

USING FARMER KNOWLEDGE TO COMBAT LOW PRODUCTIVE SPOTS  
IN RICE FIELDS OF A SAHELIAN IRRIGATION SCHEMEP. J. A. VAN ASTEN,<sup>1,2\*</sup> S. E. BARRO,<sup>3</sup> M. C. S. WOPEREIS<sup>4</sup> AND T. DEFOER<sup>5</sup><sup>1</sup>The Africa Rice Centre (WARDA), BP 96, St Louis, Senegal, Africa<sup>2</sup>Wageningen University, Department Environmental Sciences, Soil Quality, PO Box 8005, NL-6700 EC Wageningen, The Netherlands<sup>3</sup>Institut National de Recherches Agricoles (INERA), BP 910, Bobo-Dioulasso, Burkina Faso, Africa<sup>4</sup>An International Center for Soil Fertility and Agricultural Development (IFDC)–Africa Division, BP 4483, Lomé, Togo, Africa<sup>5</sup>The Africa Rice Centre (WARDA), BP 320, Bamako, Mali, Africa

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## ABSTRACT

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<sup>-1</sup> in the early 1990s, shortly after establishment of the scheme, to 2 to 4 t ha<sup>-1</sup> 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 per cent. The low productive spots are caused by Zn deficiency. Low Zn availability is related to the very low DTPA-extractable Zn content of the soil (0.08–0.46 mg kg<sup>-1</sup>), the alkaline-calcareous character of the soil, the non-application of Zn fertilizers, and a relatively large P fertilizer dose (21 kg P ha<sup>-1</sup>). 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<sup>-1</sup>) as a short-term solution that increases yields by 1.5 to 2.0 t ha<sup>-1</sup>. Application of Zn fertilizer (10 kg Zn ha<sup>-1</sup>) in 29 farmer fields in the 2001 dry season eradicated the low productive spots and increased yields from 3.4 to 6.0 t ha<sup>-1</sup>. Although application of Zn fertilizer is strongly recommended, it is not yet available in Burkina Faso. Based on a comparison of fertilizer prices on the world market and the local market, we expect that the use of Zn fertilizers will be highly profitable (cost/value ratio >> 2). Despite the relatively 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 other's knowledge and observations. Copyright © 2004 John Wiley & Sons, Ltd

KEY WORDS: *Oryza sativa* L.; zinc deficiency; Burkina Faso; organic matter management

## 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<sup>-1</sup>, with imports ranging from 105 to 240 Mt yr<sup>-1</sup> (FAO, 2002). To bridge this large gap between rice demand and local production, investments were made in an irrigation infrastructure in Burkina Faso from the mid-1980s onwards. However, rice yields in irrigation schemes often fell short of expectations, raising questions about the viability of these investments (Bélières *et al.*, 1995).

Burkina Faso's largest irrigation scheme is located in the Sourou Valley, which accounts for 10 per cent to 15 per cent of national rice production. The current 3000 ha scheme has been gradually developed from the mid-1980s

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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<sup>-1</sup> in 1986 to 5.7 t ha<sup>-1</sup> in 1991, followed by a steady decline to yields ranging from 2.2 to 4.4 t ha<sup>-1</sup> from 1995 onward (AMVS, unpublished data; Nebié, 1997). These yields are small compared to both simulated potential yields (7 to 9 t ha<sup>-1</sup>) and actual yields in most other Sahelian schemes (4 to 6 t ha<sup>-1</sup>) (Haeefe *et al.*, 2000). For farmers in the Sourou Valley to make a profit, average rice yields per season need to be at least range from 2.8 to 3.8 t ha<sup>-1</sup> (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 on the increasing appearance of low productive spots in the rice fields. Some farmers related the low productivity of such spots to salinity problems, pointing to 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 (Van Asten *et al.*, 2003a). In the Sourou Valley, irrigation water contains very little salt (EC < 0.1 dS m<sup>-1</sup>) and concentration factors are small (<6), suggesting that alkalization 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 (Van Asten *et al.*, 2003b) and could be a possible reason for the appearance of the low productive spots.

Several authors (e.g. Wopereis *et al.*, 1999; Haeefe *et al.*, 2000, 2002; Poussin and Boivin, 2002; Poussin *et al.*, 2003; Rigourd *et al.*, 2002; Van Asten *et al.*, 2003b) proposed that small rice yields in Sahelian irrigation schemes were often related to suboptimal crop and soil management practices. These authors related suboptimal management to a multitude of socioeconomic and biophysical constraints, both at plot and scheme level. Haeefe *et al.* (2000, 2001) showed that improved soil fertility and weed management raised farmers' yield by about 2 t ha<sup>-1</sup> in the Senegal River valley, without significant increase in production costs. They suggested that improved rice technologies were still needed to boost rice production. This is contested by Poussin and Boivin (2002), who believe that technologies are already available and that suboptimal 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 arises to what extent farmers can properly identify factors contributing to the small yields and the presence of the low productive spots. Many earlier researchers have observed that most African farmers have a 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 researchers using farmer' knowledge of traditional cropping systems to guide scientific research and develop solutions that better fitted farmers' 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 the 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 farmers' fields.

