Combining Field and Simulation Studies to Improve Fertilizer Recommendations for Irrigated Rice in Burkina Faso

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COMBINING FIELD AND SIMULATION STUDIES TO IMPROVE FERTILIZER RECOMMENDATIONS FOR IRRIGATED RICE IN BURKINA FASO

ABSTRACT

Development of improved fertilizer recommendations entirely based on field experiments is time-consuming and costly. We employed a combination of two simulation models and selected field data to develop alternative fertilizer recommendations (AFR) for irrigated rice in Bagré, Burkina Faso. Existing fertilizer recommendations (EFR) are 82 kg N ha^{-1} (wet season) or 105 kg N ha^{-1} (dry season), 31 kg ha^{-1} P and 30 kg K ha^{-1}. The model RIDEV was used to improve timing of sowing date to avoid cold-induced sterility and timing of N fertilizer applications. The model FERRIZ was used to determine AFR, based on estimations of indigenous nutrient supply for N, P and K, yield potential (Y_{pot}), internal N, P, and K efficiency of rice, fertilizer N, P and K recovery fractions and fertilizer and rice prices. Simulations suggested decreasing P and K doses to 21 kg P ha^{-1} and 20 kg K ha^{-1} but to increase the N dose to 116 kg N ha^{-1} in the wet season (Y_{pot} = 8 t ha^{-1}) and to 139 kg N ha^{-1} in the dry season (Y_{pot} = 9 t ha^{-1}). AFR keeps the P-balance neutral, but a negative K balance was tolerated based on the high soil K supply. Compared to existing recommendations, yield gains of up to 0.5 t ha^{-1} were simulated at equal costs. These yield gains were more than confirmed in farmers' fields during four consecutive growing seasons. AFR increased gross returns above fertilizer costs by an average of about US$ 160 per season as compared to both farmers' practice and existing recommendations.

Keywords: Burkina Faso, simulation modeling, irrigated rice, nutrient management.

Abbreviations

AFR: alternative fertilizer recommendations; **DS**, dry season; **EFR:** existing fertilizer recommendations; **FP**: farmers' practice in terms of fertilizer use; **GRF**, gross return above fertilizer cost; **IS**: indigenous soil nutrient supply; **RF**: recovery fraction of applied fertilizer nutrients; **TFC**: total fertilizer cost; **WS**, wet season.

INTRODUCTION

Rice is developing as a major staple food item of Burkina Faso. Demand has grown at an annual rate of 3% between 1973 and 1992 compared to an annual population growth rate of 2.9%, which can be explained by changing consumer preferences (WARDA, 1996, Randolph, 1997). Currently, in-country production covers about 60% of the demand and 40% are met from imports. While irrigated lowlands comprise only about 20% of the total rice area, this system is characterized by considerable higher yields and contributes about 50% to national rice production (INERA, 2002). Irrigated systems were introduced in the 1960s and the development was accentuated from the 1970s onwards. Average yields of irrigated rice in Burkina Faso were estimated at 4.0 to 4.5 t ha^{-1} (Illy, 1997; Wopereis et *al*., 1999) and in general two crops per year are grown. This compares to average yields in the Sahelian and Savannah regions of 3.0 to 5.5 t ha^{-1}. The cropping intensity in Burkina Faso is higher than in most neighbouring countries (Matlon et *al*., 1996; Miézan and Sié, 1997; Wopereis et *al*., 2001).

Segda et al. (2004) conducted an agro-economic characterization study in one of the most important rice irrigated schemes in eastern Burkina Faso (Bagré irrigation scheme), where development of irrigation is ongoing. The analysis found agronomic constraints similar to the situation in other schemes of the region. Farmers' net benefits to irrigated rice cropping were mostly positive in the dry season (DS) but often low or even negative in the wet season

(WS). Yield gaps between average farmers' yield and best farmers' yield were high and indicated considerable scope for yield and profit increases in both seasons. The observed medium to low average yields are far below the level anticipated by authorities and irrigation scheme planners. Limited productivity combined with high input prices cause low profit margins, which subsequently reduce savings for maintenance of infrastructure and machines and the reimbursement of credit. At current productivity levels, the economic viability of the irrigation schemes in the Sahel can be questioned (Bélières et *al.* 1997). Productivity increases are necessary to maintain the economic sustainability of irrigated agriculture in the region.

