HAL open science

Increase in rice productivity in the Senegal River valley due to improved collective management of irrigation schemes

Jean-Christophe Poussin, Youssouf Diallo, Jean-Claude Legoupil, Abdoulaye Sow

▶ **To cite this version:**

Jean-Christophe Poussin, Youssouf Diallo, Jean-Claude Legoupil, Abdoulaye Sow. Increase in rice productivity in the Senegal River valley due to improved collective management of irrigation schemes. Agronomy for Sustainable Development, 2005, 25 (2), pp.225-236. hal-00886297

HAL Id: hal-00886297
https://hal.science/hal-00886297

Submitted on 11 May 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Agron. Sustain. Dev. 25 (2005) 225–236
DOI: 10.1051/agro:2005021
© INRA, EDP Sciences, 2005

Research article

Increase in rice productivity in the Senegal River valley due to improved collective management of irrigation schemes

Jean-Christophe POUSSIN[a]*, Youssouf DIALLO[b], Jean-Claude LEGOUPIL[c], Abdoulaye SOW[d]

[a] Institut de Recherche pour le Développement (IRD), BP 64501, 34394 Montpellier Cedex 5, France
[b] Centre National de Recherche Agronomique et de Développement Agricole (CNRADA), BP 22, Kaédi, Mauritania
[c] Centre International de Coopération pour le Développement (CIRAD), avenue Agropolis, 34398 Montpellier Cedex 5, France
[d] West Africa Rice Development Association (WARDA), BP 255, 01 Bouaké, Côte d'Ivoire

(Accepted 27 January 2005)

Abstract – Village irrigation schemes cover about 25% of the irrigated area on the two banks of the Senegal River. We analyzed irrigation scheme and rice crop management practices during the 1998 wet season in this type of irrigation scheme in Mauritania. Average yield was 4.8 t ha^{-1}; problems with irrigation rules resulted in great variability of irrigation frequency between fields, and sub-optimal timing of nitrogen fertilizer application resulted in yield losses. Based on this diagnosis, we suggested to farmers new irrigation rules and cropping calendars planned on the scale of the irrigation scheme. Planned cropping calendars were built using CalCul, a software that we designed on the basis of the irrigated rice development model RIDEV. These suggestions of improved collective management were implemented in the 1999 and 2000 wet seasons. Average yield reached 7.2 t ha^{-1} in 1999 and 8.2 t ha^{-1} in 2000, without any significant increase in production costs. This great increase in rice productivity was mainly due to better collective management obtained through planning cropping calendars. This result showed that technical innovation is not the only way to improve productivity.

irrigated rice / West Africa / crop management / input efficiency / decision support tool

1. INTRODUCTION

Irrigation schemes in the Senegal River valley cover about 50 000 ha (SAED, 1997; SONADER, 1998). During the 1998 wet season, about 75% of this area was used, i.e. 20 000 ha in Senegal and 18 000 ha in Mauritania, almost exclusively for rice (*Oryza sativa* L.). Potential rice grain yields (limited by solar radiation and temperature only) are on average about 9 t ha^{-1} in the wet growing season from July to November (Dingkuhn and Sow, 1997) while actual average farmer yields are about 5 t ha^{-1} (SAED, 1997; SONADER, 1998). Agronomic studies (Le Gal, 1997; Wopereis et al., 1999; Haefele et al., 2001; Poussin et al., 2003) identified sub-optimal timing of crop management interventions (i.e. date of sowing or transplanting, herbicide and fertilizer applications, and harvest and post-harvest activities) as major constraints.

The structural adjustment programs of the 1990s have put the responsibility for management of irrigation schemes in Senegal and Mauritania mostly back into farmers' hands. Decision-making on irrigation schedules, land preparation, purchase of inputs (fertilizers and herbicides), harvesting and marketing of the product is done collectively on the scale of the irrigation scheme. Financing of production costs requires credit obtained through collective loans, paid back after harvest. Moreover, previous loans have to be reimbursed to obtain a new one. Decision-making at the field level by individual farmers is, therefore, strongly influenced by decisions taken collectively at the irrigation scheme level (Poussin, 1995; Le Gal and Papy, 1998). Moreover, improving the productivity for individual farmers in the collective irrigation scheme is not sustainable.

To improve rice productivity, best-bet cropping calendars need, therefore, to be determined collectively at both scheme and field levels. We hypothesize that planning crop calendars on the scale of the irrigation scheme before the beginning of the crop season can improve input efficiency and rice productivity without any technical innovation.

The objectives of this study were to (i) investigate determinants of rice yield in a village irrigated scheme of the Senegal River valley; (ii) develop and evaluate a decision-support tool for improved cropping calendars at the irrigation scheme level; (iii) analyze the effects of changes in collective decision-making on rice yields and profitability.

* Corresponding author: poussin@ird.fr

Article published by EDP Sciences and available at http://www.edpsciences.org/agro or http://dx.doi.org/10.1051/agro:2005021

2. MATERIALS AND METHODS

2.1. Site description

Studies were implemented in the village irrigation scheme of Nakhlet, a small village on the northern bank of the Senegal River, 60 km east of Rosso (16° 29' N, 15° 12' W) in Mauritania. This type of irrigation scheme (or perimeter), with an area of below 50 ha and cultivated by farmers from a single village, covers about 25% of the irrigated area on the two banks of the Senegal River (SAED, 1997; SONADER, 1998).

The perimeter of Nakhlet was built in 1981 for the Mauritanian irrigation and extension authority, the "Société Nationale de Développement Rural" (SONADER). It covers 27.5 ha, with 119 fields cultivated by 29 farmers. Irrigation is carried out through pumping from a tributary of the Senegal River. Irrigated rice is cultivated only during the wet season, from mid-June to the end of November. Crop establishment in all fields is realized using a disk plow and direct sowing of pre-germinated seed. In 1998, 1999 and 2000, farmers used three *indica* cultivars with slender grain: Sahel 108 (IR13240-108-2-2-3, short duration), Jaya (medium duration) and Sahel 202 (ITA 306, medium duration). The potential yields of these three cultivars are similar and are on average about 8 to 9 t ha^{-1} in the wet season (Dingkuhn and Sow, 1997; WARDA, 1999).

After about 10 years under semi-public management, the Nakhlet farmers' organization took over the perimeter management from 1992. The farmers' organization manages credit provision, water pumping and irrigation, input supply (i.e. herbicides, fertilizers, fuel, etc.), and land preparation. Field irrigation is done by farmers on a rotational basis. This functioning is typical of the village irrigation schemes on the two banks of the Senegal River (Diemer and van der Laan, 1987).

2.2. Agronomic, hydraulic and economic survey

All 119 fields in the Nakhlet perimeter were monitored during the wet seasons of 1998, 1999 and 2000 (1998WS, 1999WS, 2000WS). The survey carried out in the 1998WS was used to determine the initial situation in terms of crop and water management, and sources of yield gap and variability. The topsoil (0 to 0.2 m depth) from all fields was sampled in 1998 before the onset of the growing season (one composite sample from 4 samples taken at random per field). Soil analyses (clay content, C and N content, P-Olsen, pH, electrical conductivity, CEC and exchangeable K) were conducted in the IRD laboratory in Dakar, Senegal, following standard methodologies.

The cultivars sown, type of seed (certified or retained from previous harvest), types and rates of applied fertilizers, type of weed control (manual or chemical) and rates of applied herbicides were recorded for each field. The dates of each management intervention (i.e. land preparation, irrigation, sowing, weed control, fertilizer applications and harvesting) were also recorded. Moreover, visual scores of weed infestation were taken at panicle initation in each field. Four scores, corresponding to four classes of surface area coverage by weeds, were distinguished: 0 for none; 1 for weak (less than 10% of surface area coverage by weeds); 2 for strong (between 10 and 30%); 3 for very strong (more than 30% of surface area coverage by weeds). Poussin et al. (2003) showed that a weed surface cover of less than 10% at panicle initation corresponded to a dry weed biomass of between 0 and 24 g m^{-2}, a surface cover between 10 and 30% corresponded to a weed biomass of between 13 and 228 g m^{-2}, and a cover of more than 30% corresponded to a biomass greater than 130 g m^{-2}. Grain yield (corrected for 14% moisture) was determined at maturity in the center of each field using a sampling area of 25 m^2. Grain rice yield of the whole field can be slightly overestimated, but comparisons between years at the perimeter level are still relevant.

