# Explaining yield gaps on farmer-identified degraded and non-degraded soils in a Sahelian irrigated rice scheme

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## Abstract

Farmers in the Foum Gleita irrigation scheme in southern central Mauritania experienced declining rice yields, and within a decade after its establishment 12% of the scheme's land had been abandoned. Actual rice yields ($\leq$ 4.0 t ha$^{-1}$) are low in comparison with potential yield (ca. 8 t ha$^{-1}$) and with 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 lower (3.4 t ha$^{-1}$) than the yields on soils further down the slope (> 4.2 t ha$^{-1}$). Farmers classified the 'upper and middle slope' soils as degraded, but following the USDA classification the soils could not be classified saline or sodic. Low yields on the 'degraded' soils were related to co-limitation of nitrogen (N) and phosphorus (P), which was due to low soil N supply (ca. 18 kg ha$^{-1}$), low soil P supply (ca. 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$^{-1}$), or non-application of P fertilizer. On the 'non-degraded' soils, soil P supply (ca. 16 kg ha$^{-1}$) was higher and N deficiency prevailed despite a higher soil N supply (ca. 32 kg ha$^{-1}$) and a higher 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.

*Additional keywords*: *Oryza sativa* L., alkalinization, crop management, boundary line analysis, gravity irrigation, Mauritania

## Introduction

Over the last twenty 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 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. Various authors (Wopereis *et al.*, 1999; Haefele *et al.*, 2000; Rigourd *et al.*, 2002) showed that the timing of several cropping practices (sowing, transplanting, weeding, fertilizer application) was often late and fertilizer dose too low, resulting in large yield gaps, i.e., in large differences between potential and 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 the time of writing, 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 calcite residual alkalinity ($RA_{calcite}$ = Alkalinity – Ca in $mol_c\ l^{-1}$) (Valles *et al.*, 1991; Bertrand *et al.*, 1993). Accumulation of alkaline salts 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, and Zn) and the poor physical properties of the sodic horizon (Abrol *et al.*, 1988).

In this study we 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 established between 1985 and 1989. Plans to extend it to 3600 ha have so far not been materialized, partly because of productivity problems. The main crop is rice, cultivated in both the wet and dry seasons. 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%. During the same periods dry season yields increased from 2.2 t $ha^{-1}$ to 3.2 t $ha^{-1}$, but the cropped area remained relatively unimportant (25%). The Foum Gleita yields are below the 4–6 t $ha^{-1}$ range observed in most Sahelian irrigation schemes (Wopereis *et al.*, 1999; Haefele *et al.*, 2000; Rigourd *et al.*, 2002). Since the establishment of the Foum Gleita scheme, farmers increasingly complained about declining yields and by 1993 about 12% of the area had been abandoned (Anon., 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 3 times higher than the $RA_{calcite}$ values reported by Marlet *et al.* (1998) and Boivin *et al.* (2002) for the Niger and Senegal River, respectively. If alkalinization through the 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. So the appearance of alkalinity problems at this site could be an early warning of what could 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) and to what extent by sub-optimal crop management. We monitored yields and management practices in farmer fields and compared these with 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-managed nutrient omission trials were conducted to assess soil fertility and yield potential.

## Materials and methods

### The research site

Some 500 Mm$^3$ water are retained behind the Foum Gleita dam (16°08′N, 12°46′W) in central southern Mauritania (Figure 1), allowing gravity irrigation to arable land downstream. The climate in Foum Gleita is typically Sahelian. The wet season (July–October), with an erratic rainfall (ca. 250 mm year$^{-1}$), is followed by a short cool period from November till 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 year$^{-1}$. The landscape around Foum Gleita is characterized by the presence of small rock outcrops (schist, quartzite) and large, slightly sloping (< 2%) barren plains that drain their surface runoff into small valleys. Shallow soils (< 1.2 m) have formed *in situ* from the schist parent material on the upper and middle slopes. Alluvial deposits increase soil depth (1.2–4.0 m) on the lower slopes, depressions and riverbanks (Anon., 1986) (Figures 2 and 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 among the local population. Farmers obtained between 0.5 and 1.5 ha, depending on family size. The majority of

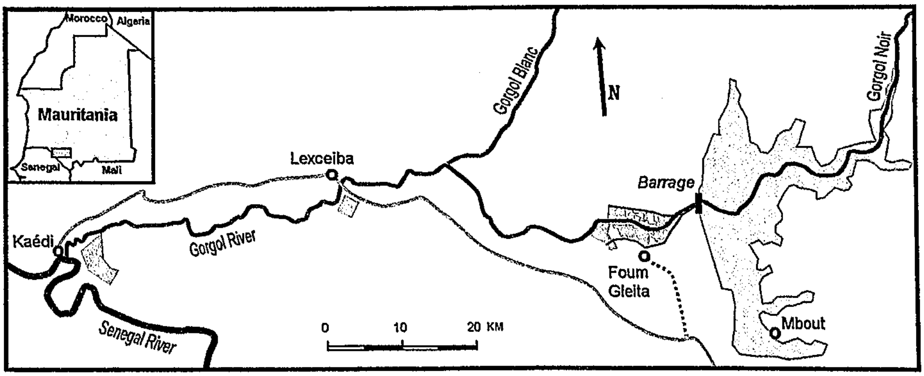



Figure 1. Map showing the location of the Foum Gleita barrage and irrigation scheme within the Gorgol River catchment, some 80 km upstream of Kaédi, Mauritania.