## MATERIALS AND METHODS

### *Site Description*

The Sourou Valley 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 ( $630 \text{ mm yr}^{-1}$ ) in the wet season (May–October), followed by a short cool period (November–February) with minimum daily temperatures as low as  $15^\circ\text{C}$  and a hot dry season (March–April) with maximum daily temperatures up to  $45^\circ\text{C}$ . The majority of the soils in the Sourou Valley are formed of thick ( $>30 \text{ m}$ ) alluvial calcareous-rich deposits and can be classified Vertisol and Gleysol (FAO, 1990A). Their high clay content (35–50 per cent) and moderately high CEC ( $15\text{--}20 \text{ cmol}_c \text{ kg}^{-1}$ ) make them very suitable for rice cultivation (Leprun, 1968). This study 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 among the population. Farmers generally obtained between 0.5 and 1.5 ha.

### *Farmer Perceptions and Practices*

In July 1998, a meeting was organized to bring together farmers, extension workers, and scientists in order 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; and  $>75$  per cent 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 the 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 I).

### *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 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  $\pm 3 \text{ m}$  interval from the center to outside the low productive spot (Figure 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 ( $80^\circ\text{C}$ ) and P and Zn were extracted with a 1 N HCl extraction (Yoshida *et al.*, 1976). Zn was analysed using an atomic absorption spectrophotometer (AAS) and P was determined colorimetrically. Soil samples were dried and sieved ( $<2 \text{ mm}$ ) and analysed for pH, electrical conductivity (EC in a 1:5 extract),  $\text{CaCO}_3$  (gravimetric loss of  $\text{CO}_2$ ), C per cent (Walkley and Black, 1934), exchangeable  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{K}^+$ , and  $\text{Na}^+$  (AAS after  $\text{NH}_4\text{Cl}$  extraction), CEC (Chapman, 1965), and soil texture (pipette method). Available phosphorus (P-Olson

Table I. The main crop and soil management variables for the 2000 dry and wet season surveys and the 2001 dry season farmer trials, compared to local recommendations

	Units	Local recommendation	2000 Dry season			2000 Wet season			2001 Dry season		
			<i>n</i>	Mean	<i>SD</i> <sup>a</sup>	<i>n</i>	Mean	<i>SD</i>	<i>n</i>	Mean	<i>SD</i>
Cultivated area	ha	—	20	0.5	0.1	20	0.7	0.3	29	0.5	0.0
Sowing date		DS 1–15 Jan.									
		WS < 30 July	20	16 Jan.	4	20	16 July	2	29	6 Jan.	1
Transplanting	DAS <sup>b</sup>	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 <sup>c</sup>	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 <sup>-1</sup>	300	20	260	104	20	200	0	29	200	0
Applied urea	kg ha <sup>-1</sup>	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%	20	55%	29		29	93%	
				Chemical 30%		Chemical 45%				Chemical 7%	
				Manual		Manual				Manual	
Yield	t ha <sup>-1</sup>	—	20	4.7	0.9	20	3.4	0.8	29	3.4	1.0

<sup>a</sup>*SD* = standard deviation.

<sup>b</sup>DAS = days after sowing.

<sup>c</sup>DAT = days after transplanting.

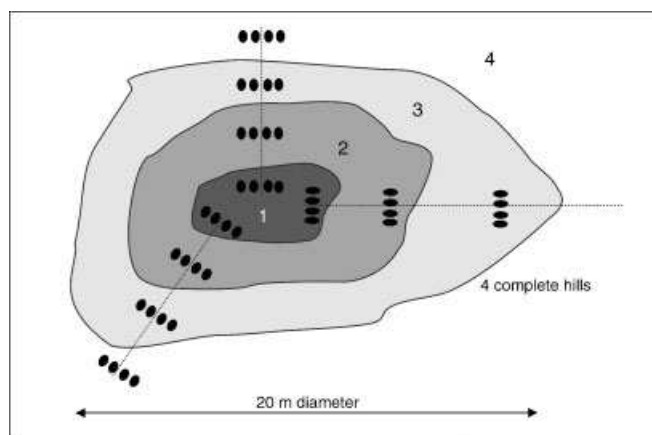


Figure 1. Schematic birds-eye view of a low productive spot. Each axe represents a sampling sequence, comprising of four hills (black dots) at four regular intervals from the center (1) to outside the low productive spots (4) shortly before panicle initiation, flowering and maturity.