The volume of water pumped into the Nakhlet perimeter in 1998 and 1999 was monitored daily during the wet season. The discharge measurement at the head of the perimeter was ensured through a rectangular weir installed at the outflow point of the stilling basin of the pump. The characteristics of this flume (length, width and discharge coefficient) enabled the calculation, using the Manning-Strickler formula, of the discharge according to the water level upstream of the flume, measured through a gauge placed inside the stilling basin (Bos et al., 1991): $Q = Cd.b.(2.g)^{0,5}.H^{1,5}$. Where Q is the discharge (in m^3 s^{-1}), b the breadth of the control section (m), Cd the discharge coefficient, g the gravitational acceleration (m s^2) and H the upstream head above the crest (m). A counter was installed on the pump to measure the operational hours. Irrigation water volume was estimated to be 70% of pumped inflow to allow for conveyance losses (Tuzet and Perrier, 1998). We further assumed that irrigation water was distributed homogeneously in the irrigated fields. No measurements were conducted during the 2000 wet season, as similar water allocation rules were applied to those in 1999.

Farmers financed their production costs through bank loans obtained by the farmers' organization. The Nakhlet farmers' organization purchased inputs and provided farmers with certified seeds, fertilizers and herbicides, according to the area of their fields. After harvest, farmers reimbursed the farmers' organization in rice paddy, which was sold by the farmers' organization to pay back the bank. Rice paddy is sold to the state, which guarantees a paddy price of between 38 and 45 Uguiya (Mauritanian currency [UM]) per kg (1 UM = 0.0032 Euro as of March 2004), depending on milling recovery (SONADER, 1998). A financial survey was conducted at the perimeter level during the 1998, 1999 and 2000 wet seasons. Production costs were calculated for each individual field. Irrigation costs included fuel, engine oil, maintenance and pump attendant salary. Cropping costs included land preparation, use of certified seeds, and purchase of fertilizers and herbicides. Their costs corresponded to suppliers' and providers' invoices. Costs of seeds retained from the previous harvest were estimated as 45 UM kg^{-1}. Harvest was done manually by each farmer in the 1998 and 1999 wet seasons and by a combine harvester through a service provider in the 2000WS. Comparison between years was made excluding harvest costs. Organizational changes in 1999 and 2000 did not modify the amount of work done by the farmers. Comparison between years was made excluding labor costs. The gross product of the perimeter corresponded to the total rice paddy production value. The average paddy selling price was 42 UM kg^{-1}.

2.3. Use of models for diagnosis: evapotranspiration, potential yield and development of irrigated rice

Daily rainfall during the 1998, 1999 and 2000 wet seasons was measured in Nakhlet using a pluviometer. Reference evapotranspiration was calculated using the Penman-Monteith equation (Smith et al., 1992; Allen et al., 1998) and weather data recorded at the experimental station of WARDA (West African Rice Development Association) in Fanaye (16° 33' N, 15° 46' W), near Nakhlet, on the Senegalese bank. The evapotranspiration of rice is calculated by multiplying the reference evapotranspiration with a varying crop factor (kc). The set of kc-values given by FAO (1986) and Siddeek et al. (1988) are used: kc being 1.15 during the vegetative growth phase, 1.3 during the reproductive phase, and 1.05 after the first week of maturation. Cumulative potential evapotranspiration of rice during the crop season was compared with the total of irrigation water supply and rainfall.

The rice growth model ORYZAS (Dingkuhn and Sow, 1997) simulates energy-limited and temperature-limited potential rice yield in the Sahel using daily minimum and maximum temperatures, solar radiation and geographical latitude (to calculate photoperiod). This model was used to calculate potential yields in the 1998WS, 1999WS and 2000WS using climatic data recorded in Fanaye.

The rice phenology model RIDEV (Dingkuhn et al., 1995) simulates irrigated rice development in the Sahel and provides crop management recommendations based on crop phenology at the field level. For a cultivar, a sowing date and a planting method (direct sowing or transplanting), RIDEV provides (i) the percentage of spikelet sterility due to cold or heat during flowering; (ii) dates of critical stages in rice development (flowering and maturity), and (iii) optimal timing for transplanting, weeding, fertilizer application, last drainage before harvest and harvest. Input data are geographical latitude of the site, daily minimum and maximum temperatures, and photothermal characteristics of the rice cultivar (Dingkuhn and Miezan, 1995). This model was used to reconstruct the rice development and to determine spikelet sterility percentage in each field during the wet seasons of 1998, 1999 and 2000 using daily temperatures recorded in Fanaye. RIDEV was also used to evaluate differences between optimal and actual cropping calendars in each field.

2.4. Planning cropping calendars at the perimeter level

RIDEV was used to develop CalCul ("Calendrier Cultural"), a software package written in the C language for the Microsoft Disk Operating System, that provides an optimal cropping calendar for irrigated rice on the scale of irrigation schemes in the Sahel (Poussin, 2000). This cropping calendar takes into account the organization of collective operations (i.e. operations that are collectively managed): mechanized land preparation, flooding before land preparation (pre-flooding) or before sowing (flooding), transplanting and mechanized harvest (manual harvest is often carried out individually, but mechanized harvest is carried out collectively). Input data are: (i) planned date for the start of the sowing period; (ii) rice cultivar sown; (iii) planting method (assumed to be common to all fields); (iv) duration of each collective operation for the whole perimeter, i.e. land preparation, flooding and pre-flooding (assumed to last the same time), transplanting (if this is the planting method chosen) and harvest. Moreover, in the case of pre-flooding, the average duration of soil drainage is needed.

To prevent leakage, flooding and land preparation are usually not performed at the same time; fields are usually flooded just before sowing or transplanting and this first flooding can last 2 days for each field. The optimal timing of transplanting, fertilizer top-dressed applications and harvest are based on rice phenology. To obtain an optimal cropping calendar in each field, operations (sowing, transplanting, fertilizer top-dressed applications and harvest) should have the same duration at the perimeter level. Without a common duration (for example, sowing nursery lasts 2 days and transplanting lasts 15 days on the scale of the perimeter), timing will be sub-optimal in some fields. The slowest collective operation set is therefore the common duration of all the cultural interventions, particularly sowing.

Farmers often choose their rice cultivar individually (Poussin, 1995) and direct sowing and transplanting can coexist in the same irrigation scheme (Poussin, 1997). Nevertheless, they can agree to choose one or two common cultivars, or cultivars with similar duration. The cultivar with the shortest duration would then be sown at the end of the sowing period to minimize the total crop duration on the scale of the perimeter. Direct sowing and transplanting lead to different crop development duration for the same cultivar. In the case of both planting methods, two cropping calendars at the perimeter level should be made.

CalCul uses the phenology model RIDEV (Dingkuhn et al., 1995) to simulate rice development for the first cultivar sown at the beginning of the sowing period (S1), and for the second cultivar sown at the end of the sowing period (S2). The duration of the sowing period is the duration of the slowest collective operation. These 2 simulations (S1 and S2) are made using historical weather data recorded near the site. Each simulation provides average and extremes of dates for several stages (Fig. 1): start of tillering, panicle initiation, heading, flowering and maturity. Spikelet sterility percentages (average and maximum) for S1 and S2 are also calculated.

At the perimeter level, the timing of each stage will be an average between the mean of dates for S1 and S2, and could start at the earliest at the minimum date for S1 and could end at the latest at the maximum date for S2. The starting and end dates (averages and extremes) of crop management interventions (weed management, fertilizer applications, last drainage and harvest) are based on rice phenology. The first flooding can last 2 days for each field and ends the day before sowing (or transplanting); land preparation ends just before flooding starts (it can end at the latest the day before the end of flooding); pre-flooding starts according to the duration of soil drainage.