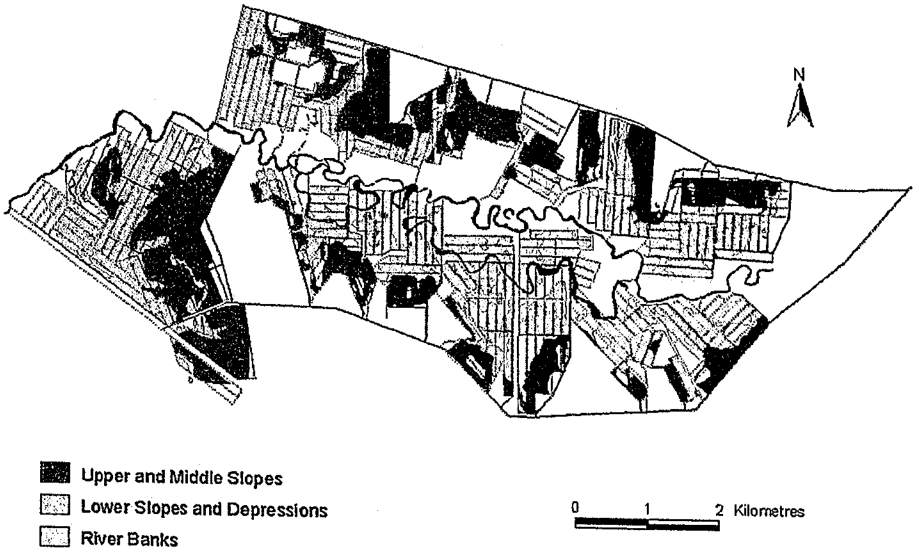



Figure 2. Foum Gleita irrigation scheme infrastructure and geomorphologic map (adapted from Anon., 1986).

the people were semi-nomadic cattle holders, who were 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 & Sow, 1997) for transplanted rice (variety Jaya) in the wet and dry seasons. The Rice Development model (RIDEV) (Dingkuhn, 1997) calculated the percentage of spikelet sterility due to cold or heat stress at flowering. The model furthermore gave predictions on growth duration and timing of phenological

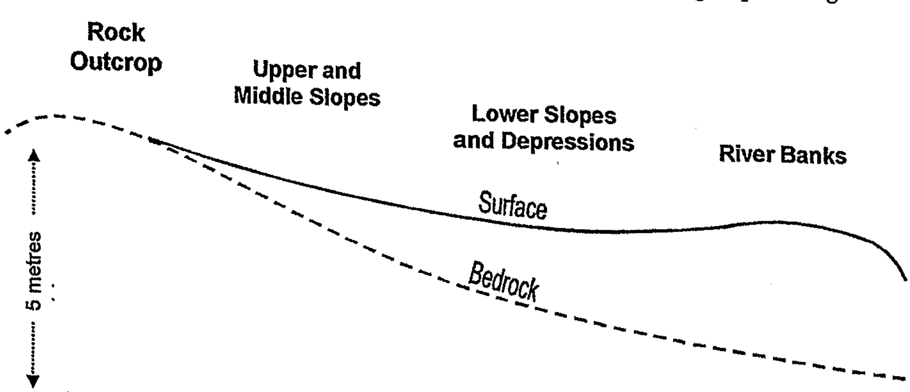



Figure 3. Schematic cross section and corresponding geomorphological units of the Foum Gleita landscape.

stages of the rice crop, which were used to derive optimal timing of transplanting, N fertilizer application, drainage and harvesting. Input weather data for both RIDEV and ORYZAS simulations were from Foum Gleita (1989–1993) and Matam (1972–1982), located 70 km south-west of Foum Gleita.

## 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 fields a 10 m × 10 m plot that received no fertilization, but was otherwise managed by the farmer in the usual way ($T_o$ plots). The rest of each field was managed by the farmer, and included fertilization ($T_F$). During the 1999 dry season, farmer surveys were repeated with another group of farmers (n = 33), but no farmer trials were conducted. Plant and soil samples were collected from the 1998 farmer trials.

### *Plant samples*

At heading, flag leaf samples were taken for P analysis. Grain yields at maturity were determined in a 6-m² area harvested in each of the $T_o$ and $T_F$ plots and expressed on the basis of 14% moisture content. Harvest index was determined from oven-dry (3% moisture content) straw and grain weight from a 12-hill subsample. N content in grain ($N_{GRAIN}$) and straw ($N_{STRAW}$) at maturity was determined using the Micro-Kjeldahl method (Bremner, 1996). Plant phosphorus contents in grain and straw ($P_{GRAIN}$ and $P_{STRAW}$) were measured using the method described by Yoshida *et al.* (1976). Soil N supply was estimated from total N uptake in the $T_o$ plots. Recovery efficiency for applied N fertilizer (REN) was based on the difference in N uptake between $T_o$ and $T_F$.