and P-Bray1) was analysed 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 farmers' 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; and T4 = cattle manure. Treatments were replicated four times in a randomized block design. Minimum size of the individual plots was  $4 \times 6 \text{ m}^2$ . The organic matter application was  $5 \text{ t dry weight ha}^{-1}$ . 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 practised by farmers. Mineral fertilizer applications were close to common farmer practices. It comprised  $200 \text{ kg ha}^{-1}$  basal application of composite cotton fertilizer (12 per cent N, 24 per cent  $\text{P}_2\text{O}_5$ , 12 per cent  $\text{K}_2\text{O}$ ) shortly before transplanting, and topdressing of  $150 \text{ kg ha}^{-1}$  urea fertilizer (about  $69 \text{ kg N ha}^{-1}$ ), divided into two split applications (50 per cent three weeks after sowing and 50 per cent at panicle initiation). Paddy yields were estimated from a  $2 \times 3 \text{ m}^2$  harvest area in the center of each plot. Harvest index was determined from oven-dry (3 per cent moisture content) straw and grain weight of a 12-hill subsample. Straw yield was derived from the harvest index and the  $6 \text{ m}^2$  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  $\times$  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  $20 \text{ kg Zn ha}^{-1}$  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 ( $10 \text{ m} \times 10 \text{ m}$ ) in their field, receiving  $10 \text{ kg Zn ha}^{-1}$  ( $\text{T}_{10\text{-Zn}}$ ),  $20 \text{ kg Zn ha}^{-1}$  ( $\text{T}_{20\text{-Zn}}$ ), and  $5 \text{ t ha}^{-1}$  of decomposed straw ( $\text{T}_S$ ), respectively. The remainder of the field received neither Zn fertilizer nor organic amendments ( $\text{T}_F$ ). Zn fertilizer ( $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$ ) 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  $6 \text{ m}^2$  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 subsample. 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 results 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 analysed 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 modelled with a linear regression after log transformation of the earthworm data.

## 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 per cent) estimated the yield loss between 25 and 50 per cent, 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 a combination of these factors. Farmers tried to combat the low productive spots through the application of manure (10 per cent), compost (12 per cent), straw (33 per cent) or a combination of these different organic matter sources (22 per cent). A considerable number of farmers (19 per cent) combined the application of organic amendments with the removal of calcareous nodules from the soil surface. The majority of farmers (55 per cent) 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<sup>-1</sup>, respectively. In many cases, cropping practices showed little or no variation amongst farmers (Table I). 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 per cent) used the medium duration ITA123 variety ( $\pm 125$  days). The other variety used was TOX 728-1, which has a slightly shorter growing cycle ( $\pm 116$  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<sup>-1</sup> less NPK fertilizer than recommended (300 kg ha<sup>-1</sup>). Farmers applied urea as topdressing in two equal splits. In the 2000 dry season, urea dose was 30 kg ha<sup>-1</sup> higher and in the 2000 wet season 50 kg ha<sup>-1</sup> lower, than the recommended 150 kg ha<sup>-1</sup>.

### *Detailed Monitoring of Low Productive Spots*

The low productive spots appeared shortly after transplanting. Plants inside the spots either did not or only slowly recovered from the transplanting shock (Figure 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 per cent of grain yield outside the low productive spots (Figure 3).

Shoot samples taken at the end of the vegetative growth stage (i.e. 45 days after transplanting) contained  $2.6 \pm 0.3$  g P kg<sup>-1</sup> and  $15.7 \pm 2.3$  mg Zn kg<sup>-1</sup> independent of sample site. At maturity, P and Zn concentrations in



Figure 2. Even  $\pm$  four weeks after transplanting, many plants either had not or had slowly recovered from the transplanting shock.

the straw had decreased to  $1.0 \pm 0.5 \text{ g kg}^{-1}$  and  $11.8 \pm 2.1 \text{ mg kg}^{-1}$  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 II). The pH was slightly alkaline (7.5–8.5), but EC ( $< 0.6 \text{ dS m}^{-1}$ ) 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 ( $< 2 \text{ mm}$ ) of all soil samples, but  $\text{CaCO}_3$  content was generally small (0.2 per cent) in the sampled topsoil (0–20 cm).

#### Researcher-managed Trials

Averaged over the two fields and seasons, yields of T1 ( $3.5 \text{ t ha}^{-1}$ ) and T2 ( $3.7 \text{ t ha}^{-1}$ ) were significantly ( $p < 0.001$ ) smaller than yields of T3 and T4 (both  $5.0 \text{ t ha}^{-1}$ ) (Figure 4). Treatment, field, season and field  $\times$  season interaction all had significant effects ( $p < 0.001$ ) on yield. All other interactions (field  $\times$  treatment, treatment, season  $\times$  treatment, field  $\times$  treatment  $\times$  season) were not significant. The surface area of the low productive spots seemed to decrease in time for all treatments (Figure 5), but more so in treatments T3 and T4.

#### Farmer-managed Trials

Most farmers (27) used the ITA123 rice cultivar and a minority (two 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

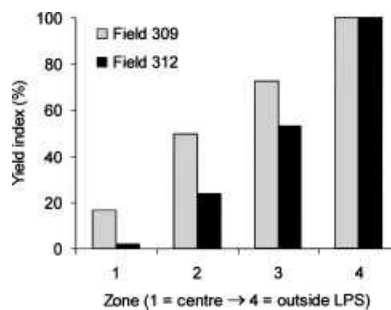


Figure 3. Rice yields in the low productive spots (LPS), as a percentage of yields measured outside the LPS of two sites (fields 309 and 312) in the 1999 wet season.

