{-1}$, onafhankelijk van de samenstelling en de grootte van de kunstmestgift (Hoofdstuk 4). Slechts wanneer de gewasopbrengst zijn potentieel naderde had stro toediening geen opbrengstverhogend effect. Het positieve effect van stro wordt toegedicht aan een verbeterde N beschikbaarheid. We vonden geen duidelijke aanwijzingen dat stro toediening de P beschikbaarheid verhoogt. Uit de resultaten van veld- en potproeven concluderen we dat de verbeterde N beschikbaarheid het gevolg was van mineralisatie van stro-N, mineralisatie van bodem-N door een lage C:N verhouding ($\leq 7.2$) in de bodem, en een verbeterde opname van kunstmest-N door de plant. We veronderstellen dat de verbeterde kunstmest-N opname werd veroorzaakt door een afname van nitrificatie-denitrificatieverliezen.

In z'n algemeenheid concluderen we dat een verbeterd beheer van organische stof kan leiden tot een duidelijke verhoging van de gewasopbrengst, terwijl de kosten voor kunstmest op een aanvaardbaar niveau kunnen blijven. Een verbetering van het kunstmestbeheer blijft echter noodzakelijk voor boeren in Foum Gleita en de Sourou Vallei omdat: (i) sommige nutriëntenvoorraden (P, Zn) in de bodem ondanks toediening van organische stof verder kunnen worden uitgeput, (ii) het toedienen van organische stof soms te arbeidsintensief is, en (iii) organische stof bronnen soms ook voor andere doeleinden worden ingezet (b.v. stro als diervoeder of compost als meststof in de tuinbouw).

In Hoofdstuk 5 hebben we de actuele en potentiële bodemdegradatie door (alkalische) zouten bestudeerd in Foum Gleita. Het irrigatiewater van Foum Gleita behoort tot het meest alkalische van de Sahel. Indien er sprake is van ophoping van alkalische (zouten) in de rijst-irrigatieschema's van de Sahel, dan is het te verwachten dat dit proces relatief snel verloopt in Foum Gleita. Het Foum Gleita irrigatieschema kan dus fungeren als alarmsysteem voor alkalinisatiegevaar elders in de Sahel. In Hoofdstuk 3 concludeerden we al dat de geringe N en P beschikbaarheid voor de plant op de 'gedegradeerde' bodems mede werd veroorzaakt door hoge concentraties alkalische zouten. In Hoofdstuk 5 bespreken we de oorsprong en geografische distributie van deze zouten. Uit bodem- en grondwatermonsters van een 532 m lange toposequentie blijkt dat de alkalische zouten in de 'gedegradeerde' bodems bovenin de toposequentie afkomstig zijn van het schist moedermateriaal. Het schist bevindt zich op geringe diepte (<1.2m). Lagergelegen bodems zijn dieper en bestaan uit (deels) alluviale afzettingen. Jaarlijkse overstroming van deze bodems vóór de aanleg van het irrigatieschema voorkwam een accumulatie van alkalische zouten. Opvallend zijn de grote verschillen in zoutgehalte en alkaliniteit van de bodem op korte afstand in de toposequentie. Dit duidt op een geringe horizontale grondwaterstroming en een grote variatie in de samenstelling van het verticaal gestelde moedermateriaal. De geografische verdeling van de zouten lijkt niet gerelateerd te zijn aan de aanwezigheid van irrigatie- of drainagekanalen. We vonden dus geen bewijs voor de hypothese dat irrigatie leidt tot een ophoping van alkalische zouten in de bodem. Deze conclusie wordt ondersteund door een historische vergelijking van bodemstudies in Foum Gleita. De bodem pH en het zoutgehalte in de wortelzone (20 cm) zijn in de afgelopen 30 jaar niet significant toegenomen. Hieruit concluderen we dat de huidige alkaliniteits-problemen in Foum Gleita worden veroorzaakt door het moedermateriaal en niet door zoutophoping als gevolg van irrigatieactiviteiten. Om een uitspraak te kunnen doen over het potentiële gevaar van alkalinisatie in de toekomst, hebben we gebruik gemaakt van het geochemisch model PHREEQC 2.0. Hiermee simuleerden we de excessieve verdamping van irrigatiewater. De door de simulatie voorspelde evolutie tot een sterk alkalisch en natriumrijk water kwam niet overeen met veldgegevens, waar alkaliniteit bij hoge zoutconcentraties geochemisch wordt gecontroleerd. De toevoeging van kation-omwisselprocessen in het model leidde tot een veel betere overeenstemming tussen simulatie en veldgegevens. De beste overeenstemming werd behaald met een klein (1 $mmol_c$ 100 g droge $bodem^{-1}$) maar calcium verzadigd kation-omwisselcomplex (CEC). De modelsimulaties tonen aan dat de bodems in Foum Gleita een erg grote, maar niet oneindige, buffercapaciteit hebben tegen alkalinisatie. De resultaten van Hoofdstuk 5 geven aan dat een snelle alkalinisatie van geïrrigeerde rijstvelden in Foum Gleita niet waarschijnlijk is.