### *Soil samples*

A composite topsoil sample (0–0.2 m) was taken from each $T_o$ plot before the start of the growing season. The samples were analysed for pH and pH-KCl in a 1:2.5 paste, EC in a 1:5 paste, P-Olsen and P-Bray 1. Exchangeable cations ($Ca^{2+}$, $Mg^{2+}$, $K^+$, $Na^+$) were determined using an atomic absorption spectrophotometer (AAS) after extraction with ammonium chloride. Cation exchange capacity (CEC) of the soil samples was determined as described by Chapman (1965). Exchangeable sodium percentage (ESP) was calculated using exchangeable $Na^+$ and CEC. The Walkey-Black method (Nelson & Sommers, 1996) was used to determine %C. Total N was determined using a macro-version of the Kjeldahl method, which was 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 $T_F$ and $T_o$ yields 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 (Anon., 1986), major soil and crop management variables of the 1998 farmer trial were classified according to topographic position; i.e., (1) upper and middle slope, (2) lower slope and depressions, and (3) river banks. Statistically significant differences between means of the soil and crop data from these geomorphological classes were established with the Newman-Keuls test using the STATISTICA software.

## Analysis of the farmer trials

The boundary line approach was used to obtain a semi-quantitative estimate of the contribution of both crop management and soil properties to the $T_0$ and $T_F$ 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 ($T_F$ and $T_0$ yields) 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 & Frijs-Nielsen, 1976; Frasor & Eaton, 1983; Walworth *et al.*, 1986). Later it was used to describe the relationship between soil nutrient contents and yields (Evanylo & 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 calculated 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. 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 were taken into account that had a correlation coefficient $\geq 0.3$ with $T_0$ and $T_F$ yields. The resulting boundary functions for selected soil and crop management variables were used to calculate the maximum attainable $T_0$ and $T_F$ 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 yields (i.e., the yield gap) can largely be explained using the boundary line approach. However, if the maximum attainable yield exceeds the actual yield, then this difference is considered 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 wet season of 1998 and the dry seasons of 1999 and 2000 at two sites that had been identified by farmers as degraded (DG) and non-degraded (NDG). According to the BCEOM map (Anon., 1986), the DG site was located on the upper slope and the NDG site on the lower slope.

The rice variety IR-13240-108-2-2-3, locally known as Sahel 108, was used. The trial consisted of the following 6 fertilizer treatments (T0–T5) replicated 4 times:

| | |
|---|---|
| T0: no fertilizer applied; | T3: as T1 but without P; |
| T1: N, P, K and Zn applied; | T4: as T1 but without K; |
| T2: as T1 but without N; | T5: as T1 but without Zn. |

The total N fertilizer (urea) dose was 175 kg ha$^{-1}$, split into three 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 was applied at 26 kg ha$^{-1}$ as triple super phosphate (TSP), K at 53.8 kg ha$^{-1}$ as muriate of potash and Zn at 5.5 kg ha$^{-1}$ as ZnO. In the 1999 and 2000 dry season trials no Zn was applied due to non-availability. In the 2000 dry season only the treatments T0, T1 and T3 were repeated and the number of replications was reduced from 4 to 3. Individual plot size was 5 m × 5 m. The methods to estimate yield and determine plant nutrient uptake, soil nutrient supply and fertilizer recovery efficiency were similar to the methods used in the farmer trials. Zn and K contents in the straw were determined in a 1 N HCl extract using an AAS (Yoshida *et al.*, 1976). N and P fertilizer recommendations were developed for the DG and NDG soils on the basis of a 6.0 t ha$^{-1}$ target yield, taking into account the average soil N and P supply, and the average recovery efficiency of applied N and P fertilizer of the researcher-managed nutrient omission trials. The N (87 kg ha$^{-1}$) and P uptake (14.5 kg ha$^{-1}$) that corresponded with a 6.0 t ha$^{-1}$ target yield were based on average nutrient uptake in irrigated rice in the Sahel and in Asia (Haefele *et al.*, 2001; Witt *et al.*, 1999).

Before the start of the 1998 trial two topsoil samples (0–0.2 m) were taken from each plot and analysed for pH in a 1:2.5 paste and for EC in a 1:5 paste. Statistically significant differences between treatment means were established with the Newman-Keuls test using the STATISTICA software.

# Results

## 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$^{-1}$. The dry season potential yield showed a higher variation (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 to Jaya yields (< 0.8 t ha$^{-1}$ difference).

## Farmer survey and farmer trials

Only 34 out of the 60 volunteering farmers started the wet season campaign in 1998. According to farmers, the primary reasons for not starting, in order of importance, were: (1) non-availability of machinery for land preparation (9 farmers), (2) delay of the wet season preparations due to late harvest of the previous dry season, followed by heavy rains (7 farmers), (3) no irrigation water in the secondary canals (7 farmers), and (4) non-payment of the annual water fees (3 farmers). Soil quality problems were never mentioned as primary reasons for not starting the campaign.