The weeding and fertilizer management suggested by CalCul complies with WARDA recommendations (Wopereis et al., 2001). The first weeding can be done chemically with pre-emergence or post-emergence herbicides, and a second weeding can be done manually before the second N top dressing. Nitrogen fertilizer supply is suggested to be split into 2 or 3 top-dressed applications at the start of tillering, panicle initation and possibly heading. P and K fertilizer management is not specified. Contrary to SONADER and SAED ("Société d'Aménagement

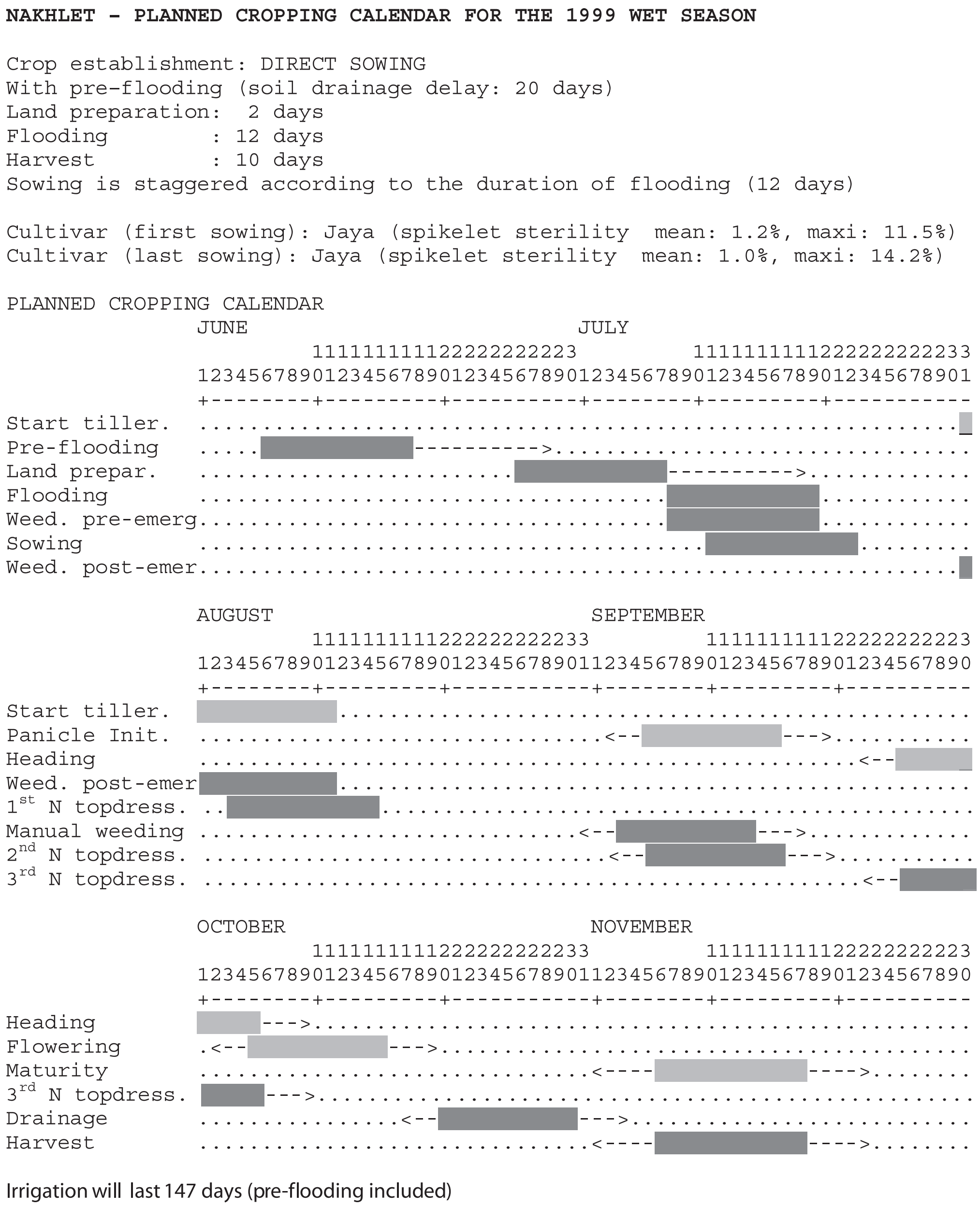


Figure 1. Planned cropping calendar at the scheme level determined with CalCul software for the 1999 wet season. Averages in rice phenology stages are indicated with light gray blocks; averages in crop management interventions are indicated with dark gray blocks. Earliest and latest dates are indicated by '<' and '>', respectively, if they differ from average dates. Land preparation can be done at the latest 1 day before flooding, and pre-flooding has to be done at the latest 20 days (soil drainage delay) before land preparation.

et d'Exploitation des terres du Delta et de la vallée du Sénégal", Senegalese irrigation and extension authority) recommendations, farmers generally merge P fertilizer with the first N topdressed application (Wopereis et al., 1999; Poussin et al., 2003). Basal application of K fertilizer before land preparation depends on soil exchangeable K status (Haefele et al., 2001). Cropping calendars for each field should follow the cropping calendar built on the scale of the perimeter. The realization of each operation in the fields should follow the water allocation cycle.

CalCul software was used to make the planned cropping calendars of the 1999 and 2000 wet seasons. Simulation calendars were made taking into account technical choices made by farmers (cultivar, sowing period, planting method and use of pre-flooding) and using historical weather data recorded in Rosso between 1970 and 1984.

2.5. Technical organization changes

Surveys during the 1998WS showed great variability in irrigation frequency between fields, and sub-optimal timing of nitrogen fertilizer application resulted in rice yield losses (see details in results and discussion). This diagnosis of the 1998WS was explained and discussed with farmers during a general meeting in Nakhlet in April 1999. Farmers were invited to implement several changes in their technical organization. These changes were meant to (i) reduce the variability in irrigation frequency between fields and (ii) reduce the gap between optimal and actual cropping calendars.

Thus, it was suggested to continue the water allocation cycle after rain (i.e. water allocation is not re-initialized and re-starts after rain in the next fields). In order to install an information system on field irrigation, a map of the perimeter (based on a cadastral survey; all the farmers could identify their own fields on this map) was posted showing weekly which fields had to be irrigated (based on the irrigation schedule). The farmer who was in charge of field irrigation had to notify on this map which fields were irrigated in order to inform the other farmers (field irrigation is done by farmers on a rotational basis). It was also suggested they should plan cropping calendars at the perimeter level for the next wet season and post a map of the perimeter (based on a cadastral survey) showing weekly which operation had to be done and which field had to be treated (based on the planned cropping calendars and water allocation cycle). Agricultural advisors of SONADER, that were present at the general meeting, also suggested in the 1999WS pre-flooding one month before land preparation in order to reduce early weed infestation, and using certified seed of Sahel 202 in the 2000WS. Farmers accepted these suggestions. They chose furthermore to grow only one cultivar (Jaya in the 1999WS and Sahel 202 in the 2000WS) and to delay the sowing period to make sure harvest would be after the rainy period.

Planned cropping calendars were built for the 1999 and 2000WS using CalCul (Fig. 1). Flooding was the slowest collective operation and set the common duration of crop management interventions on the scale of perimeter. After this planning, there was no interference in farmers' practices during the cropping season. The surveys made in the 1999WS and 2000WS were compared with the 1998WS to evaluate the effects of these changes on yields and profitability.

3. RESULTS AND DISCUSSION

3.1. Diagnosis of the 1998 wet season

In the 1998WS, farmers sowed Jaya between 20 June and 1 July (Tab. I) on 15.5 ha (65 fields) and Sahel 108 on 12.5 ha (54 fields). Sahel 108 was cultivated in Nakhlet for the first time that year. Sahel 108 seeds were certified; Jaya seeds were retained from the previous harvest. Harvest occurred from 4 to 7 November, an average of 135 days after sowing for Jaya and 129 days after sowing for Sahel 108. All fields were manually harvested. Maturity dates simulated with the model RIDEV for each field were an average of 118 days after sowing for Jaya and 109 days after sowing for Sahel 108. The average harvest delay was, therefore, 17 days for Jaya and 20 days for Sahel 108.