Table II. Basic parameters for the studied topsoils (0–40 cm)

	Mean	SD <sup>a</sup>	Range
Clay (%)	42.3	6.2	37.3–52.2
Silt (%)	31.8	5.8	23.5–29.2
Sand (%)	25.9	3.5	23.5–31.4
Ca <sup>2+</sup> (cmol <sub>c</sub> kg <sup>-1</sup> )	10.6	1.7	7.5–13.3
Mg <sup>2+</sup> (cmol <sub>c</sub> kg <sup>-1</sup> )	5.5	1.6	2.2–8.2
K <sup>+</sup> (cmol <sub>c</sub> kg <sup>-1</sup> )	0.18	0.03	0.14–0.21
Na <sup>+</sup> (cmol <sub>c</sub> kg <sup>-1</sup> )	0.04	0.01	0.01–0.05
CEC (cmol <sub>c</sub> kg <sup>-1</sup> )	17.9	2.3	13.3–21.8
pH–H <sub>2</sub> O	8.0	0.3	7.1–8.3
pH–KCl	6.5	0.4	5.5–7.4
EC (dS m <sup>-1</sup> )	0.3	0.1	0.1–0.6
CaCO <sub>3</sub> (%)	0.2	0.1	0.06–0.38
P <sub>Olson</sub> (mg kg <sup>-1</sup> )	4.8	1.0	3.3–6.8
P <sub>Bray1</sub> (mg kg <sup>-1</sup> )	2.4	1.9	0.6–9.5
Zn <sub>total</sub> (mg kg <sup>-1</sup> )	24.3	3.1	21.0–28.7
Zn <sub>DTPA</sub> (mg kg <sup>-1</sup> )	0.21	0.10	0.08–0.46

<sup>a</sup>SD = standard deviation.

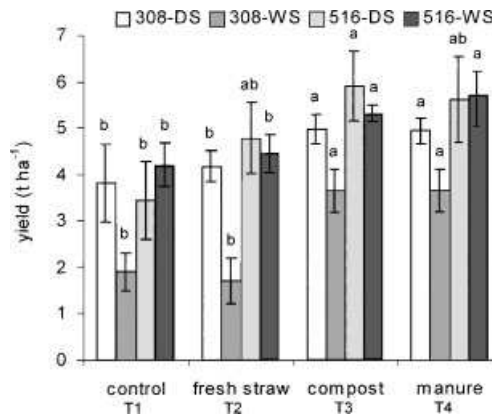


Figure 4. Average paddy yields  $\pm$  standard deviation for different organic amendment treatments (5 t ha<sup>-1</sup>) in the 1999 dry season (DS) and wet season (WS) at two sites (fields 308 and 516). Letters represent LSD test significant differences ( $p < 0.05$ ) between treatments for each field  $\times$  season combination.

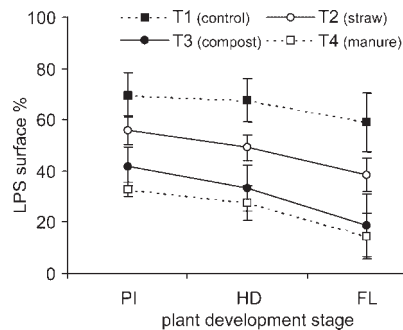


Figure 5. The percentage surface area of the field that is part of the low productive spots (LPS)  $\pm$  standard error for different organic amendment treatments at panicle initiation (PI), heading (HD) and flowering (FL).

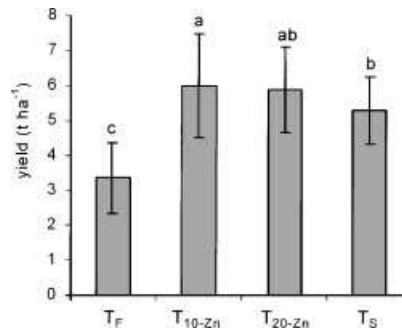


Figure 6. Average paddy yields  $\pm$  standard deviation for the 2001 dry season farmer-managed trials (T<sub>F</sub> = control; T<sub>10-Zn</sub> = 10 kg Zn ha<sup>-1</sup>; T<sub>20-Zn</sub> = 20 kg Zn ha<sup>-1</sup>; T<sub>S</sub> = 5 t decomposed straw ha<sup>-1</sup>). Letters represent differences ( $p < 0.05$ ) between treatments for LSD-test.