In Hoofdstuk 6 bestuderen we het effect van geïrrigeerde rijstbouw en organisch stofbeheer op de alkaliniteit van twee van de meest alkalische natriumbodems in de Sahel. Kolommen met behandelingen variërend met of zonder rijst, kunstmestgift, en/of stro toediening werden afwisselend gevuld met grond van een ‘gedegradeerde’ bodem uit Foum Gleita en een alkalische natriumbodem uit de Office du Niger in Mali. De kolomproeven vonden plaats op het WARDA onderzoeksstation in Senegal. Het irrigatiewater dat werd gebruikt voor de proeven was typisch voor de Sahel; het bevatte weinig zout, maar was relatief carbonaatrijk. De percolatiesnelheid werd gehandhaafd op 3-4 mm $dag^{-1}$. Complete water- en alkaliniteitsbalanzen werden opgesteld voor alle kolommen en vergeleken met bodemmonsters van voor en na het groeiseizoen. In alle behandelingen nam de pH en het uitwisselbaar natriumpercentage (ESP) zeer sterk af, met name bovenin de kolommen. De grootste veranderingen vonden plaats in de Office du Niger bodem door zijn geringe buffercapaciteit (weinig $CaCO_3$ en lage CEC). De grote afname in ESP en alkaliniteit werd met name veroorzaakt door het spoelen van de bodem met water met een laag zoutgehalte. Proton uitscheiding door planten droeg 8-30% bij aan het alkaliniteitsverlies. Deze verzuring was gelijk aan, of groter dan de alkaliniteit die door irrigatiewater werd toegevoegd in een scenario zonder percolatie. Dit betekent dat wanneer rijstgraan en -stro van de velden wordt verwijdert, de ophoping van alkalische zouten in de bodem door indamping van irrigatiewater wordt voorkomen, zelfs wanneer er geen percolatie plaatsvindt. Echter, gezien de positieve effecten op de gewasopbrengst, wordt verwijdering van stro niet aangeraden (zie Hoofdstukken 3 en 4). De kolomproeven tonen verder aan dat in Foum Gleita strotoediening resulteerde in een toename van de $pCO_2$ (i.e., koolzuurgasdruk) wat leidde tot een versterkte oplossing van kalk. Hierdoor nam de $Ca^{2+}$ concentratie in de bodemoplossing toe. Dit versterkte de adsorptie van $Ca^{2+}$ aan het kation-omwisselcomplex ten koste van uitwisselbaar $Na^+$. Dit proces draagt bij aan een versnelde afname van de bodemalkaliniteit en ESP. In theorie kan de reductie van ijzerhydroxides leiden tot ferrolyse, waardoor de verzuring van de bovenste bodemlagen wordt versneld. In de huidige proefopzet vonden we echter geen bewijs dat ferrolyse de alkaliniteitsbalans op korte termijn kan beïnvloeden. Onze resultaten zijn in overeenstemming met recente veldstudies en suggereren dat de geïrrigeerde rijstteelt leidt tot een verlaging van de bodemalkaliniteit en ESP van alkalische natriumbodems in de Sahel.