Of the remaining 34 plots 6 were excluded because of severe crop damage by birds or rats (3 farmers) or non-respect of the trial setup (3 farmers). Descriptive statistics of key crop and soil management variables at Foum Gleita are given in Table 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.

Tables 1 and 2 show large differences in crop management practices among farmers and in correlation of crop management variables with yields. In comparison with the RIDEV recommendations, transplanting, fertilizer applications and harvesting were delayed (Figure 4). Basic statistics on the chemical characteristics of topsoil samples from the 1998 farmer surveys are given in Table 3.

## Farmer trials

The analysis of the spatial distribution of yield, soil properties and crop variables from

Table 1. The main crop and soil management variables for the 1998 wet season rice crop at Foum Gleita and their linear correlation with $T_O$ and $T_F$ yield.

| | n | Mean | SD[1] | Min | Max | Corr. coeff.[2] | |
|---|---|---|---|---|---|---|---|
| | | | | | | $T_O$ yield | $T_F$ yield |
| Cultivated area (ha) | 28 | 1.2 | 1.0 | 0.3 | 4.0 | 0.10 | 0.29 |
| Sowing date | 28 | 27 July | 13 days | 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-Total (kg $ha^{-1}$) | 28 | 226 | 75 | 100 | 500 | n.a. | 0.47* |
| Growing period (days) | 28 | 131 | 12 | 108 | 166 | 0.11 | 0.04 |
| $T_O$ yield (t $ha^{-1}$) | 28 | 2.18 | 0.89 | 0.33 | 4.28 | n.a. | 0.69**[3] |
| $T_F$ 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] * = statistically significant at $P < 0.05$; ** = statistically significant at $P < 0.01$.

[4] DAT = days after transplanting.

[5] n.a. = not applicable.

Table 2. The main crop and soil management variables for the 1999 dry season rice crop at Foum Gleita and their linear correlation with $T_0$ and $T_F$ yield.

| | n | Mean | SD[1] | Min | Max | Corr. coeff.[2] $T_F$ yield |
|---|---|---|---|---|---|---|
| Cultivated area (ha) | 33 | 0.8 | 0.5 | 0.5 | 2.5 | 0.11 |
| Sowing date | 33 | 10 March | 16 days | 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-Total (kg $ha^{-1}$) | 33 | 75 | 41 | 25 | 250 | 0.47* |
| Growing period (days) | 33 | 131 | 12 | 111 | 162 | −0.23 |
| $T_F$ 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] * = statistically significant at $P < 0.05$.

[5] No data available for 5 fields.

[6] n.a. = not applicable.

the farmer trials in the 1998 wet season showed strong spatial relationships (Table 4). Yield, P-Olsen and P-Bray 1 increased and pH, EC, Ca, and the percentage of farmers not starting the campaign (% abandoned) decreased along the toposequence going from the 'upper and middle slopes' down to the 'river banks'. The N and P contents in the straw ($N_{STRAW}$ and $P_{STRAW}$, respectively) increased moving from the top to the bottom of the toposequence, except for $N_{STRAW}$ in the $T_0$ treatment, which showed the reverse trend, although not statistically significant. Plant analyses revealed that P plant contents were low. A third (32%) of the P contents in the straw ($P_{STRAW}$) was lower than 0.6 g $kg^{-1}$, indicating P deficiency (Kanareugsa, 1980) at maturity. P contents in 88% of the flag leaf samples were below 1.8 g $kg^{-1}$, indicating P deficiency during vegetative growth (Dobermann & Fairhurst, 2000).

## Analysis of the farmer trials

The variables taken into account in the $T_0$ boundary line analysis (correlation coefficient ≥ 0.3) were: sowing density, pH, pH-KCl, EC, Ca, P-Bray 1 and P-Olsen. The variables used in the $T_F$ boundary line analysis were: sowing density, first urea application (Urea-1), second urea application (Urea-2), total urea application (Urea-Total), pH, pH-

Table 3. Chemical data of topsoil samples (0–0.2 m) from farmers' fields at the onset of the 1998 wet season at Foum Gleita and their linear correlation with $T_O$ and $T_F$ yield.