with low temperatures, Zn deficiency or P deficiency. Fertilizer use was similar for all farmers and was close to local recommendations (Table I). However, the second urea application was somewhat delayed. The application of 10 kg Zn ha<sup>-1</sup> increased farmer yield (T<sub>F</sub>) by 80 per cent from 3.4 to 6.0 t ha<sup>-1</sup> (Figure 6). Applying more Zn (T<sub>20-Zn</sub>) did not further increase yields. The application of decomposed straw (T<sub>S</sub>) increased farmer yields by 60 per cent to 5.3 t ha<sup>-1</sup>. The application of Zn fertilizer increased Zn<sub>STRAW</sub> significantly ( $p < 0.01$ ). Zn<sub>STRAW</sub> was 13 mg kg<sup>-1</sup> in the T<sub>F</sub> and T<sub>S</sub> treatment and 30 mg kg<sup>-1</sup> in T<sub>10-Zn</sub> and T<sub>20-Zn</sub> treatments. Trends were similar for Zn<sub>GRAIN</sub> with small concentrations (9 mg kg<sup>-1</sup>) for T<sub>S</sub> and T<sub>F</sub> and larger concentrations (16 mg kg<sup>-1</sup>) for T<sub>10-Zn</sub> and T<sub>20-Zn</sub>. P straw concentrations were significantly higher ( $p < 0.01$ ) for T<sub>F</sub> (1.0 g kg<sup>-1</sup>) than for treatments T<sub>S</sub> (0.7 g kg<sup>-1</sup>), T<sub>10-Zn</sub> and T<sub>20-Zn</sub> (0.6 g kg<sup>-1</sup>). In the Zn treatments, P concentrations were close to deficiency (<0.6 g kg<sup>-1</sup>) (Kanareugsa, 1980). Nitrogen concentrations in the straw showed similar trends with significant differences ( $p < 0.001$ ) between T<sub>F</sub> (7.3 g kg<sup>-1</sup>), T<sub>S</sub> (5.9 g kg<sup>-1</sup>), and T<sub>10-Zn</sub> and T<sub>20-Zn</sub> (4.7 g kg<sup>-1</sup>). The small plant N concentrations correspond to N dilution in the straw and Zn treatments (Figure 7; T<sub>20-Zn</sub> not represented, but similar to T<sub>10-Zn</sub>) and plant N accumulation in farmer fields (T<sub>F</sub>).

#### 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

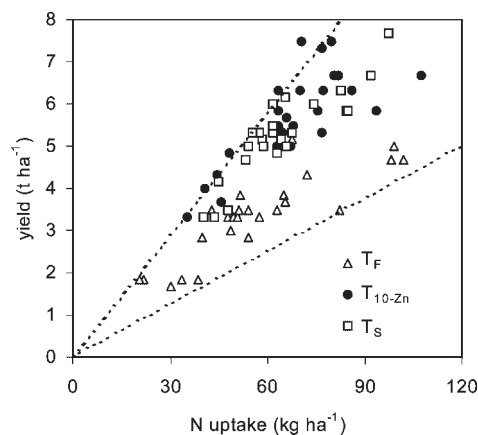


Figure 7. Grain yield as a function of N uptake in the total above-ground plant matter of the 2001 dry season farmer-managed trials. Slopes of the linear functions represent maximum dilution (upper line) and maximum accumulation (lower line) according to Witt *et al.* (1999).

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.

## 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 per cent, which corresponds to the AMVS reported yield decline from  $5.7 \text{ t ha}^{-1}$  in 1991 to yields between  $2.2 \text{ t ha}^{-1}$  and  $4.4 \text{ t ha}^{-1}$  from 1995 onward. Similar yield differences were observed in the 2001 dry season farmer-managed trials, i.e. with Zn fertilizer application yields were  $6.0 \text{ t ha}^{-1}$  and without  $3.4 \text{ t ha}^{-1}$ . The spots occupy up to 70 per cent of the surface area (see Figure 5) and grain yield of plants in the low productive spots is less than 50 per cent (see Figure 3) of the grain yield observed outside the low productive spots.

We hypothesized that the low productive spots were 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 ( $0.2 \text{ mg kg}^{-1}$ ) was well below the critical level ( $0.8 \text{ mg kg}^{-1}$ ) for Zn deficiency in lowland rice (Dobermann and Fairhurst, 2000). The observed range ( $0.08\text{--}0.46 \text{ mg kg}^{-1}$ ) at the study site was also low when compared to areas elsewhere in the world where Zn deficiency occurs, e.g.  $0.08\text{--}49.4 \text{ mg kg}^{-1}$  in old rice soils of the Cauvery Delta in India (Savithri *et al.*, 1999),  $0.9\text{--}3.0 \text{ mg kg}^{-1}$  in the Fars province of Iran (Karimian and Yasrebi, 1995),  $0.4\text{--}9.8 \text{ mg kg}^{-1}$  in Ontario Canada (Shang and Bates, 1987),  $0.3\text{--}4.9 \text{ mg kg}^{-1}$  in Minnesota, USA (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 colouration 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 I). Zn concentrations in rice shoots ( $15.7 \text{ mg kg}^{-1}$ ) and straw ( $11.8 \text{ mg kg}^{-1}$ ) 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  $T_F$  and  $T_S$  plots were about half the concentrations found in  $T_{10\text{-Zn}}$  and  $T_{20\text{-Zn}}$ . The basal application of 10 or  $20 \text{ kg Zn ha}^{-1}$  (as  $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$ ) 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  $T_F$  are signs of N and P accumulation in the plant (see also Figure 7), which proves that factors other 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 Zn fertilizer is certainly the most convenient and rapid management option to increase yields. Further study will be necessary to determine the optimum Zn fertilizer dose. Most likely, Zn fertilizer dose can be lowered, as the recommendation for lowland rice is generally below 6 kg Zn ha<sup>-1</sup> (Dobermann and Fairhurst, 2000; Savithri *et al.*, 1999).