Based on the agro-economic characterization study, Segda et al. (2004) concluded that the most promising ways to achieve higher productivity and input use efficiency are: (*i*) to improve timing and quality of crop management practices, and (*ii*) to improve existing fertilizer recommendations. Fertilizer recommendations in Burkina Faso have not changed since introduction of irrigated rice and are presently uniform over large areas and cut across diverse climatic and edaphic environments. Especially the widespread use of compound fertilizers, not tailored to the needs of the rice crop, constitutes an obstacle for optimization of nutrient management. Other factors included problems with collective and individual planning of the cropping calendar for double cropping of rice (two rice crops on the same field per year), and the need to also attend to rainfed crops outside the scheme.

To improve existing crop and nutrient management recommendations and practices, an integrated approach is vital, taking the farmers' socio-economic as well as bio-physical environment into account. Nutrient management for rice should focus on developing fertilizer recommendations for spatial domains with relatively uniform agro-ecological characteristics, cropping practices, and socio-economic conditions (Dobermann et al., 2002; 2003a and b). To reach that goal with agronomic trials is rather costly and time consuming, and simulation tools are increasingly used as a complement (Smaling, 1993). The present study used a framework for improved soil fertility management presented by Haefele et al. (2003a). This approach combines field data with simulation tools in a flexible framework. It helps the user to diagnose limiting factors as well as to develop soil fertility management strategies as a function of his or her goals, e.g. profit maximisation, yield maximisation or minimising risk, given biophysical and socio-economic settings.

This study intended to: (i) estimate climatic risk in Bagré for the two rice growing seasons and for different crop establishment modes and dates, (ii) develop agro-economically sound fertilizer recommendations for a range of target yields using the framework presented by Haefele et al. (2003a); and (iii) evaluate such model-based alternative recommendations in farmers' fields.

MATERIAL AND METHODS

Site description

The Bagré irrigation scheme (11º30'N, 0º25'W) is located in the eastern part of Burkina Faso, on the central plateau. The scheme is situated in the Boulgou province, approximately 150 km south-east of the capital Ouagadougou and about 50 km north of the border with Togo. The African basement complex and Precambrian sediments determine the geology of the region, but soils in the irrigation scheme are developed in alluvial sediments of Quaternary age. Frequent primary minerals are biotite and amphibole. Montmorrillonic and kaolinite are dominating clay minerals (BUNASOLS, 1994). Soils of the irrigation scheme (600 ha on the left bank of the Nakambe river) were classified according to the FAO soil classification (FAO, 1988) as Gleysols and dystric Fluvisols (62% of total area). Soil depth was on average between 0.4 to 1.2 m.

The climate is typical for the agro-ecological zone of the Sudan Savannah with average rainfall of 900 mm yr^{-1} in the wet season from July to October, followed by a cold dry season in November to February and a hot dry season from March to June. Minimum air temperatures below 15ºC occur in the cold dry season and maximum air temperatures above 40ºC occur in the hot dry season.

Irrigation for the Bagré irrigation scheme is gravity driven and is supplied from the Nakambe river (formerly White Volta). Cultivation of the first irrigation scheme started in 1997, in which the here presented study was conducted (Nimatoulaye scheme or V1 with a total area of 106 ha). The main crop is irrigated rice, which is cultivated in the wet season (WS; main sowing time from July to August) and the hot dry season (DS; main sowing time from January to February). Almost 100% of the irrigated area is cropped twice a year. Direct seeding and transplanting are both practiced. Existing fertilizer recommendations are 300 kg ha^{-1} "cotton fertilizer" ($N/P_2O_5/K_2O$ 12/24/12) applied basally or shortly after transplanting and 100 kg ha^{-1} urea (46/0/0) in the WS or 150 kg ha^{-1} urea in the DS. Recommended total NPK dose therefore is 82/31/30 kg ha^{-1} and 105/31/30 kg ha^{-1} in the WS and DS respectively. Urea is recommended to be top-dressed in two equal splits at early tillering and panicle initiation. Dominating cultivars are FKR19 (TOX 728-1) and FKR14 (4418). Apart from irrigated rice, most farmers grow rainfed maize, millet or sorghum in the surroundings of the scheme during the wet season and some farmers grow vegetables during the dry season. Most farmers also have some livestock (cattle).