RIDEV simulations indicated no problems with spikelet sterility in any field (i.e. simulated spikelet sterility ratio < 5%) and average of potential yield calculated with the model ORYZAS was 8.7 t ha^{-1} for Jaya and 8.2 t ha^{-1} for Sahel 108. Rice grain yield measured at maturity ranged from 2.7 t ha^{-1} to 7.1 t ha^{-1}, with an average of 4.8 t ha^{-1}. Low yields were mainly localized in the fields far away from the irrigation source. The average yield for Jaya (5.5 t ha^{-1}) was significantly higher (Student's test, $P < 0.0001$) than for Sahel 108 (4.0 t ha^{-1}). Farmers wanted therefore to understand the origins of yield variability and the clear differences between cultivars.

3.1.1. Soil variability

The results of soil analyses corresponded well with soil characteristics in irrigated schemes of the Senegal River valley described by Haefele et al. (2001). Topsoil clay content varied with distance from the bank, ranging from about 35% to 55%. C content ranged from 4.4 to 7.9 g mg kg^{-1} soil, with an average of 6.2 g kg^{-1}, and N content ranged from 0.37 to 0.71 g kg^{-1} soil, with an average of 0.52 g kg^{-1}. CEC varied from 18 to 29 cmol kg^{-1} and was well correlated with clay content (r^2 = 0.823). Exchangeable K ranged from 0.4 to 0.9 cmol kg^{-1} soil, with an average of 0.7 cmol kg^{-1}. P-Olsen ranged from 4.3 to 17 mg kg^{-1} soil, with an average of 10.2 mg kg^{-1}. P and K availabilities are above the critical levels for rice (Dobermann et al., 1995; Sanchez, 1976). Electrical conductivity ranged from 0.4 to 1.5 mS cm^{-1} with an average of 0.9 mS cm^{-1}, and pH ranged from 5.8 to 6.5 with an average of 6.1, which do not constitute constraints for irrigated rice cropping when irrigation is well managed (Asch and Wopereis, 2000). We assumed, therefore, that initial soil P and K status, and soil salinity levels when irrigation is well managed, were not hampering rice growth.

3.1.2. Irrigation management

Irrigation started on 19 June 1998 with flooding before direct sowing and ended on 30 September 1998. The total pumped water volume was 265 700 m^3, including 79 000 m^3 for flooding (Tab. II). The average irrigation water supply in the fields was estimated at 756 mm and rainfall was 207 mm, whereas evapotranspiration of the rice was estimated at 802 mm. The total of irrigation water supply and rainfall was about 160 mm above the evapotranspiration of the rice, but water losses through percolation could be estimated at about 2 mm per day (i.e. more than 200 mm from sowing to maturity) for this type of soil (Raes et al., 1997).

Fields were irrigated 4 to 9 times after flooding. Estimated irrigation water supply (flooding included) ranged from 528 mm to 828 mm as a function of irrigation frequency (Tab. III). Irrigation frequency and irrigation water supply were lower in the fields relatively far away from the irrigation source, that were mostly sown with Sahel 108. Water allocation rules based on re-initializing the water allocation cycle after rain contributed to this irrigation frequency heterogeneity (water allocation cycle started in the fields near to the irrigation source). Effects of irrigation frequency (through irrigation water supply and risk of water shortage) on rice yield during the 1998WS were strongly significant (Student's test, $P < 0.0001$). Fields irrigated

Table I. Actual and planned cropping calendars at the perimeter level during the 1998, 1999 and 2000 wet seasons. DAS: days after sowing; SD: standard deviation; PI: panicle initiation; TSP: triple superphosphate (20% P); DAP: diammonium phosphate (18% N, 20% P).

		1998 wet season	1999 wet season		2000 wet season	
		Actual	Planned	Actual	Planned	Actual
Pre-flooding	timing	None	5/6–17/6	16/5–7/6	None	none
Land preparation	timing	14/6–17/6	25/6–7/7	5/7–8/7	7/7–18/7	10/7–14/7
Flooding	timing	19/6–1/7	8/7–19/7	10/7–22/7	19/7–30/7	21/7–4/8
Sowing	timing	20/6–1/7	11/7–22/7	11/7–22/7	22/7–2/8	22/7–4/8
	Sown cultivar and area	Jaya: 15.0 ha	Jaya: 27.5 ha	Jaya: 26.6 ha	Sahel 202: 27.5 ha	Sahel 202: 22.5 ha
		Sahel 108: 12.5 ha		Sahel 108: 0.9 ha		Jaya: 5.0 ha
Weeding	type and rate	2 l 2-4D ha^{-1} + 4 l Propanil ha^{-1}	2 l 2-4D ha^{-1} + 4 l Propanil ha^{-1}	manual	2 l 2-4D ha^{-1} + 4 l Propanil ha^{-1}	2 l 2-4D ha^{-1} + 4 l Propanil ha^{-1}
	timing	17/7–2/8	1/8–11/8	15/7–13/9	11/8–22/8	19/8–25/8
	DAS (days): average (SD)	27 (4.2)	21	25 (10)	21	24 (3.6)
1st fertilizer application:	type and rate	100 kg TSP ha^{-1} + 125 kg urea ha^{-1}	100 kg DAP ha^{-1} + 50 kg urea ha^{-1}	150 kg urea ha^{-1}	100 kg DAP ha^{-1} + 50 kg urea ha^{-1}	150 kg urea ha^{-1}
	timing	24/7–9/8	3/8–13/8	10/8–1/9	14/8–25/8	22/8–4/9
	DAS (days): average (SD)	36 (4.4)	23	32 (3.8)	23	29 (4.4)
2nd fertilizer application:	type and rate	125 kg urea ha^{-1}	150 kg urea ha^{-1}	150 kg urea ha^{-1}	150 kg urea ha^{-1}	150 kg urea ha^{-1}
	timing	19/8–6/9	5/9–15/9	8/9–19/9	18/9–27/9	25/9–4/10
	DAS (days): average (SD)	Jaya: 60 (4.2)	56	59 (3.2)	58	62 (4.5)
		Sahel 108: 59 (5.5)				
Total N applied (kg ha^{-1}):	average (SD)	117 (11)	110	152 (22)	110	152 (23)
Total P applied (kg ha^{-1}):	average (SD)	19 (4)	20	0	20	0
Weed infestation score at PI	average (SD)	1.5 (1.2)		1.1 (1.6)		0.8 (1.2)
Irrigations after flooding:	average (min-max)	6.5 (4–9)		8.2 (8–9)		8.7 (8–9)
Maturity:	DAS (days)	Jaya: 118	118	116	121	122
		Sahel 108: 109				
Harvest:	type	manual		manual		combine harvesting
	timing	04/11–7/11	6/11–17/11	12/11–14/11	20/11–1/12	08/12–9/12
	DAS (days): average (SD)	Jaya: 135 (2.3)	118	118 (3.3)	121	133 (4.0)
		Sahel 108: 129 (2.5)				
Actual yield (Mg ha^{-1}):	average (SD)	4.80 (1.0)		7.2 (1.4)		8.2 (1.8)

less than 7 times after flooding were mainly sown with Sahel 108 (Tab. III); the irrigation water supply was below 700 mm and the average yield was 4.2 t ha^{-1}. Fields irrigated at least 7 times after flooding were mainly sown with Jaya; the irrigation water supply was above 700 mm and the average yield was 5.3 t ha^{-1}. This could explain the yield gap between Jaya and Sahel 108. Nevertheless, the average of yield obtained with Jaya was still significantly higher in the fields irrigated 6 to 7 times after flooding, where both cultivars were sown (see Tab. III).