| | n | Mean | SD[1] | Min | Max | Corr. coeff.[2] | |
|---|---|---|---|---|---|---|---|
| | | | | | | $T_O$ yield | $T_F$ yield |
| pH-$H_2O$ | 28 | 7.49 | 0.56 | 5.62 | 8.40 | −0.30 | −0.47**[3] |
| pH-KCL | 28 | 6.41 | 0.57 | 5.01 | 7.50 | −0.37 | −0.53** |
| EC (dS $m^{-1}$) | 28 | 0.13 | 0.05 | 0.06 | 0.27 | −0.37 | −0.50** |
| Ca (cmol per kg soil) | 28 | 11.5 | 3.1 | 7.3 | 18.4 | −0.48*[3] | −0.30 |
| Mg (cmol per kg soil) | 28 | 4.4 | 1.3 | 2.6 | 7.0 | −0.06 | 0.24 |
| K (cmol per kg soil) | 28 | 0.36 | 0.07 | 0.24 | 0.47 | 0.20 | 0.24 |
| Na (cmol per kg soil) | 28 | 0.51 | 0.21 | 0.22 | 1.06 | −0.16 | −0.40* |
| CEC (cmol per kg 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-Bray 1 (mg per kg soil) | 28 | 3.9 | 2.3 | 1.1 | 8.6 | −0.55** | 0.22 |
| P-Olsen (mg per kg soil) | 28 | 4.4 | 1.4 | 2.5 | 7.2 | −0.64** | 0.54** |
| N total (g per kg soil) | 28 | 0.6 | 0.1 | 0.3 | 0.7 | 0.14 | 0.06 |
| C (g per kg soil) | 28 | 3.4 | 0.8 | 1.8 | 5.6 | −0.18 | −0.15 |

[1] SD = standard deviation.

[2] Pearson bivariate correlation coefficient.

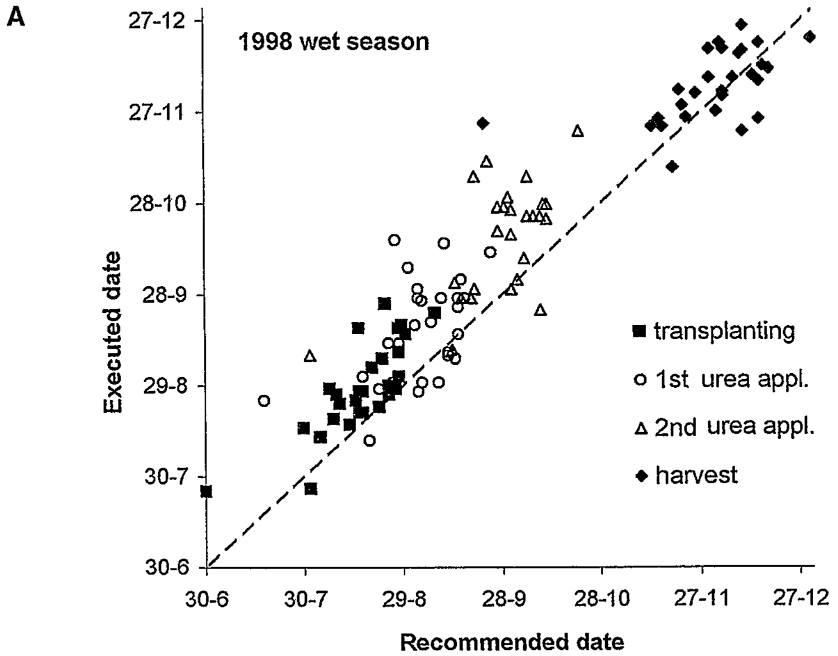
[3] * = statistically significant at $P < 0.05$; ** = statistically significant at $P < 0.01$.

[4] Values higher than 100 are due to dissolved $CaCO_3$.

KCl, EC, $Ca^{2+}$, $Na^+$, ESP, P-Olsen and P-Bray 1. The variables limiting maximum attainable $T_o$ yields – in order of importance – were: P-Olsen (32% = 9 out of 28 farmers), $Ca^{2+}$ (25%), P-Bray 1 (14%), pH (10%), pH-KCl (7%), EC (7%) and sowing density (4%). The variables limiting maximum attainable $T_F$ yield were: P-Olsen (18%), pH (18%), $Ca^{2+}$ (14%), EC (14%), pH-KCl (10%), sowing density (7%), Urea-Total (7%), Urea-1 (4%), Urea-2 (4%) and ESP (4%). Figure 5 shows the calculated predicted $T_o$ and $T_F$ yields plotted against actual $T_o$ and $T_F$ yields. Linear regression between maximum attainable and actual yields (line not shown) accounted for 63% and 48% of the rice yield variation for $T_o$ and $T_F$, respectively.

## Researcher-managed nutrient omission trials

pH was distinctly higher for the DG soil (pH 8.26) than for the NDG soil (pH 6.12). Soil depth at the DG site was 0.6–0.8 m and up to 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 the treatments To and T3 in different seasons are summarized in Table 5. Yields, N uptake and P uptake for T4