Simulation tools

Two simulation tools were used to develop alternative fertilizer recommendations (AFR). The rice phenology model RIDEV (Dingkuhn, 1997) assists in the optimal timing of crop management interventions and a modified version of QUEFTS (Janssen et al., 1990) called

FERRIZ is used to calculate N, P and K doses for specific target yields. The framework and the simulation tool FERRIZ are described in detail by Haefele et al. (2003a). A short description of the models is given below.

RIDEV

The rice phenology model "RIce DEVelopment" (RIDEV) was developed by Dingkuhn (1997). It provides a time axis from germination to maturity depending on daily minimum and maximum temperatures and varietal constants. Furthermore, the percentage of spikelet sterility resulting from extreme temperatures can be estimated. Inputs for the model are daily minimum and maximum air temperature, photo-thermal constants of the cultivar used, sowing date, and establishment method (transplanting or direct seedling). The model was developed and validated for Sahel and Sudan Savannah regions and repeatedly used to analyse and improve farmers' crop management practices (e.g. Wopereis et al., 2003).

Actual weather data from the survey site were not available. Historical data (1969-1978) from the closest weather station (Fada N'Gourma, 12°05' N, 0°26' E; located at about 75 km from Bagré) were used for the simulations. Photo-thermal constants were chosen from a cultivar similar to the one mainly used by farmers (i.e. short duration cultivar IR13240-108-2-2-3 which resembles farmers' cultivar TOX 728-1).

FERRIZ

The model FERRIZ (Haefele et al., 2003a) is a modified version of the empiric and static model QUEFTS (Janssen et al., 1990). It can be used to estimate rice yields based on indigenous soil nutrient supply (IS) and potential yield (FERRIZ_Y), or to calculate N, P and K doses for specific target yields depending on IS and potential yield (FERRIZ_F).

Potential yield can be estimated using simulation models, like the ORYZAS model (Dingkuhn and Sow, 1997) as proposed by Haefele et al. (2003a), or estimated from best-farmer yields or from yields obtained at research stations under high-input conditions and optimal crop management. In our case, the ORYZAS model could not be used due to missing weather data on solar radiation. Dingkuhn and Sow (1997) observed a relationship between simulated potential grain yield (Y_{pot} at 14% moisture) and geographical latitude, separately for the dry and wet seasons. Following that relationship, we estimated that average Y_{pot} for sowing in February (DS) is about 9 t ha^{-1}, and average Y_{pot} for sowing in July (WS) is about 8 t ha^{-1}.

Parameters for maximum dilution and maximum accumulation of rice N, P and K uptake were included according to Witt et al. (1999) and Haefele et al. (2003b). Using data from farmers' surveys conducted under a wide range of environmental and crop management conditions, both studies defined borderlines of maximum dilution (*d*) and accumulation (*a*) of nutrients in modern rice cultivars as follows: *a*N = 42 kg paddy kg^{-1} N uptake and *d*N = 96 kg paddy kg^{-1} N uptake; *a*P = 206 kg paddy kg^{-1} P uptake and *d*P = 622 kg paddy kg^{-1} P uptake; *a*K = 36 kg paddy kg^{-1} K uptake and *d*K = 115 kg paddy kg^{-1} K uptake.

Recovery fractions (RF) are defined as the amount of fertilizer nutrient taken up by the crop, divided by the amount of fertilizer applied. In all FERRIZ_F simulations for the calculation of fertilizer doses, RFN was set to 0.45 kg kg^{-1}, RFP was set to 0.25 kg kg^{-1} and RFK was set at 0.45 kg kg^{-1}. These values represent average values observed in various field surveys (e.g. Witt and Dobermann, 2001; Haefele, 2001).