Zinc sulfate-based fertilizers are currently not readily available in Burkina Faso. Zn fertilizer (ZnSO<sub>4</sub>·7H<sub>2</sub>O) can be bought in Abidjan, Ivory Coast, for 560 CFA kg<sup>-1</sup>. This corresponds approximately to 4.70 US\$ kg<sup>-1</sup> Zn. Transport and handling costs to Burkina Faso would further increase the price to an estimated 6 US\$ kg<sup>-1</sup> Zn. This price is about three times higher than that of the world market, which varies around 2 US\$ kg<sup>-1</sup> Zn (The Innovation Group, 2004). This difference in local and world-market price corresponds with price trends of other more popular fertilizers, which generally cost about 2–3 times more on local markets in West Africa than on the world market. With a Zn fertilizer recommendation of 6 to 10 kg ha<sup>-1</sup> and an expected yield benefit of 2 to 3 t ha<sup>-1</sup>, the costs would be between 36 and 60 US\$ ha<sup>-1</sup> and the added value would be between 360 and 540 US\$ ha<sup>-1</sup> given the current paddy price of around 0.18 US\$ ha<sup>-1</sup> in Burkina Faso. Even when additional transport and handling costs are taken into account, the value/cost ratio, indicating the relationship between the total increased value and the amount spent to get that value, will certainly be much higher than two. A value/cost ratio of two is generally being considered the lowest threshold for farmer fertilizer adoption (Mokwunye *et al.*, 1996). Farmer cooperations and AMVS are currently trying to convince fertilizer companies to import Zn fertilizer. With an estimated rice production area of 2000 ha and two cropping seasons a year, the potential benefit of Zn fertilizer application is obviously large (i.e. over 1 million US\$ annually). However, for the time being, the application of organic amendments (i.e. manure, compost or decomposed straw) seems the only readily available method of increasing yields by 1.5 to 2.0 t ha<sup>-1</sup>. 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<sup>-1</sup> and 9 mg kg<sup>-1</sup>, respectively) i.e. the application of organic amendments increased Zn uptake, but Zn concentrations remained at the deficiency level, indicating that the 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 (Van Asten *et al.*, 2004). The decrease in the surface area of the low productive spots during the growing season (Figure 5) is probably related to crop recovery at later growth stages, as often observed on Zn deficient soils (Dobermann and Fairhurst, 2000).

At present, farmers apply 200 kg ha<sup>-1</sup> of NPK fertilizer (12 24 12) and 180 kg urea ha<sup>-1</sup>, corresponding to 106 kg N ha<sup>-1</sup> and 21 kg P ha<sup>-1</sup>. 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-Olsen 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<sup>-1</sup>). However, at yield levels of 3 to 4 t ha<sup>-1</sup>, the current P fertilizer dose is large and not only results in a poor cost–benefit ratio, but is also 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 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 also 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 Zn availability (Ponnamperuma, 1975). Farmers correctly mentioned that the low productive spots were related to a soil-related problem. However, their perception about the relation between low productivity spots and earthworms could not be confirmed. It would be interesting to try and 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, 2002). However, it was not suboptimal N and P fertilizer and weed management, but Zn deficiency that appeared to be the main constraint limiting yield at the study site; application of Zn fertilizer nearly doubled yield, while N and P 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 ( $200 \text{ kg ha}^{-1}$ ) than the AMVS recommendation ( $300 \text{ kg ha}^{-1}$ ). Note, however, that a lowering in NPK dose could even be recommended at current low yield levels ( $3$  to  $4 \text{ t ha}^{-1}$ ), in view of the negative effect of P on Zn availability (Dobermann and Fairhurst, 2000). In other words, current farmer fertilizer management at present is more profitable than that recommended by the AMVS.

The application of organic amendments was, according to farmers, the only potential solution to the problem. Indeed, the application of  $5 \text{ t ha}^{-1}$  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 labour intensive, which is a constraint for many farmers who 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 may be further depleted.

Both researchers and farmers appreciated the pre-testing of Zn fertilizer applications in two farmer fields in the 2000 wet season (see materials and methods of the farmer-managed trials). The positive visual effect of Zn fertilizer application not only convinced 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 conducting capital- and labour-intensive trials at a research station.

## CONCLUSION

We conclude that the appearance of low productive spots in the Sourou irrigation scheme and the subsequent yield decline in the early mid-1990s was caused by Zn deficiency. Yield losses due to Zn deficiency are between 25–50 per cent. Zn deficiency can be eradicated when Zn fertilizer is used. With an estimated rice production area of 2000 ha and two seasons, the benefits of Zn fertilizer application can potentially exceed 1 million US\$ per year. 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 has 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  $10 \text{ kg ha}^{-1}$ . So far, little is known about the 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 labour extensive and more effective than use of organic amendments, it is not yet available in Burkina Faso. Despite efforts by AMVS and farmer cooperations in obtaining Zn fertilizer, the application of decomposed rice straw seems the only solution available to farmers at present. Despite the relative recent introduction ( $\pm 15$  years ago) of irrigated rice cropping, most farmers proved to have a 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.