In ons onderzoek hebben we aangetoond dat lage rijstopbrengsten in de Sahel te wijten zijn aan inadequate kunstmestgiften (N, P, Zn), een relatief geringe opname door de plant van nutrienten uit kunstmest (N, P), en een voor de planten geringe beschikbaarheid van nutriënten (N, P, Zn) in de bodem. Veel boeren zullen de herziene kunstmestadviezen niet kunnen opvolgen omdat de benodigde kunstmest te duur of niet in voldoende mate beschikbaar is op de lokale markten. Een beter organisch stof beheer is daarom een van de weinige mogelijkheden om de gewasopbrengsten te verhogen zonder een grote verhoging van de kunstmestkosten. Organische stof giften van 5 t ha$^{-1}$ verhogen de rijstoogst met 1-2 t ha$^{-1}$. De geringe beschikbaarheid van nutrienten in de bodem blijkt vaak gerelateerd te zijn aan de aanwezigheid van carbonaatzouten. De meeste bodems in deze studie kunnen echter niet als zoute- of natriumbodem worden geclassificeerd. De carbonaatzouten waren reeds in de bodem aanwezig voordat de geïrrigeerde rijstteelt werd geïntroduceerd. Rijstboeren in de Sahel hoeven onder standaard teeltomstandigheden dan ook geen snelle alkalinisatie van hun bodems te verwachten. In tegendeel, de rijstteelt kan worden gebruikt voor het verbeteren van alkalische natriumgronden in de Sahel, aangenomen dat enige (natuurlijke) drainage mogelijk is. In bodems die van origine calciet bevatten kunnen organische stof giften dit proces nog versnellen.

# RESUME

La culture irriguée du riz fut introduite à grande échelle au Sahel dans les années 1970 et 1980, après que des sécheresses sévères eurent dévasté les cultures et le bétail. Les investissements massifs dans les infrastructures d'irrigation avaient pour but l'amélioration de la sécurité alimentaire tout en générant un revenu pour les fermiers localement. De plus, la demande de riz augmentait, stimulée par la croissance régulière de la population urbaine. La production de riz dans les pays sahéliens était censée réduire le recours à des importations coûteuses. Les périmètres irrigués furent construits le long des principaux cours d'eau sahéliens et de leurs affluents. De manière générale, l'eau nécessaire à l'irrigation est abondante le long de ces rivières et le climat sec et ensoleillé permet d'obtenir de hauts rendements potentiels aussi bien en saison sèche qu'en saison humide, allant de 7 à 9 t $ha^{-1}$ avec des records allant jusqu'à 12 t $ha^{-1}$. Cependant, les rendements réels varient entre 4 et 6 t $ha^{-1}$ et l'intensité culturale est souvent faible. Plusieurs recherches ont révélé que de nombreuses contraintes socio-économiques entraînaient une gestion non optimale de la culture et de la terre, de faibles doses de fertilisants et un retard d'application des engrais et des sarclages étant les principales contraintes expliquant des rendements limités. Sur certains périmètres irrigués, les rendements ont commencé à baisser à des niveaux inférieurs à 4 t $ha^{-1}$ quelques années seulement après la construction des périmètres. Agriculteurs et chercheurs craignaient que cette baisse ne soit due à une accumulation de sels alcalins. Bien que les eaux d'irrigation au Sahel contiennent peu de sel, elles présentent des quantités relativement importantes de bicarbonate ($RA_{calcite} > 0$). Une concentration excessive et continue de telles eaux peut entraîner la formation de sols alcalins (pH élevé) et sodiques (haute teneur en sodium). De tels sols ont un faible potentiel agricole et leur réhabilitation est souvent coûteuse et demande beaucoup de temps. Au début des années 1990, les premiers signes d'alcalinisation étaient rapportés sur le plus ancien périmètre irrigué du Sahel, au Mali et des efflorescences de sel étaient observées sur d'autres périmètres irrigués Sahéliens. Au milieu des années 1990, le «scénario catastrophe» de la dégradation de la terre la plus précieuse du Sahel provoquée par l'action de l'homme devint rapidement populaire parmi les scientifiques et les agents de vulgarisation agricole en activité dans la région. C'est dans ce contexte que l'ADRAO (en anglais : WARDA) a lancé une recherche dans le but d'étudier les causes des baisses de rendements et les dangers potentiels de l'alcalinisation du sol. Les résultats de cette recherche constituent la substance de cette thèse.

Dans les chapitres 2 et 3, nous avons étudié les causes des baisses de rendement sur les périmètres irrigués de Foum Gleita en Mauritanie et de la Vallée du Sourou au Burkina Faso. Sur les deux périmètres, les rendements ont chuté d'environ 4,5–5,5 t $ha^{-1}$ à 3–4 t $ha^{-1}$, cinq à dix ans après leur création. Sur les deux sites, nous avons organisé des réunions avec les agriculteurs pour discuter des causes possibles et des solutions aux problèmes de productivité du riz. Les résultats de ces réunions furent utilisés pour établir un suivi des agriculteurs et mener des essais, certains gérés par les cultivateurs, certains par les chercheurs.