3.1.3. Weeding and fertilizer management

A total of 110 liters of propanil and 55 liters of 2,4-D amine were bought by the Nakhlet farmers' organization before the 1998WS and distributed to farmers according to the surface area of their fields. The first weeding was done using herbicides in all fields with an average of 4 liters of propanil ha^{-1} and 2 liters of 2,4-D amine ha^{-1}, combined. The timing of herbicide application was on average 27 days after sowing. The delay between optimal (simulated with the model RIDEV) and actual weeding timing ranged from –2 to 17 days. Despite heavy weed infestation observed at panicle initation (average of visual score > 1, see Tab. I), a second manual weeding was only done on a minority of fields. Late weeding with low herbicide rates and virtual absence of manual weeding was also observed by Haefele et al. (2001) as a usual practice in Mauritania, and by Poussin et al. (2003) in Senegal. Moreover, visual scores of weed infestation at panicle initation were greater in the fields far from the irrigation source (with low irrigation frequency and, therefore, high risk of water shortage), mostly sown with Sahel 108.

The Nakhlet farmers' organization bought 7 tonnes of urea (46% of N) and 2.75 tonnes of triple superphosphate (20% of P). Fertilizers were given to farmers proportionally to their cultivated area at the rate of 250 kg urea ha^{-1} (115 kg N ha^{-1}) and 100 kg triple superphosphate (20 kg P ha^{-1}), i.e. close to the recommendations of 120 kg N ha^{-1} and 20 kg P ha^{-1}. 117 kg N ha^{-1} and 19 kg P ha^{-1} were applied in two top-dressed applications (Tab. I). Farmers had problems dividing fertilizer bags.

Table II. Pumped water volumes and estimated water supply for the entire irrigation scheme of Nakhlet (averages and standard deviations) for pre-flooding, flooding, and irrigation during the 1998 and 1999 wet seasons. Evapotranspiration (ETP) of rice, number of irrigations and rainfall contributions are also indicated. Standard deviations (SD) are given between brackets.

	1998 wet season			1999 wet season		
	Pumped water volume ($m^3 \times 1000$)	Estimated water supply in the fields (mm) average (SD)	Number of irrigations after flooding (no) average (min–max)	Pumped water volume ($m^3 \times 1000$)	Estimated water supply in the fields (mm) average (SD)	Number of irrigations after flooding (no) average (min–max)
Pre-flooding	none			70.1	171 (14)	
Flooding	79	202 (18)		70.3	181 (35)	
Irrigation	216.3	554 (105)	6.5 (4–9)	233.0	589 (67)	8.2 (8–9)
Total	295.3	756 (110)		373.4	939 (72)	
Rainfall		207			183	
ETP of rice		802			774	

Table III. Irrigation water supply, number of fields sown with Jaya and Sahel 108, and rice grain yield during the 1998 wet season as a function of the number of irrigations after flooding. Standard deviations are given between brackets. (***: simple comparison between cultivars with Student's test and $P < 0.001$).

Irrigations after flooding (no)	4	5	6	7	8	9
Average of irrigation water supply (mm)	528	602	666	720	774	828
Fields (no)	11	21	26	33	14	14
Average of yield (Mg ha^{-1})	4.07 (0.24)	4.03 (0.18)	4.50 (0.21)	5.04 (0.14)	5.37 (0.17)	5.92 (0.18)
Fields sown with Jaya (no)	1	6	11	20	13	14
Average of yield (Mg ha^{-1})	5.47*** (0.90)			5.41*** (0.79)		
Fields sown with Sahel 108 (no)	10	15	15	13	1	0
Average of yield (Mg ha^{-1})	3.79*** (0.47)			4.48*** (0.55)		

That explained the variability of applied N fertilizer, that ranged from 90 kg N ha^{-1} to 150 kg N ha^{-1}. Nevertheless, rates over 90 kg N ha^{-1} did not have a significant effect on rice yield (Fig. 2). This corresponded to a strong variability of N fertilizer efficiency already observed by Wopereis et al. (1999) and Haefele et al. (2001) in similar situations.

All farmers applied fertilizer in two top-dressings (Tab. I). With the first split, on average at 36 days after sowing, all of the triple superphosphate and half of the urea were applied. The rest of the urea was applied at about 60 days after sowing. Optimal dates simulated with RIDEV for these two splits were on average 23 days after sowing and 60 days after sowing for Jaya and 23 days after sowing and 50 days after sowing for Sahel 108. The delay between actual and optimal dates ranged from 2 to 23 days for the first split and from –9 to 21 days late for the second split. Increasing delay of N application led to considerable drops in maximum yield (Fig. 3), i.e. decreasing applied N efficiency. The delay of the second split for Sahel 108 (on average 11 days) was greater than for Jaya (on average 1 day). Farmers respected quite well agricultural advice that recommended a second split at 60 days after sowing (SONADER, 1998). However, this recommendation did not concord with Sahel 108 duration, which is on average 10 days shorter than Jaya duration in the wet season (RIDEV simulations with daily temperatures recorded in Rosso, 1970–1984).

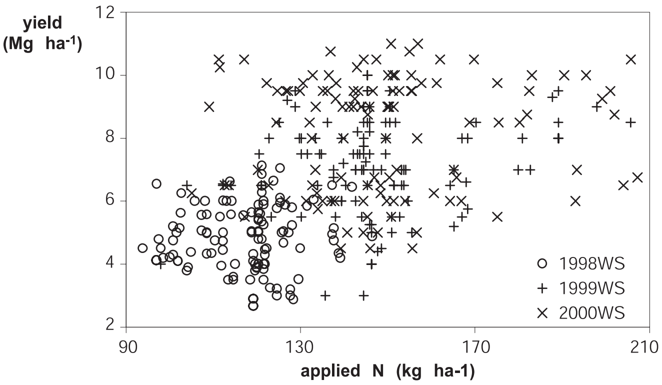
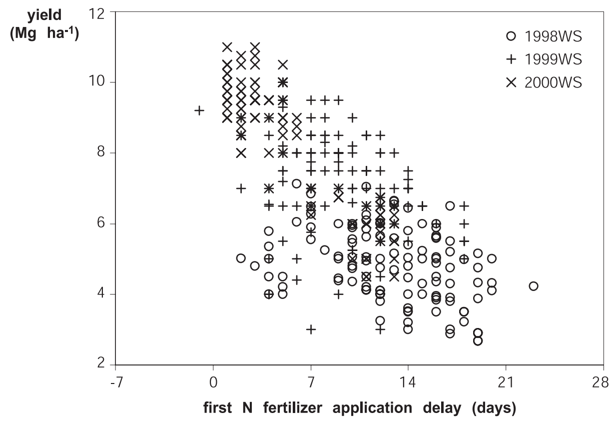


Figure 2. Rice grain yield (Mg ha^{-1}) determined in all fields in the 1998, 1999 and 2000 wet seasons (1998WS, 1999WS, 2000WS) as a function of total applied N fertilizer (kg ha^{-1}).

Therefore, lower irrigation frequency combined with stronger weed infestation and greater delays for N fertilizer application in fields sown with Sahel 108 than in fields sown with Jaya explained the yield differences observed between the two cultivars.



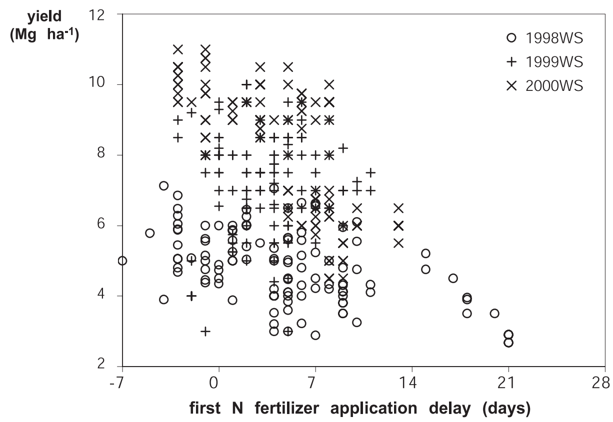


Figure 3. Rice grain yield (Mg ha^{-1}) measured in all fields in the 1998, 1999 and 2000 wet seasons (1998WS, 1999WS, 2000WS) as a function of gap (in days) between actual and optimal N fertilizer application timing (optimal date for the first split: 21 days after sowing; optimal date for the second split: panicle initiation; optimal dates determined for each field with RIDEV).