Indigenous soil N, P and K supplies and responses to N, P and K fertilizer application were determined using a fertilizer trial conducted in a farmer's field in the Nimatoulaye irrigation scheme during the 1999 dry season (DS, February sowing) and the 1999 wet season (WS, July sowing). Experimental treatments were chosen to provide optimal concentrations of two elements, whereas the remaining element was increased stepwise (Table 1). A randomized complete block design with four replications and thirteen different treatments was installed. Each sub-plot had a size of 6 m x 4 m. The short duration cultivar FKR14 (4418) was used and transplanted at a density of 25 hills m^{-2}. Fertilizer treatments were applied to the same plots in both seasons in a continuous rice-double cropping system. Nitrogen was applied as urea (46% N), P as triple-super phosphate (20% P), and K as KCl (50% K). P and K were broadcast with the first N-application (14 days after transplanting). The remaining two nitrogen splits were applied at panicle initiation and heading with doses according to Table 1. Grain yield was determined from a $6m^2$ area in the center of each subplot. Grain moisture content at harvest was determined with the Kett Grain moisture Tester Riceter J. P. Results from this trial were used to estimate nutrient (N, P and K) uptake in the subplots without N (0N subplot), without P (0P subplot) and without K (0K subplot) from dry season grain yield at 3% moisture, using conversion factors determined by Dobermann et al. (2003a and b). The conversion factor for N is 13.4 kg N per 1000 kg grain yield, the conversion factor for P is 2.9 kg P per 1000 kg grain yield and the conversion factor for K is 15.8 kg K per 1000 kg grain yield. Such estimates have a precision of about ± 5-10 kg N ha^{-1}, ± 2-3 kg P ha^{-1}, ± 10-20 kg K ha^{-1} (Dobermann et al., 2003a and b). The N uptake thus calculated in the 0N omission plot was considered a proxy for the indigenous soil supply of N, the P uptake calculated for the 0P plot was considered a proxy for the indigenous soil supply of P, and the K uptake calculated for the 0K plot was considered a proxy for the indigenous soil supply of K.

Developing site-specific nutrient management recommendations

RIDEV simulations of crop duration and sterility were conducted for the cultivar Sahel 108 (IR 13240-108-2-2-3), which is similar to short duration cultivar FKR 19 (TOX 728-1).

Simulations were conducted at 7-days intervals over a period of 10 years. The simulations used the dominant crop establishment techniques in each season, which is direct seeding in the dry season and transplanting in the wet season (Segda et al., 2004). Best timing of crop management interventions as a function of sowing date and risks of yield loss due to temperature extremes (low temperatures in WS and high temperatures in DS) were determined.

FERRIZ_F was used to calculate fertilizer doses for target yields ranging from 6.0 to 8.0 t ha^{-1} in 0.5 t ha^{-1} intervals in the dry season (Y_{pot} = 9.0 t ha^{-1}) and from 5.0 to 7.0 t ha^{-1} in the wet season (Y_{pot} = 8.0 t ha^{-1}). Total N, P and K uptake at harvest were estimated as well. Fertilizer costs were based on average prices for the 2003 and 2004 wet and dry seasons of the most commonly applied fertilizers in the Bagré plain, i.e. urea (247 FCFA kg^{-1}, containing 46% N) and "cotton fertilizer" (257 FCFA kg^{-1}, containing 12% N, 10.5% P and 10% K). The paddy price depends on the milling recovery rate, and the producers of Bagré achieved an average price of 101 FCFA per kg paddy over the four growing seasons in 2003 and 2004. The average exchange rate of the West African currency FCFA to the US dollar in the period 1 January 2003 – 31 December 2004 was US$ 1.00 = 554 FCFA.

The outcome of the FERRIZ_F simulations allowed the development of alternative fertilizer recommendations (AFR). FERRIZ_Y was then used to estimate yields and yield differences that can be expected from existing fertilizer recommendations (EFR) and from the alternative fertilizer recommendations (AFR) in both wet and dry seasons.