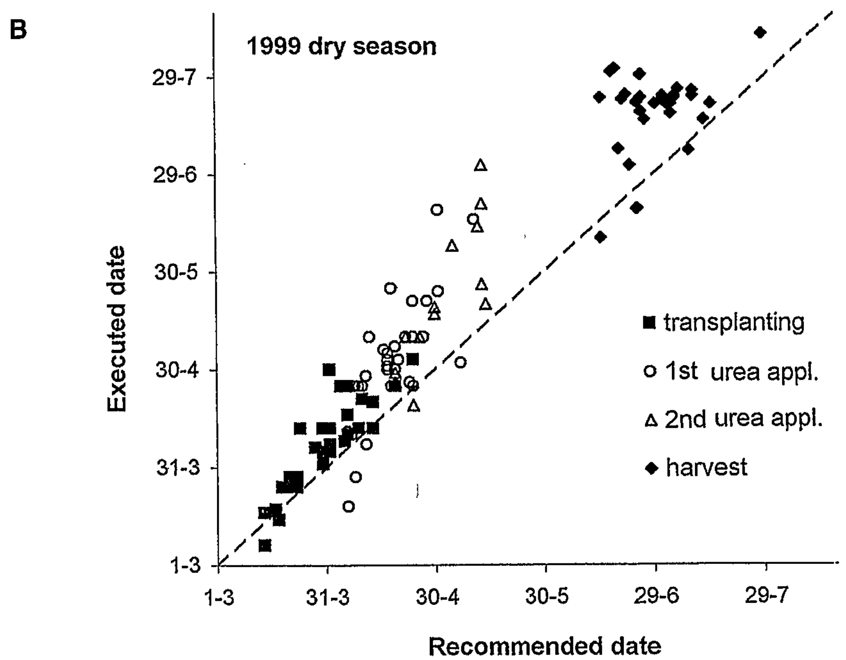




Figure 4. Dates of cultivation practices by farmers in comparison with RIDEV recommendations for the 1998 wet season and 1999 dry season. Points above the broken line indicate a delay of farmer practices compared with RIDEV recommendations.

Table 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 slope and depressions | River banks | *P* level[2] |
|---|---|---|---|---|
| *Farmers' performance* | | | | |
| Participants | 26 | 28 | 6 | – |
| Abandoned | 62 | 50 | 33 | – |
| $T_O$ yield (t ha$^{-1}$) | 1.56c | 2.35b | 4.22a | < 0.005 |
| $T_F$ yield (t ha$^{-1}$) | 3.42 | 4.22 | 5.34 | n.s. |
| *Soil properties* | | | | |
| EC (dS m$^{-1}$) | 0.17a | 0.14ab | 0.09b | < 0.05 |
| pH-$H_2O$ | 7.64a | 7.17b | 7.13ab | < 0.05 |
| P-Bray 1 (mg kg$^{-1}$) | 2.63c | 4.37b | 7.39a | < 0.05 |
| P-Olsen (mg kg$^{-1}$) | 3.37c | 4.78b | 6.49a | < 0.05 |
| Ca (cmol kg$^{-1}$) | 12.8 | 11.0 | 9.4 | n.s. |
| N total (g kg$^{-1}$) | 0.06b | 0.05ab | 0.07a | < 0.10 |
| *$T_O$ 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 | < 0.05 |
| *$T_F$ 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 | < 0.05 |
| *Farmer management* | | | | |
| P applied (kg ha$^{-1}$) | 0 | 0 | 0 | – |
| N applied (kg ha$^{-1}$) | 102 | 92 | 109 | n.s. |
| REN[3] | 0.31 | 0.33 | 0.39 | n.s. |

[1] The values for the variables CEC, K, Na, %C, $T_O$ $N_{GRAIN}$, $T_O$ $P_{GRAIN}$, $T_F$ $N_{GRAIN}$ and $T_F$ $P_{GRAIN}$ were not statistically different ($P < 0.10$) and are not therefore included in this table.

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

[3] REN = N recovery efficiency (kg N taken up per kg fertilizer N applied).

and T5 are not shown, but were similar to those in T1. At both sites, K application did not affect yield and K contents in the straw (15–36 g kg$^{-1}$) were independent of treatment and exceeded the critical level for deficiency (≥ 15 g kg$^{-1}$) (Dobermann & Fairhurst, 2000). Omission of Zn fertilizer reduced Zn content in the flag leaf at panicle initiation from 25–30 mg kg$^{-1}$ to 15–18 mg kg$^{-1}$ on both soils. However, application