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#### REFERENCES

- Barro SE, van Asten PJA, Nebié B, Wopereis MCS, Thio B, Sié M, Dakouo D, Ouedraogo I, Miézan KM. 2000. Dégradation des sols ou carence en éléments nutritifs dans les périmètres rizicoles de la Vallée du Sourou? *FRSIT conference proceedings*, 4–7 April 2000, Ouagadougou.
- Bélières JF, Camara S, Touré EHA. 1995. Diversité et devenir des résultats technico-économiques de la production rizicole irriguée des exploitations agricoles du delta du fleuve Sénégal. In *Irrigated Rice in the Sahel: Prospects for Sustainable Development*, Miézan KM, Wopereis MCS, Dingkuhn M, Deckers J, Randolph TF (eds). West Africa Rice Development Association: Bouaké, Ivory Coast; 99–129.
- Bremner JM. 1996. Nitrogen-total. In *Methods of Soil Analysis: Part 3. Chemical Methods*, Sparks DL (ed.). SSSA Book Series 5: Madison, WI; 1085–1122.
- Chambers R, Pacey A, Thrupp LA (eds). 1989. *Farmer First: Farmer Innovation and Agricultural Research*. Intermediate Technology Publications: London; 219.
- Chapman HD. 1965. Cation-exchange capacity. In *Methods of Soil Analysis—Chemical and Microbiological Properties*, Black CA (ed.). *Agronomy* 9: 891–901.
- Defoer T, Budelman A, Toulmin C, Carter S. 2000. Building common knowledge: a textbook for participatory learning and action research (PLAR). In *Managing Soil Fertility in the Tropics: A Resource Guide for Participatory Learning and Action Research*, Defoer T, Budelman A (eds). Royal Tropical Institute: Amsterdam.
- Dobermann A, Fairhurst T. 2000. *Rice: Nutrient Disorders and Nutrient Management*. International Rice Research Institute: Los Baños; 191 pp.
- FAO. 1990A. *FAO–Unesco Soil Map of the World: Revised Legend*. Soils Bulletin 60, Food and Agriculture Organization of the United Nations: Rome; 119 pp.
- FAO. 1990B. *Guidelines for Soil Description 3rd edition (revised)*. Soil Resources, Management and Conservation Service; Land and Water Development Division: Rome; 70.
- FAO. 2002. *Commodity Balances Database*. <http://apps.fao.org>: Rome.
- Haefele SM, Johnson DE, Diallo S, Wopereis MCS, Janin I. 2000. Improved soil fertility and weed management is profitable for irrigated rice farmers in Sahelian West Africa. *Field Crops Research* 66: 101–113.
- Haefele S, Wopereis MCS, Donovan C, Maubuisson J. 2001. Improving productivity and profitability of irrigated rice production in Mauritania. *European Journal of Agronomy* 14: 181–196.
- Haefele SM, Wopereis MCS, Donovan C. 2002. Farmers' perceptions, practices and performance in a Sahelian irrigated rice scheme. *Journal of Experimental Agriculture* 38: 197–210.
- Karimian N, Yasrebi J. 1995. Prediction of residual effects of zinc sulfate on growth and zinc uptake of corn plants using three zinc soil tests. *Communications in Soil Science and Plant Analysis* 26: 277–287.
- Kanareugs C. 1980. Critical concentrations of nitrogen, phosphorus, and potassium in rice plants; Effect of fertilizers. *Katesart Journal of Natural Sciences* 14: 69–80.
- Leprun JC. 1968. *Carte Pédologique de Reconnaissance au 500-000ème de la Haute-Volta: Etude Préliminaire Succincte de la Région du Sourou*. ORSTOM: Dakar, Senegal; 12 pp.
- Lindsay WL, Norvell WA. 1978. Development of a DTPA soil test for zinc, iron, manganese and copper. *Soil Science Society of America Journal* 42: 421–428.
- Marchal JY. 1976. Un périmètre agricole en Haute-Volta; Guiedougou—Vallée du Sourou. *Cahiers ORSTOM (Série Sciences Humaines)* 8: 57–73.