A Foum Gleita, les faibles rendements étaient dus à un déficit en éléments N et P. Les rendements les plus faibles se trouvaient en haut des pentes ou à mi-pente, où les sols sont peu profonds (<1,2 m). Les agriculteurs ont classé ces sols comme dégradés. Bien que ces sols «dégradés» fussent plus alcalins et salins que des sols situés plus bas, les valeurs de CE (conductivité électrique), pH, et ESP (pourcentage de sodium échangeable) étaient généralement trop faibles pour considérer ces sols comme salins ou sodiques selon la classification internationale. L'insuffisance de N et P dans les sols dégradés était causée par un faible approvisionnement du sol en N et en P, une faible application d'engrais N et une absence d'application d'engrais P. La nature alcalino-calcaire des sols «dégradés» contribuait probablement à une faible disponibilité en N par volatilisation et une faible disponibilité en P par adsorption ou précipitation des minéraux carbonatés.

Dans la Vallée du Sourou, le déclin des rendements a coïncidé avec l'apparition de zones de faible productivité. Ceci résultait d'une insuffisance de Zn, elle-même due à la faible teneur du sol en DTPA extractible, au caractère alcalin-calcaire du sol et la non application d'engrais Zn combinée avec une dose relativement forte d'engrais P. La carence en Zn est un problème connu sur les sols rizicoles alcalino-calcaires à cause des fortes concentrations en carbonate du sol. Au Sahel, on trouve fréquemment des sols rizicoles présentant un caractère alcalino-calcaire, mais cette étude est l'une des premières à montrer que le manque de Zn peut constituer une importante contrainte culturale sur les périmètres irrigués sahéliens.

A Foum Gleita comme dans la Vallée du Sourou, la gestion des cultures par les cultivateurs a quelque peu dévié des recommandations locales. Cependant, le fait de ne pas se conformer aux recommandations locales ne constituait pas la cause principale des faibles rendements. C'est au contraire le fait que les recommandations locales n'étaient pas adaptées (de petites doses de fertilisant N et aucune dose de P à Foum Gleita, et aucune application de Zn dans la Vallée du Sourou) qui contribuaient le plus aux problèmes de productivité observés. A Foum Gleita et dans la Vallée du Sourou, les rendements pourraient aisément passer de 3–4 t $ha^{-1}$ à 5–6,5 t $ha^{-1}$ grâce à une application suffisante de fertilisants N, P et Zn. Cependant, soit les doses recommandées de fertilisants sont très coûteuses, soit le fertilisant n'est pas réellement disponible sur les marchés locaux. Par conséquent, nous avons testé l'application d'amendements organiques à un taux de 5 t $ha^{-1}$ de matière sèche pour tenter d'améliorer la fertilité du sol.

Dans la Vallée du Sourou, l'application d'amendements organiques décomposés a entraîné une augmentation des rendements de l'ordre de 1,5–2 t $ha^{-1}$. Nous avons trouvé que l'application de paille de riz décomposée dans 29 champs a augmenté le rendement ainsi que l'assimilation de Zn par les plantes, mais les concentrations en Zn restaient faibles. Ceci indique que l'insuffisance en Zn n'était pas totalement résolue. L'effet positif de l'application de matière organique sur l'assimilation de Zn pourrait avoir un lien avec l'augmentation de la dissolution du Zn associé aux sels carbonatés. L'augmentation de la dissolution des sels carbonatés naturels par application de matière organique fut observée sur un sol calcaire de Foum Gleita (chapitre 6). Des études supplémentaires sont nécessaires pour caractériser les mécanismes qui expliquent pourquoi la part de Zn disponible sur la teneur totale en Zn de la zone racinaire (0 - 0,2 m) est plus de 50 fois supérieure à la quantité appliquée avec 10 kg de fertilisant Zn par ha et plus de 100 fois supérieure à la teneur en Zn DTPA extractible.