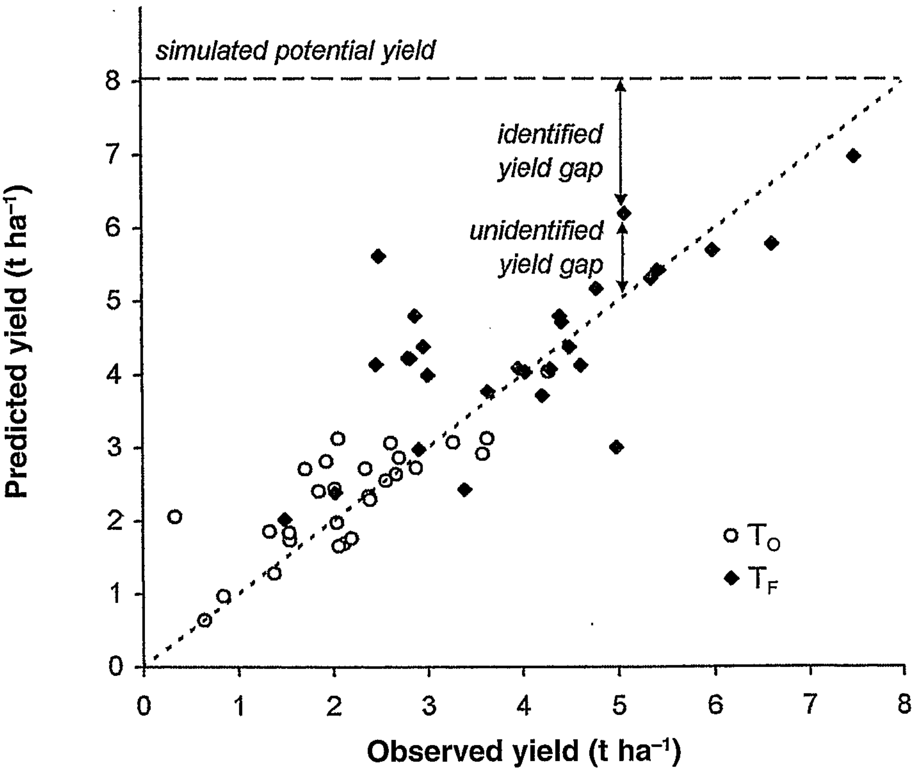



Figure 5. Comparison of predicted yields – using the boundary line approach – and observed farmer yields ($T_F$ and $T_O$) with a graphical presentation of the potential yield (broken line), the identified yield gap and the unidentified yield gap. Points above the dotted 45° line represent yields that could not fully be explained by the variables used in the boundary line approach.

of Zn did not have an effect on yield. Plant analyses of the 1998 wet season and 2000 dry season trials showed that on the DG soils average $P_{STRAW}$ contents were low (0.5–0.7 g $kg^{-1}$) for the zero N treatments (To and T2) and very low (0.2–0.4 g $kg^{-1}$) for the 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) were higher on the NDG soils than on the DG soils (Table 6). Also N contents of the straw were lower for the DG than for the NDG soils. On the DG soils, $N_{STRAW}$ varied between 3.5 g $kg^{-1}$ and 4.4 g $kg^{-1}$ irrespective of fertilizer treatment. On the NDG soils $N_{STRAW}$ varied between 4.4 g $kg^{-1}$ and 6.2 g $kg^{-1}$, with lowest N contents measured in the treatments without N (To and T2). Plant N uptake and REN were distinctly higher on the NDG than on the DG soils (Table 6).

The low soil N supply (= N uptake in T2), soil P supply (= P uptake in T3), REN, and REP significantly increased fertilizer needs on the DG soils in comparison with the NDG soils. To obtain the target yield of 6.0 t $ha^{-1}$, farmers on the DG soils need to apply 265 kg N $ha^{-1}$ and 50 kg P $ha^{-1}$, against 138 kg N $ha^{-1}$ and 0 kg P $ha^{-1}$ on the NDG soils.

Table 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 different letter are statistically different (Newman-Keuls test; $P < 0.05$).

# Discussion

Average simulated potential yields in Foum Gleita are high in the wet (8.0 t ha$^{-1}$) and dry seasons (7.8 t ha$^{-1}$). Farmer yields ($T_F$) in the 1998 wet season (4.0 t ha$^{-1}$) and 1999 dry season (2.4 t ha$^{-1}$) were low, but the large variation among farmers' yields and the large yield gap show that there is considerable scope for improvement.

The boundary line analysis revealed that both soil quality (EC, pH, pH-KCl, $Ca^{2+}$, $Na^+$, ESP, P-Olsen and P-Bray 1) and crop management (sowing density, Urea-1, Urea-2 and Urea-Total) contributed to the productivity problems in Foum Gleita. Yields were negatively correlated with EC, $Ca^{2+}$, $Na^+$ and ESP. But given their currently low values it is unlikely that these soil variables form a direct production constraint. Following USDA classification (Richards, 1954), topsoils in Foum Gleita were not saline ($EC_e < 4$ dS m$^{-1}$ ≈ EC in 1:5 paste $< 0.63$ dS m$^{-1}$) nor sodic (ESP $< 15$; pH $< 8.5$). However, the accumulation of alkaline salts simultaneously increases EC, $Ca^{2+}$, $Na^+$, ESP and pH. A higher pH decreases N availability due to volatilization (Reddy & Patrick, 1984) and decreases P availability due to chemisorption of P on calcite and the formation of poorly soluble Ca-P minerals (Fixen & Grove, 1990; Samadi & Gilkes, 1999). EC, $Ca^{2+}$, $Na^+$ and ESP could therefore be indirectly related to N and P deficiency problems.