- Mokwunye AU, de Jager A, Smaling EMA (eds). 1996. Restoring and maintaining the productivity of West African soils: key to sustainable development. *Miscellaneous Fertilizer Studies No. 14*. International Fertilizer Development Center (IFDC): Lomé, Togo.
- Moraghan T, Simis A, Smith L. 1999. Zinc in wheat grain as affected by nitrogen fertilization and available soil zinc. *Journal of Plant Nutrition* **22**: 709–716.
- Nébie B. 1997. *Rapport sur la Gestion de la Fertilité des Sols pour une Riziculture Irriguée Performante et Durable au Sahel*. Institut d'Etude et de Recherches Agricoles: Ouagadougou; 10 pp.
- Neue HU, Quijano C, Senadhira D, Setter T. 1998. Strategies for dealing with micronutrient disorders and salinity in lowland rice systems. *Field Crops Research* **56**: 139–155.
- Ponnamperuma FN. 1975. Growth-limiting factors of aerobic soils. In *Major Research in Upland Rice*. International Rice Research Institute: Los Baños, Philippines; 3–19.
- Poussin JC, Boivin P. 2002. Performance des systèmes rizicoles irrigués sahéliens. *Cahiers Agricultures* **11**: 65–73.
- Poussin JC, Wopereis MCS, Debouzie D, Maeght JL. 2003. Determinants of irrigated rice yield in the Senegal River valley. *European Journal of Agronomy* **19**: 341–356.
- Quansah C, Drechsel P, Yirenyi BB, Asante-Mensah S. 2001. Farmers' perceptions and management of soil organic matter—a case study from West Africa. *Nutrient Cycling in Agroecosystems* **61**: 205–213.
- Reardon TR, Dione J, Adesina A, Tefft J. 1997. Rice in West Africa before and after CFA franc devaluation: focus on CILSS countries. In *Irrigated Rice in the Sahel: Prospects for Sustainable Development*, Miézan KM, Wopereis MCS, Dingkuhn M, Deckers J, Randolph TF (eds). West Africa Rice Development Association: Bouaké, Côte d'Ivoire; 137–158.
- Rigourd C, Hermiteau I, Nepveu de Villemarceau A, Vidal A. 2002. La riziculture irriguée en Afrique sahélienne: Rompre avec le pessimisme. *Cahiers Agricultures* **11**: 65–73.
- Savithri P, Perumal R, Nagarajan R. 1999. Soil and crop management technologies for enhancing rice production under micronutrient constraints. *Nutrient Cycling in Agroecosystems* **53**: 83–92.
- Scoones I, Thompson J (eds). 1994. *Beyond Farmer First. Rural People's Knowledge, Agricultural Research and Extension Practice*. International Institute for Environment and Development: London; 301 pp.
- Shang C, Bates TE. 1987. Comparison of zinc soil tests adjusted for soil and fertilizer phosphorus. *Fertilizer Research* **11**: 209–220.
- Steiner KG. 1998. Using farmers' knowledge of soils in making research results more relevant to field practice: experiences from Rwanda. *Agriculture, Ecosystems and Environment* **69**: 191–200.
- The Innovation Group. 2004. Internet site <http://www.the-innovation-group.com/ChemProfiles/Zinc%20Sulfate.htm>.
- Traoré O. 2002. Experience de l'AMVS. In *Améliorer les Productivités et Production en Riziculture Irriguée dans la Vallée du Sourou, Burkina Faso: Alternative et Perspectives*, Barro SE (ed.). Rapport de synthèse sur l'atelier tenu à Niassan du 13 au 15 Mars 2002. Institut National de Recherches Agricoles: Ouagadougou, Burkina Faso.
- Van Asten PJA, Barbiero L, Wopereis MCS, Maeght JL, Van der Zee SEATM. 2003a. Actual and potential salt-related soil degradation in an irrigated rice scheme in the Sahelian zone of Mauritania. *Agricultural Water Management* **60**: 13–32.
- Van Asten PJA, Wopereis MCS, Haefele S, Ould Isselmou M, Kropff MJ. 2003b. Explaining yield gaps on farmer-identified degraded and non-degraded soils in a Sahelian irrigated rice scheme. *Netherlands Journal of Agricultural Science* **50**: 277–296.
- Van Asten PJA, Van't Zelfde JA, Van der Zee SEATM, Hammecker C. 2004. The effect of irrigated rice cropping on the alkalinity of two alkaline rice soils in the Sahel. *Geoderma*, in press.
- Veldhuizen L, Waters-Bayer A, Ramirez R, Johnson DA, Thompson J. 1997. *Farmers' Research in Practice. Lessons from the Field*. ILEIA. Immediate Technology Publications: London; 285 pp.
- Walkley A, Black IA. 1934. An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Science* **37**: 29–38.
- Witt C, Dobermann A, Abdulrachman S, Gines HC, Guanghuo W, Nagarajan R, Satawatananont S, Tran Thuc Son, Pham Sy Tan, Van Tiem L, Simbahan GC, Oik DC. 1999. Internal nutrient efficiencies of irrigated lowland rice in tropical and subtropical Asia. *Field Crops Research* **63**: 113–118.
- Wopereis MCS, Donovan C, Nebié B, Guindo D, N'Diaye MK. 1999. Soil-fertility management in irrigated rice systems in the Sahel and savanna regions of West Africa. Part I: agronomic analysis. *Field Crops Research* **61**: 125–145.
- Yoshida S. 1981. *Fundamentals of Rice Crop Science*. International Rice Research Institute: Los Baños; 46–71.
- Yoshida S, Forno DA, Cock JH, Gomez KA. 1976. *Laboratory manual for physiological studies of rice*. Third edition. International Rice Research Institute: Los Baños, Philippines; 83 pp.