Au chapitre 4, nous avons examiné plus en détails l'effet des amendements de paille fraîche sur les rendements ainsi que la présence de N et de P à Foum Gleita. L'application de 5 tonnes de paille fraîche par ha a permis un accroissement des rendements de 1,1 t ha$^{-1}$ en moyenne, indépendamment du type de sol ou de l'engrais minéral utilisé. L'effet de la paille était nul uniquement lorsque les rendements étaient proches du potentiel. L'effet positif de la paille fut attribué à l'amélioration de la disponibilité de N, mais nous n'avons trouvé aucune preuve d'amélioration de la disponibilité de P. A partir d'un essai en champ et en pots, nous avons conclu que l'amélioration de la présence de N était due à la minéralisation du N contenu dans la paille, à l'augmentation de la minéralisation de la matière organique du sol avec un faible taux C/N ($\leq$ 7.2), et à l'augmentation du taux de recouvrement de l'engrais azoté (urée). Nous avons émis l'hypothèse selon laquelle l'amélioration du taux de recouvrement de l'engrais azoté par application de paille était due à la diminution des pertes par nitrification-dénitrification. En général, nous concluons qu'une meilleure gestion de la matière organique peut améliorer les rendements de façon sensible tout en maintenant les coûts des engrais à un niveau acceptable. Cependant, une meilleure gestion des engrais minéraux sera toujours nécessaire pour de nombreux paysans à Foum Gleita et dans la Vallée du Sourou car (i) des réserves de certains éléments nutritifs (P, Zn) peuvent continuer à s'épuiser en dépit des amendements de matière organique, (ii) les paysans peuvent considérer que l'application d'amendements organiques leur demande trop de travail et (iii) certaines sources de matière organique (comme la paille fraîche) peuvent être utilisées comme fourrage pour le bétail ou réservées à la fertilisation d'autres cultures telles que les legumes.

Au chapitre 5, nous avons étudié la dégradation effective et potentielle du sol par salinisation à Foum Gleita. L'eau d'irrigation à Foum Gleita est l'une des eaux les plus alcalines utilisées au Sahel. Par conséquent si l'alcalinisation des périmètres rizicoles du Sahel est un processus continu, nous devrions nous attendre aux taux d'alcalinisation les plus élevés à Foum Gleita. Ceci conférerait au périmètre irrigué de Foum Gleita une fonction de système de pré-alerte au regard de ce qui pourrait arriver à l'avenir aux autres périmètres sahéliens. Au chapitre 3, nous avions déjà conclu que de plus fortes concentrations de sels alcalins sur les sols «dégradés» contribuaient très probablement à la faible disponibilité de N et de P. Au chapitre 5, nous avons essayé d'expliquer comment ces sels étaient répartis et quelle était leur origine. Des échantillons détaillés de sol le long d'une toposéquence de 532 mètres, couplés avec des fosses pédologiques et des analyses de l'eau souterraine ont révélé que les sols "dégradés", qui occupaient la partie supérieure de la toposéquence, provenaient de la roche mère, un schiste situé à de faible profondeur (≤ 1,2 m). Les sols situés plus bas dans la toposéquence sont plus épais et formés en partie de dépôts d'alluvions. Les crue annuelles lessivent les sols les plus bas et empêchent l'accumulation de sels alcalins. La toposéquence était marquée par d'importantes variations de salinité et d'alcalinité du sol même pour des points proches, ce qui révèle la faiblesse des écoulements horizontaux d'eau souterraine et une forte variation dans la composition géochimique du substrat rocheux, disposé verticalement. La présence de sel ne semblait pas être liée à celle des canaux d'irrigation et de drainage. Par conséquent, nous n'avons pas trouvé de preuve qui corrobore l'hypothèse selon laquelle la pratique de l'irrigation augmenterait l'alcalinité du sol. De plus, une comparaison de nos données avec des données anciennes n'a révélé aucun changement significatif de la salinité de la zone racinaire (0-0,2 m) et du pH au cours des 30 dernières années. Nous en avons conclu que les problèmes actuels d'alcalinité à Foum Gleita provenaient de la roche-mère et non d'une alcalinisation provoquée par l'homme. Nous avons utilisé le modèle PHREEQC 2.0 pour simuler une concentration excessive de l'eau d'irrigation par évapotranspiration. La transformation avec le temps en une solution fortement sodique et alcaline n'était pas conforme aux données du terrain, qui révélaient un contrôle géochimique de l'alcalinité dans des solutions à forte concentration. Ce n'est qu'en faisant intervenir des processus d'échange de cations que les résultats du modèle concernant l'ion $Ca^{2+}$ et l'alcalinité de la solution du sol furent compatibles avec les données du terrain. La meilleure correspondance avec les données de terrain fut obtenue avec un CEC faible (1 $mmol_c$ 100 g de sol $sec^{-1}$) mais saturé en calcium. Les simulations effectuées grâce au modèle ont montré que la capacité du sol à contrer l'alcalinisation était très forte, bien que non infinie. La comparaison avec les données pédologiques, l'étude détaillée de la toposéquence et les simulations prouvent tous qu'une alcalinisation rapide des sols irrigués de Foum Gleita n'est pas probable.