A qualitative analysis of crop management practices showed that these were often

Table 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 | – |

sub-optimal. In comparison with RIDEV recommendations, farmers transplanted up to 5 weeks later and in both seasons a 1–2 week delay in the second urea application was observed. Late timing of urea application decreases its efficiency. Similarly, harvesting was often delayed and the harvesting 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 a statistically 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 per kg soil) for irrigated rice are low (Dobermann & Fairhurst, 2000). According to the boundary line analysis P-Olsen was the primary constraint limiting farmer $T_F$ and $T_0$ yields. This corresponds with the large percentage of flag leaf samples (88%) and straw samples (32%) with P contents below the deficiency limit. The boundary line analysis led to a good prediction of actual yields. The regression model for $T_0$ and $T_F$ yield explained 63% and 48% of the rice yield variation, respectively, which is similar to findings of other studies where soil properties were used to explain irrigated rice yield variation (Casanova *et al.*, 1999; Dobermann, 1994). Nonetheless, two critical remarks can be made with respect to the use of boundary line analysis in this type of study. Firstly, for some fields a large part of the yield gap remains unidentified, which may be related to measuring errors, methodological errors, or variables such as bird damage and weed pressure, which were not taken into account. Secondly, omission of N fertilizer in the $T_0$ plots could not be identified as a production constraint. This 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 among farmers, i.e., when no boundary function can be established.

Both $T_0$ and $T_F$ yield showed a strong spatial distribution. Yields increased along the toposequence moving from the 'upper and middle slopes' down to the 'river banks'. The number of farmers leaving their fields uncultivated showed the opposite trend, although neither soil quality problems nor topographic position had been mentioned as a primary constraint for not starting the agricultural campaign. We had the impression that in the past, lower yields had resulted in an incomplete reimbursement of agricultural loans. This would exclude farmers from obtaining new credit for the purchasing of agricultural inputs, for renting soil tillage equipment (tractor), and for paying the annual water fees that are needed to start the following season. 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 along 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. For the soils on the 'upper and middle slopes' pH and $Ca^{2+}$ were significantly higher ($P < 0.05$), and P-Olsen and P-Bray 1 significantly lower ($P < 0.05$) than for the soils further down the slope. These observations correspond with the low P contents (0.6 g $kg^{-1}$) in the straw of farmer fields ($T_F$) on the 'upper and middle slopes'. Similarly, P contents in the straw of the nutrient omission trials on the DG soils 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). The above observations indicate that P deficiency is a major cropping constraint on the 'upper and middle slopes' if 175 kg N fertilizer $ha^{-1}$ is applied. To obtain a yield of 3.0 t $ha^{-1}$, a 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 soils. This N dose corresponds with farmer practices. So given the current fertilizer practices, co-limitation of N and P is likely to occur in farmer fields on the 'upper and middle slopes'. The low N straw contents in farmer fields ($T_F$) on the 'upper and middle slopes' strengthen this hypothesis. On the soils of the 'lower slopes and depressions' and 'river banks', $N_{STRAW}$ is very low in the $T_0$ plots, indicating that N has been diluted at maximum. N deficiency at a 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 yield, but low Zn contents on the DG soil in treatments with both N and P, but without Zn fertilizer, indicated a likely Zn deficiency (Yoshida, 1981). Zn deficiency 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 & Fairhurst, 2000).

From the farmer and the nutrient omission trials, it follows that yield levels and nutrient availability were significantly lower on the DG than on the NDG soils. So the farmer classification terms 'degraded' and 'non-degraded' do reflect production constraints in the irrigation scheme, but do not refer to international standards on salinity or sodicity. Rice yields were not directly influenced by EC, $Ca^{2+}$, $Na^{+}$ or ESP, but merely reflected an alkalinity-induced nutrient constraint.

On the DG soils, the 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 for a target yield of 6 t $ha^{-1}$. On the NDG soils, the average soil N supply and REN were much higher, resulting in a moderate N fertilizer recommendation (138 kg $ha^{-1}$). At present, for a yield of 6 t $ha^{-1}$ no P fertilizer is needed on the NDG soils, since soil P supply (16 kg $ha^{-1}$) still exceeds P uptake (14.5 kg $ha^{-1}$). The fertilizer recommendations for the DG soils are unlikely to be adopted by farmers, as they will not be able to pay for the high costs. These recommended fertilizer doses would be smaller (e.g. similar to T1 in the researcher-managed nutrient omission trial), if maximum dilution of N and P in the rice plant was taken into account. Alternatively, fertilizer recommendations can be lowered if the target yield is lower and/or if recovery efficiency of applied fertilizer increases through improved organic matter management (P.J.A. Van Asten, unpublished). Nonetheless, the fertilizer recommendation calculations are instrumental, as they reveal a strong contrast in fertilizer needs between DG and NDG soils.

## Conclusions

Large yield gaps between actual farmers' yield and simulated yield proved that there is considerable scope for improvement of rice yield and productivity in Foum Gleita. A low dose and late timing of N fertilizer application and non-application of P fertilizer were identified as the main agronomic constraints. Alkalinity and low P availability were the main soil quality variables contributing to the observed productivity problems. These variables showed a strong relation with topographic position, explaining the lower yields and the higher abandonment of land on the 'upper and middle slope'. The highest yields obtained in the nutrient omission trials on these farmer-identified degraded soils were not significantly lower than on soils further down the 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 be more easily 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 of 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 as to the origin and evolution of the alkaline salts. Detailed research on the salt and water balance will be needed to understand the evolution of these soils under present land use management, and the extent to which Foum Gleita could function as an early warning system for other Sahelian irrigation schemes.

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