3.2. Diagnosis of the 1999 and 2000 wet seasons

In the 1999 and 2000 wet seasons, the potential rice grain yields were between 8.8 t ha^{-1} and 9.2 t ha^{-1} (i.e. about 1 t ha^{-1} more than in the 1998WS) whilst the average of the actual yield increased greatly (Tab. I). It reached 7.2 t ha^{-1} in 1999 and 8.2 t ha^{-1} in 2000 (i.e. 2.4 and 3.4 t ha^{-1} more than in the 1998WS). Nevertheless, the standard deviation of yield increased slightly (1.4 t ha^{-1} in 1999 and 1.8 t ha^{-1} in 2000), indicating continued heterogeneity between fields.

3.2.1. Irrigation management

In the 1999WS, the total pumped water was 78 100 m^3 higher than in the 1998WS (Tab. II). This increase was mainly due to a pre-flooding irrigation that used 70 100 m^3 of pumped water. The first flooding used 70 300 m^3 (8 700 m^3 less than in the 1998WS) and irrigation after flooding used 233 000 m^3 (16 700 m^3 more than in the 1998WS). The average irrigation water supply (excluding pre-flooding) in the fields was estimated at 768 mm. Rainfall contributed 183 mm. Total water supply after pre-flooding was estimated at 961 mm compared with 951 mm in the 1998WS, whereas evapotranspiration of the rice was estimated at 774 mm compared with 802 mm in the 1998WS. The irrigation water supply variability between fields was lower in 1999 than in 1998 (72 mm vs. 110 mm, see Tab. II). Farmers respected the new water allocation rules and the irrigation planning, and all fields were irrigated 8 or 9 times after flooding. The increase in irrigation frequency compared with the 1998WS did not lead to a strong increase in pumped water amount. In the 2000WS, farmers did not pre-flood and all fields were irrigated 8 or 9 times after flooding, respecting the water allocation rules and irrigation plan.

The increase in irrigation frequency reduced the risk of water shortage. Based on the 1998WS results (Tab. III), the increase in irrigation frequency alone could not explain the increase in rice yield with the Jaya cultivar (1.7 t ha^{-1} in 1999 and 2.7 t ha^{-1} in 2000). Irrigation management was therefore not the only factor contributing to yield increase.

3.2.2. Land preparation, flooding and sowing

In the 1999 and 2000WS, farmers chose to delay the sowing period to make sure that harvesting would not occur during the rainy period, while keeping a spikelet sterility percentage lower than 10% (simulated with the software CalCul using daily temperatures recorded in Rosso, 1970–1984). In the 1999WS, most farmers used the cultivar Jaya, with seeds retained from the previous harvest (despite the recommendations of agricultural advisors). With sowing between 7 and 22 July, maturity came in early November (Tab. I). In the 2000WS, they used cultivar Sahel 202, with certified seeds (as recommended by agricultural advisors). With sowing between 19 July and 4 August, maturity came at the end of November. Spikelet sterility simulated with the model RIDEV for both wet seasons was lower than 10% in all fields.

Planned sowing dates were well respected in the 1999 and 2000WS (see Tab. I). The planned cropping calendar indicated the start of first flooding 3 days before sowing, but farmers sowed the same day as flooding. Land preparation was realized using disk plows 2 days before flooding in the 1999WS and one week before flooding in the 2000WS, and lasted 3 or 4 days in both wet seasons. The gap between actual and planned dates for land preparation and flooding had no effect on following crop management interventions.

In the 1999WS, fields were pre-flooded about 2 weeks before the planned period (from 5 May to 6 June vs. from 5 to 17 June, see Tab. I) to be sure that weeds could come up before land preparation. Weeds were eliminated by land preparation about 1 month after pre-flooding. Early weed infestation was low and farmers refrained from herbicide use. In spite of its efficiency on early weed control and its low cost (fuel consumption was about 1 000 liters for pre-flooding, corresponding to 66 000 UM; see Tab. IV), farmers did not repeat pre-flooding in the 2000WS. Pre-flooding requires the farmers' presence at Nakhlet one month before the beginning of the crop season, but the farmers have other activities as well as irrigated agriculture (Diemer and van der Laan, 1987).

Table IV. Perimeter financial results of the 1998, 1999 and 2000 wet seasons. UM: Mauritanian currency; TSP: triple superphosphate (20% P); DAP: diammonium phosphate (18% N, 20% P).

	1998 wet season			1999 wet season			2000 wet season		
	Amount (l or kg)	Unit price (UM)	Value (UM × 1000)	Amount (l or kg)	Unit price (UM)	Value (UM × 1000)	Amount (l or kg)	Unitprice (UM)	Value (UM × 1000)
Fuel	4100	65	266.5	5100	66	336.6	4200	88	369.6
Engine oil			18.2			24.2			23.8
Pump driver salary			64.0			64.0			64.0
Maintenance			55.2			66.2			78.7
Sub-total			403.9			491.0			536.1
Land preparation			132.4			132.9			134.5
Retained seeds	2000	45	90.0	3000	45	135.0	600	45	27.0
Certified seeds	1500	90	135.0				2280	90	205.2
Herbicides			252.0			74.2			233.4
Urea	7 000	42	294.0	8500	44	374.0	8500	45	382.5
Other fertilizers (TSP or DAP)	2 500	38	95.0						
Sub-total			998.4			716.1			982.6
Micellaneous expenses (transport etc.)			170.5			194.2			226.6
Total costs			1 652.8			1 481.3			1 825.3
Gross product	128 500	42	5 397.0	197 000	42	8 274.0	223 000	42	9 366.0
Gross margin			3 744.2			6 792.7			7 540.7

3.2.3. Weed and fertilizer management

In the 1999WS, early weed infestation levels were low. Most farmers preferred manual weeding to save money (about 150 000 UM for the whole perimeter; see Tab. IV). Manual weeding was done at 25 days after sowing (see Tab. I), but it lasted until 13 September in some fields and therefore delayed the first N application. Visual scores of weed infestation at panicle initation were on average lower than in the 1998WS, but standard deviations (1.6 in the 1999WS vs. 1.2 in the 1998WS) indicated strong variability between fields.

In the 2000WS, farmers applied a combination of propanil (4 liters ha^{-1}) and 2,4 D amine (2 liters ha^{-1}) as in the 1998WS (Tab. I). Herbicides were applied 6 days late compared with the planned timing. This delay is partially due to the delivery date (19 August 2000) of the fertilizer and herbicides. Weeding on fields sown before 29 July was therefore inevitably delayed (Fig. 4). This delay of the herbicide treatment directly induced a delay of the first N application. Weed infestation at panicle initation was not very serious in most fields (average visual score < 1), but it was greater in fields sown before 29 July (average visual score 1.8).

In the 1999 and 2000WS, farmers ordered 3 tonnes of diammonium-phosphate (18% N, 20% P) and 5.5 tonnes of urea (46% N) with planned application rates of 100 kg diammonium-phosphate ha^{-1} and 200 kg urea ha^{-1}, i.e. 20 kg P ha^{-1} and 110 kg N ha^{-1}. However, diammonium-phosphate fertilizer was not available. Thus, 8.5 tonnes of urea were delivered and given to farmers at the rate of 300 kg urea ha^{-1}. Total applied N was on average 152 kg ha^{-1} in the 1999 and 2000WS, with a standard deviation of about 20 kg ha^{-1}. Compared with the 1998WS, the increase in applied N alone could not explain the increase in rice yield. The relation between total applied N and rice yield showed, in fact, that the maximum yield (about 10 t ha^{-1}, see Fig. 2) was reached in the 2000WS with a minimum rate of about 120 kg N ha^{-1}, i.e. equal to the average applied N rate in the 1998WS. This observation agrees well with WARDA recommendations about N fertilizer rates (Wopereis et al., 2001). Yield measured on samples overestimated the yield of fields and could therefore exceed the potential yield calculated with the model ORYZAS. Nevertheless, the maximum yield observed in the 1999 and 2000WS indicated that the potential yield for Jaya and Sahel 202 should be reached in many fields.