Au chapitre 6, nous avons étudié l'effet de la culture du riz irrigué et de la gestion de la matière organique sur deux des sols les plus alcalino-sodiques du Sahel ; un sol "dégradé" de Foum Gleita et un sol alcalino-sodique de l'Office du Niger (Mali). Ces sols furent utilisés pour confectionner des colonnes de sols avec des traitements différenciés: avec ou sans riz, avec ou sans engrais minéral et avec ou sans amendements de paille de riz. Les tests en colonnes furent conduits à la station de recherche de l'ADRAO au Sénégal. L'eau utilisée était pauvre en sel et riche en carbonates, ce qui est typique des eaux d'irrigation au Sahel. La percolation était maintenue de façon artificielle à 3-4 mm par jour. Des bilans complets de l'eau et d'alcalinité furent établis pour toutes les colonnes. Ces bilans d'alcalinité furent comparés avec des analyses du sol avant et après l'essai. Pour tous les traitements, les sols sodiques sont devenus non sodiques et le pH avait considérablement diminué, particulièrement près de la surface. Les changements étaient plus importants sur les sols de l'Office du Niger à cause de sa faible capacité tampon (peu de $CaCO_3$ et faible CEC). La forte baisse de sodicité et d'alcalinité était principalement due au lessivage par une eau non saline. La contribution de l'excrétion des protons par les plantes dans la diminution de l'alcalinité s'élevait à 8-30%. En outre, l'excrétion des protons compensait au minimum (mais était souvent supérieure en valeur absolue) au surcroît d'alcalinité apporté par l'eau d'irrigation dans un scénario sans percolation. Cela signifie que le retrait de la paille et du grain empêcherait la poursuite de l'alcalinisation des sols en cas d'absence de percolation. Toutefois, le retrait de la paille est déconseillé comme il a été montré aux chapitres 3 et 4. De plus, l'application de paille a entraîné la dissolution de la calcite naturelle due à une augmentation du $pCO_2$ dans les sols de Foum Gleita. La dissolution de la calcite a entraîné une augmentation de la teneur en $Ca^{2+}$ de la solution du sol et accru la désorption du $Na^+$ échangeable. Le résultat de ce processus fut une inversion accélérée de l'alcalinisation et de la sodification accélérées du sol. La réduction d'hydroxydes de fer pourrait en théorie accélérer la désalcalinisation de la couche supérieure du sol. Cependant, nous n'avons trouvé aucune preuve indiquant que la ferrolyse avait modifié à court terme l'équilibre alcalin des sols étudiés. Nos résultats sont en accord avec des études de terrain récentes et suggèrent une désalcalinisation des sols rizicoles sodiques et alcalins du Sahel.

Nous avons montré que les faibles rendements rencontrés sur certains périmètres irrigués du Sahel étaient liés à une application inadéquate ou nulle d'engrais minéraux (N, P, Zn), une faible assimilation des engrais appliqués (N,P), et une faible teneur en éléments nutritifs du sol mobilisables par les plantes (N, P, Zn). Les engrais minéraux sont coûteux ou non disponibles sur les marchés locaux, donc de nombreux paysans ne sont pas en mesure d'adopter les recommandations pour une meilleure application d'engrais minéraux. L'amélioration de la gestion de la matière organique est l'un des quelques moyens pouvant être utilisés par les paysans pour améliorer leurs rendements sans augmenter les coûts de façon substantielle. Des amendements organiques de 5 t $ha^{-1}$ peuvent entraîner une augmentation des rendements de 1–2 t $ha^{-1}$. Les faibles teneurs en nutriments disponibles dans le sol (N, P, Zn) étaient souvent liés à la présence de sels carbonatés. Cependant, la majorité des sols ne pouvait être considérés comme salins ou sodiques. De plus, les sels alcalins étaient présents dans les sols étudiés avant l'introduction du riz irrigué. Dans des conditions classiques de riziculture au Sahel, les paysans n'ont aucune raison de prévoir une alcalinisation rapide de leurs champs. Au contraire, à condition qu'il y ait un drainage naturel, la culture du riz peut contribuer à réhabiliter les sols alcalins sodiques du Sahel. Les amendements de matière organique peuvent accélérer l'amélioration des caractéristiques des sols alcalins sodiques qui contiennent de la calcite naturel.