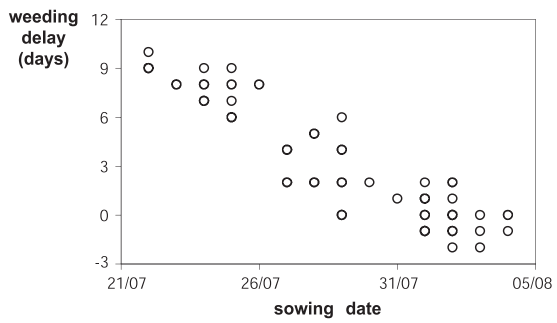


Figure 4. Difference between RIDEV simulated optimal timing of weeding and actual weeding (weeding delay) as a function of sowing date during the 2000 wet season.

As in the 1998WS, N fertilizer was applied in two equal splits. The planned timing for the first split was 23 days after sowing (from 3 to 13 August in the 1999WS and from 14 to 25 August in the 2000WS, see Tab. I) and the planned timing for the second split was 56 days after sowing in the 1999WS (from 5 to 15 September) and 58 days after sowing in the 2000WS (from 18 to 27 September). The delays between optimal and actual timings were on average 9 days in the 1999WS and 6 days in 2000WS for the first split, and 2 days in the 1999WS and 4 days in the 2000WS for the second split. The first split delay was still greater than the second split delay. In the 1999WS, manual weeding partially explained the delay in the first N; in the 2000WS, the herbicide and fertilizer delivery date partially explain this delay in fields sown before 29 July. Nevertheless, delays were significantly reduced (Fischer's test, $P < 0.05$) in the 1999 and 2000WS as compared with the 1998WS. As in the 1998WS, N fertilizer application delay in the 1999 and 2000WS induced a great drop in maximum yield (Fig. 3).

3.2.4. Harvest

Farmers were able to harvest their fields on time, close to maturity of the rice plants in the 1999WS, with an average grain yield of 7.2 t ha^{-1}. In the 2000WS, combine harvesters were used about 13 days after maturity, and the average grain yield was 8.2 t ha^{-1}.

3.3. Financial profits

During the 1998WS, total costs at the perimeter level (excluding harvesting) amounted to 1.7 million UM, whilst rice paddy production value was 5.4 million UM, and the gross margin was 3.7 million UM (Tab. IV). The gross margin increased to 6.8 million UM in the 1999WS and to 7.5 million UM in the 2000WS. Gross margins roughly doubled, therefore, compared with 1998. Moreover, except for pre-flooding, organizational changes did not increase labor input: timings of crop interventions were modified, but the amount of work done was unchanged.

Rice yield increase is the main factor contributing to this result. As compared with the 1998WS, production costs decreased slightly in 1999 as less herbicides were used despite the introduction of pre-flooding. Production costs further increased in the 2000WS due to the use of certified seeds and the fuel price increase. Similar results were obtained in Mauritania by WARDA working with large-scale farmers cultivating their own irrigation scheme (Haefele et al., 2001).

At the field level, gross margins ranged from about 50 000 to 250 000 UM ha^{-1} in the 1998WS, from 50 000 to 375 000 UM ha^{-1} in the 1999WS and from 100 000 to 400 000 UM ha^{-1} in the 2000WS (Fig. 5). The increase in gross margins per hectare was strongly significant (multiple comparison using Sheffe's test, $P < 0.0001$). Moreover, gross margin per hectare for the fields sown after 29 July in the 2000WS (late arrival of fertilizers and herbicides did not affect these fields) varied from about 250 000 to 400 000 UM ha^{-1}, i.e. above the gross margin range in the 1998WS. Combine harvesting in the 2000WS cost about 40 000 UM ha^{-1}. Each farmer could easily pay for this supplementary expense.

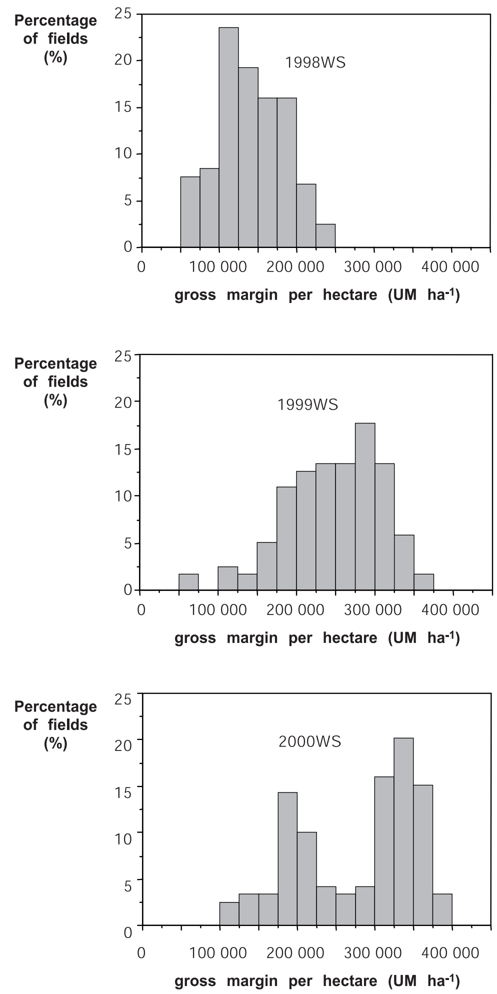


Figure 5. Frequency distribution of gross margins per hectare in Mauritanian currency (UM) for the 1998, 1999 and 1999 wet seasons (1998WS, 1999WS, 2000WS).

4. CONCLUSION

Despite roughly similar growth conditions for rice cropping, the gap between potential and actual yield ranged from 2.7 to 7.1 t ha^{-1} in the 1998WS. Farmers used two cultivars (Jaya and Sahel 108) that had similar potential yields, but the actual yield obtained with Sahel 108 was lower as compared with Jaya. As shown by another study in the Senegal River valley (Poussin et al., 2003), variability in crop management practices was the main contributing factor to this heterogeneity. The survey during the 1998WS revealed high variability for irrigation frequency, for weeding and N application timing, and for total applied N rate. Irrigation frequency, through risk of water shortage, had a significant effect on yield, and increasing delay of N application led to large yield drops. Total applied N ranged from 90 to 150 kg ha^{-1}, but no direct relation was found with rice yield, suggesting a strong variability of N fertilizer apparent recovery rate. The water allocation rules led to low irrigation frequency in fields far from the irrigation source. These fields were mainly sown with Sahel 108. Higher weed infestation (partially due to lower irrigation frequency) combined with greater delay for a second N application in fields sown with Sahel 108 explained the yield gap compared with Jaya.

Based on this diagnosis, farmers were invited to change their water allocation rules in order to homogenize fields' irrigation frequency, and to make on the scale of the perimeter a planned cropping calendar for the next season to improve the timing of crop management interventions in all fields. During the 1999 and 2000WS, all fields were irrigated 8 to 9 times after flooding and delays between optimal and actual N fertilizer application timings were reduced. The average rice grain yield reached 7.2 $t\,ha^{-1}$ in the 1999WS and 8.2 $t\,ha^{-1}$ in the 2000WS, whereas production costs at the perimeter level remained stable. Overall, gross margins at the perimeter level increased by more than 80% as compared with the 1998WS. This increase in irrigated rice productivity was mainly due to better collective management improving input use efficiencies.

These results confirm the importance of good crop management in general in irrigated systems in the Sahel (Wopereis et al., 2001). Current crop management techniques allow one to reach the potential yields of the rice cultivars used. However, farmers' collective organization at the perimeter level and farmers' individual practices at the field level are often sub-optimal. If herbicide and fertilizer rates are often close to recommendations, crop management operation timings are often delayed. Making a planned cropping calendar can therefore assist farmers with crop management. Technical innovation is, therefore, not the only way to improve agricultural productivity.