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Seven years ago, when I received my MSc diploma at Wageningen University, I especially thanked the supervisor of my second MSc thesis, Theo Bruggenwert, for teaching me the ABC of science and more. When I first approached him in 1995, he asked me what I wanted my MSc thesis to be about. I was baffled, because normally supervisors determine the research subject. I went back home and approached Theo some days later with a bold plan, which consisted of the following steps: (a) to quantify soil alkalinity and sodicity constraints in a certain region, (b) to identify the origin of the salts, and (c) to quantify the alkalinization/sodication processes in order to (d) propose alternative management options. Theo thought it was a great plan, but far too ambitious for an MSc thesis. His 40-year experience and great teaching abilities helped me to write a modest but much appreciated MSc thesis. I was very grateful to him (and still am), but little could I know that he would pass away just a few years later.

After graduation Anneke and I wanted to leave Wageningen and soon found ourselves working in beautiful Cape Town. Just before leaving to South Africa, the Netherlands Directorate for International Cooperation (DGIS) advertised a vacancy for an associate scientist at the West Africa Rice Development Association. The scientist would have to work on alkalinity/sodicity problems in irrigated rice schemes in West Africa. The research objectives seemed copied from the ambitious plan I earlier proposed to Theo. They were not, but the person who had formulated the job description turned out to be Marco Wopereis, who had a Wageningen background as well. After a year, we traded South Africa for West Africa and I soon found myself amidst sand dunes and camels, drinking tea with farmers of different ethnic groups, hours away from the nearest electricity pole or telephone line. Although temperatures were skyrocketing, I soon realized that I was in a very fortunate position. Shortly before my arrival, Marco managed to get a research project funded by the British Department for International Development (DFID). The research project proved to be the framework of my activities and allowed me to collaborate with partners in Mauritania and Burkina Faso. Marco, you did not only prove to be a very nice guy, but also a very motivating supervisor, an excellent scientist, and a successful manager. Without you Marco, this thesis would not have started in the first place.

At WARDA, Stephan Haefele became my office mate. He was a great (discussion) partner in science and windsurfing. Thanks Stephan, for your friendship and support. On many of my fieldwork ventures, I was accompanied by Ndiack Mall and Salif Diack who teached me all about rice, its farmers and its scientists. Sitapha Diatta from WARDA headquarters also joined our missions several times. Back home in Senegal, I would like to give special thanks to Djibi Sagna. His dedication and skills in the laboratory were of great value. I could write another page about my fantastic colleagues at WARDA, but allow me just to tell you that it was a great privilege to be part of the WARDA-St.Louis family for four years. Of course, I cannot forget the head of this family, Dr. Kouamé Miézan. He does not only have great knowledge of African proverbs, but also managed to build the coherent team of which I enjoyed the benefits. A special thanks also to Arjan van 't Zelfde and Linda Mulder. They came all the way from the Netherlands to Senegal to work on their MSc thesis. I enjoyed working with them and their trials provided very useful data. In the Netherlands, Linda was supervised by Peter van Bodegom, who was most helpful in taking 'de krenten' out of Linda's 'pap'.

Conducting fieldwork in Foum Gleita (Mauritania) was not easy. About half of our trials failed, but things would have been a lot worse if Moctar ould Isselmou and some of his colleagues of the Mauritanian Agricultural Extension Service (SONADER) would not have been there. Apart from some minor environmental events (dust storms, floodings, 45+ temperatures, mosquito invasions), our stays in Foum Gleita were comfortable thanks to Hawa, who prepared tasteful 'Tiéboudienne' (rice and fish) with a minimum of utensils. In Burkina Faso, it was Soma Etienne Barro of the national research institute (INERA) who supervised the activities. Thanks to his perseverance, we obtained many good results. I would also like to thank his colleagues, in particular Sié Moussa, Armand Bazoum, Thio Bouma and Albert Rouamba. Furthermore I would like to thank the Sourou agricultural extension service (AMVS) for supporting our research activities.

Much good research on alkalinization was conducted by the scientists of the 'Office du Niger' in Mali. I would like to thank Kabirou Ndiaye, Mohamed Dicko and Nicolas Condom for their hospitality and for sharing their research findings with me. I would also like to thank Kabirou Ndiaye for inviting me to Niono to participate in the AQUA geochemical simulation course organized by Vincent Valles in February 1999.

In Dakar, I collaborated with scientists from the French 'Institut de Recherché pour le Développement' (IRD, ex-ORSTOM). We conducted fieldwork together in Foum Gleita and IRD provided office space and a computer for me in December 2001 when Anneke and I stayed in Dakar awaiting the birth of our daughter Eva. I would like to give special thanks to Claude Hammecker, Jean-Luc Maegth and Laurent Barbiero for sharing their knowledge and friendship with me.

Life in West-Africa would have been much less fun without all our friends over there. Sigrid, Myra, Mohamed, Xavier, Hélène & Olivier, Mildred, Dudu, Wim, Arie & Fatou, Jos & Aby, Dick & Amal, all our friends at CIRAD – St.Louis, Ankie & Frank, Marij & Joris, Lieke & Paul, Marja and many more. Thank you all for making living and traveling in West-Africa fun and memorable! A very special thanks to Florence and Pierrick Fraval for the translation of the French summary and for our friendship, which I cherish.

Back in the Netherlands I would first like to give my special thanks to my promoters Sjoerd van der Zee and Martin Kropff. Sjoerd, you have been very supportive. I will never forget our trip to Foum Gleita; you just arrived from the Netherlands and here you were eating dust and sampling soil at 48 °C, while still maintaining enough brain capacity to come up with a lot of good ideas. Martin, thanks for the nice discussions we had, both in the Netherlands as well as in Senegal and Burkina Faso. Thanks also to Gon van Laar, who helped with the editorial part of the thesis. During my stays in Wageningen, I always enjoyed discussing with Chris van Uffelen. Thanks Chris for all your advice, for your work visit to Senegal, and for helping me whenever I needed to sort something out in far-away Wageningen. From May to December 2002, I enjoyed working at the sub department of Soil Quality. A special thanks to Bert Janssen who shared some of his vast knowledge on soil fertility with me. In ‘de Kelder’ I really enjoyed my time with the fellow PhD students. Having no fixed office for a long time, I had many different roommates, but Renske Landeweert managed to keep up with me longest!

Let me finish with thanking my family. First of all I would like to thank my parents, brothers, parents in law and sisters in law. You have always been very supportive of what I did, even though it meant that we could not see each other for long periods. Last but not least I would like to thank my wife Anneke. We are together for almost ten years now. Being a soil scientist yourself, you have not only supported me morally but also scientifically. It’s just great that we can discuss about the importance of P-Olson and soil pH, but it is far greater that we can share the joy of family life with our beautiful daughter Eva. Thanks for all your love and support!

# CURRICULUM VITAE

Petrus Johannes Antonius van Asten (Piet) was born in Beek en Donk (*trsl. brook and higher sandy ground*) on the 17th of May 1972. At the age of two, he moved to Lierop, a small rural village in the south of the Netherlands.

In 1990, after finishing secondary school at the Strabrecht College in Geldrop, he started his MSc studies 'Soil, Water, and Atmosphere' at the Wageningen Agricultural University. His first MSc thesis was on soil, land use, and erosion risk mapping in the Sanmatenga province of Burkina Faso, using GIS and remote sensing tools. His second MSc thesis was on sodication processes in the Great Hungarian plain under supervision of Dr. ir. M.G. Bruggenwert (in memoriam). This thesis was awarded the 1995–1996 Hissink award for best Dutch MSc thesis in soil science. Piet graduated in 1996 (with distinction).

In 1997, he worked as an agroforestry project coordinator at the Western Cape University in South Africa. The research project focused on improved management options for 'urban agriculture' in the townships around Cape Town. From 1998 to 2002, Piet worked as an associate expert at the West Africa Rice Development Association (WARDA) station in Saint Louis, Senegal. His position was financed by the Dutch 'Directoraat Generaal voor Internationale Samenwerking' (DGIS). His research at WARDA formed the basis for this PhD thesis.

At present, Piet is living with his wife Anneke Fermont and their daughter Eva in Kampala, Uganda. If everything goes as planned, he will soon start working as an associate scientist at the East Africa office of the International Institute for Tropical Agriculture (IITA-ESARC) in Uganda. His position will be financed by the Flemish development organisation 'Vlaamse Vereniging voor Ontwikkelingssamenwerking en Technische Bijstand' (VVOB). His research will focus on the role of soil fertility in declining banana yields in Uganda and neighboring countries.