Soil fertility and crop management by farmers in the Senegal River valley could also depend on other external actors, such as suppliers and motorized service providers. In our study, soil P fertility management depended on the availability of P fertilizer in the suppliers, and late input delivery led to delayed herbicide and fertilizer applications. Le Gal (1997) showed the dependence on combine harvester availability for double rice cropping farmers in the Senegal River delta. In order to prepare for these delivery delays or input and agricultural machinery availabilities, planning cropping calendars can help farmers' organizations to enter early into a contract with suppliers and providers.

Acknowledgements: We thank the farmers of Nakhlet. We also thank Marco Wopereis for his comments and corrections. This study was financed by the "Pôle Regional de Recherche sur les Systèmes Irrigués" (PSI, i.e. Regional Research Initiative on irrigated systems) of WECARD/CORAF.

REFERENCES

Allen R.G., Pereira L.S., Raes D., Smith M. (1998) Crop evapotranspiration Guidelines for computing crop water requirements. FAO Irrigation and Drainage, Paper 56, Food and Agriculture Organization of the United Nations (UN-FAO), Rome.

Asch F., Wopereis M.C.S. (2000) Responses of field-grown irrigated rice cultivars to varying levels of floodwater salinity in a semi-arid environment, Field Crops Res. 70, 127–137.

Bos M.G., Replogle J.A., Clemmens A.J. (1991) Flow Measuring Flumes for Open Channel Systems, American Society of Agricultural Engineers, New York.

Diemer G., van der Laan E. (1987) L'irrigation au Sahel : la crise des périmètres irrigués et la voie haalpulaar, Karthala/CTA, Paris/ Wageningen.

Dingkuhn M., Le Gal P.Y., Poussin J.C. (1995) RIDEV, un modèle de développement du riz pour le choix des variétés et des calendriers, in: Boivin P., Dia I., Lericollais A., Poussin J.C., Santoir C., Seck S.M. (Eds.), Nianga, laboratoire de l'agriculture irriguée en moyenne vallée du Sénégal. Editions de l'ORSTOM, Coll. Colloques et Séminaires, Paris, France, pp. 205–222.

Dingkuhn M., Miézan K.M. (1995) Climatic determinants of irrigated rice performance in the Sahel, Part II - Validation of photothermal constants and characterization of genotypes, Agr. Syst. 48, 411–434.

Dingkuhn M., Sow A. (1997) Potential yields of irrigated rice in the Sahel, in: Miézan K.M., Wopereis M.C.S., Dingkuhn M., Deckers J., Randolph T.F. (Eds.), Irrigated rice in the Sahel: Prospects for sustainable development, West Africa Rice Development Association (WARDA), Bouaké, Ivory Coast, pp. 361–379.

Dobermann A., Cassman K.G., Sta. Cruz P.C., Neue H.U., Skogley E.O., Pampolino M.F., Adviento M.A.A. (1995) Dynamic soil tests for rice, in: Fragile Lives in Fragile Ecosystems. Proceedings of the International Rice Research Conference, 13–17 February 1995, International Rice Research Institute (IRRI), Manila, the Philippines, pp. 343–365.

FAO (1986) Yield response to water, FAO Irrigation and Drainage, Paper 33, Food and Agriculture Organization of the United Nations (UN-FAO), Rome.

Haefele S.M., Wopereis M.C.S., Donovan C., Maubuisson J. (2001) Improving the productivity and profitability of irrigated rice production in Mauritania, Eur. J. Agron. 14, 181–196.

Le Gal P.Y. (1997) Le développement de la double culture irriguée au Sahel : contraintes et perspectives pour les agriculteurs, in: Miézan K.M., Wopereis M.C.S., Dingkuhn M., Deckers J., Randolph T.F. (Eds.), Irrigated rice in the Sahel: Prospects for sustainable development, West Africa Rice Development Association (WARDA), Bouaké, Ivory Coast, pp. 161–189.

Le Gal P.Y., Papy F. (1998) Co-ordination processes in a collectively managed cropping system: double cropping of irrigated rice in Senegal, Agr. Syst. 57, 135–159.

Poussin J.C. (1995) Gestion technique de la riziculture irriguée, in: Boivin P., Dia I., Lericollais A., Poussin J.C., Santoir C., Seck S.M. (Eds.), Nianga, laboratoire de l'agriculture irriguée en moyenne vallée du Sénégal, Éditions de l'ORSTOM, Coll. "Colloques et Séminaires", Paris, France, pp. 153–170.

Poussin J.C. (1997) Direct seeding or transplanting? An example from the Senegal middle valley, in: Miézan K.M., Wopereis M.C.S., Dingkuhn M., Deckers J., Randolph T.F. (Eds.), Irrigated rice in the Sahel: Prospects for sustanaible development, West Africa Rice Development Association (WARDA), Bouaké, Ivory Coast, pp. 191–200.

Poussin J.C. (2000) CalCul : un outil pour construire un calendrier cultural prévisionnel du riz irrigué au Sahel, in: Legoupil J.C., Dancette C., Godon P., Maïga I.M., N'Diaye M.K. (Eds.), Pour un développement durable de l'agriculture irriguée dans la zone Soudano-Sahélienne. Synthèse des résultats du Pôle Régional de Recherche sur les Systèmes Irrigués (PSI/CORAF), WECARD-CORAF, Dakar, Senegal, pp. 87–99.

Poussin J.C., Wopereis M.C.S., Debouzie D., Maeght J.L. (2003) Determinants of irrigated rice yield in the Senegal River valley, Eur. J. Agron. 19, 341–356.

Raes D., Sy B., Deckers J. (1997) Simulation of irrigation water requirements of rice schemes in the Senegal river delta and valley, in: Miézan K.M., Wopereis M.C.S., Dingkuhn M., Deckers J., Randolph T.F. (Eds.), Irrigated rice in the Sahel: Prospects for sustanaible development, West Africa Rice Development Association (WARDA), Bouaké, Ivory Coast, pp. 411–419.

SAED (1997) Recueil des statistiques de la vallée du fleuve Sénégal, annuaire 1995/1996, version détaillée, Ministère de l'Agriculture du Sénégal – Société d'Aménagement et d'Exploitation des terres du Delta et de la vallée du Sénégal (SAED), St Louis, Senegal.

Sanchez P.A. (1976) Properties and management of soils in the tropics, Wiley, New York.

Siddeek F.Z., Dillaha T.A., Loganathan G.V. (1988) Water management for lowland rice irrigation, J. Irrig. Drain. Eng.-ASCE 114, 407–423.

Smith M., Allen R.G., Monteith J.L., Perrier A., Pereira L., Segeren A. (1992) Report of the expert consultation on procedures for revision of FAO guidelines for prediction of crop water requirements, Food and Agriculture Organization of the United Nations (UN-FAO), Rome.

SONADER (1998) Étude de la filière riz en Mauritanie, Rapport définitif, Société Nationale de Développement Rural (SONADER) / CLG Consultants, Nouakchott / Paris.

Tuzet A., Perrier A. (1998) Les besoins en eau des cultures : analyse et applications, in: Tiercelin J.R. (Ed.), Traité d'irrigation, Lavoisier, Technique et documentation, Paris, pp. 147–256.

WARDA (1999) Returns to irrigated cultivar in Senegal, West Africa Rice Research Brief No. 1, West Africa Rice Development Association (WARDA), Bouaké.

Wopereis M.C.S., Donovan C., Nebié B., Guindo D., N'Diaye M.K. (1999) Soil fertility management in irrigated rice systems in the Sahel and Savanna regions of West Africa, Part I – Agronomic analysis, Field Crops Res. 61, 125–145.

Wopereis M.C.S., Haefele S.M., Kebbeh M., Miézan K.M., Diack B.S. (2001) Improving the productivity and profitability of irrigated rice production in Sahelian West Africa, in: Proceedings of the Expert Consultation Meeting on Yield Gap and Productivity Decline in Rice Production at FAO, 5–7 September 2000, Food and Agriculture Organization of the United Nations (UN-FAO), Rome, pp. 117–142.

To access this journal online:
www.edpsciences.org