Validation trials

Three fertilizer treatments were tested with 7 farmers in the 2003 DS (February sowing), 14 farmers in the 2003 WS (July sowing), 17 farmers in the 2004DS (February sowing) and 12 farmers in the 2004WS (July sowing):

- *(i)* farmers' practice in terms of fertilizer use (FP);
- *(ii)* EFR, with urea applied in two splits; i.e. 35% at 15 days after transplanting and 65% at panicle initiation):
  - ➢ in the dry season: 105 kg N, 31 kg P, 30 kg K ha^{-1} as 300 kg 'cotton fertilizer' (N/P$_2$O$_5$/K$_2$O 12/24/12) and 150 kg urea ha^{-1}
  - ➢ in the wet season: 82 kg N, 31 kg P, 30 kg K ha^{-1} as 300 kg 'cotton fertilizer' and 100 kg urea ha^{-1}
- *(iii)* AFR, with urea applied in three splits: 3/8 at early tillering; 3/8 at panicle initiation and 2/8 at booting; timing of fertilizer application guided by RIDEV. Although AFR were developed for both WS and DS, farmers only adopted the 'low' AFR developed for the WS, i.e.: 116 kg N, 21 kg P and 20 kg K, as 200 kg 'cotton fertilizer' and 200 kg urea ha^{-1}

Farmers typically used short duration rice cultivar TOX 728-1, or similar short-stature high yielding cultivars. In each rice field (typically about 1ha in size), three subplots of 10 m x 10 m were installed to evaluate AFR, EFR and FP. For AFR and EFR, all management practices were left to the farmer, except fertilizer applications. For FP, all management practices, including fertilization were left to the farmer. At maturity, rice yields were obtained from a 6m^2 surface area in the center of each subplot and yields were corrected for 14% moisture. Profit margins from fertilizer use were determined for each treatment using prices for each season. Paddy rice price was 102 FCFA kg^{-1} during the 2003 DS and 2003 WS; 87 FCFA

kg^{-1} during the 2004 DS and 111 FCFA kg^{-1} during the 2004 WS. Urea price was 237 FCFA kg^{-1} during the 2003 DS; 230 FCFA kg^{-1} during the 2003 WS and 260 FCFA kg^{-1} in 2004. The complex cotton fertilizer price was 237 FCFA kg^{-1} during the 2003 DS, 250 FCFA kg^{-1} during the 2003 WS and 270 FCFA kg^{-1} in 2004.

Financial calculations were made on a per crop basis following Dobermann et al. (2002) using FCFA as standard currency:

$$TFC = P_N F_N + P_P F_P + P_K F_K$$

$$GRF = P_R Y_R - TFC$$

where TFC is the total fertilizer cost (FCFA ha^{-1}), GRF the gross return above fertilizer cost (FCFA ha^{-1}), Y_R the rice yield (kg ha^{-1}), P_R the price for rice (FCFA kg^{-1} paddy), P_N the price of N fertilizer (FCFA kg^{-1} N), P_P the price of P fertilizer (FCFA kg^{-1} P), and P_K the price of K fertilizer (FCFA kg^{-1} K), F_N the quantity of N fertilizer applied (kg N ha^{-1}), F_P the quantity of P fertilizer applied (kg P ha^{-1}) and F_K the quantity of K fertilizer applied (kg K ha^{-1}).

The incremental profitability of AFR (dGRF) was determined as the difference in gross returns above fertilizer costs between AFR and FP and between AFR and EFR:

$$dGRF = GRF_{AFR} - GR_{FP} \qquad \text{or}$$

$$dGRF = GRF_{AFR} - GR_{EFR}$$

RESULTS

Fertilizer response curves and indigenous soil nutrient supply

In the 1999 DS, observed mean grain yields in the N, P and K omission plots were 2.6 t ha^{-1} (0-N), 6.1 t ha^{-1} (0-P) and 6.3 t ha^{-1} (0-K). The same treatments yielded 2.5 t ha^{-1} (0-N), 3.2 t ha^{-1} (0-P) and 4.0 t ha^{-1} (0-K) in the 1999 WS. This indicated that mainly N and P were limiting yields and that indigenous K supply was considerable. The same conclusion can be drawn from the N, P and K response curves obtained with the same trial (Figure 1). Highest grain yields were achieved with 120 kg N ha^{-1} (both seasons), with 39 kg P ha^{-1} in the dry season and with 25 kg P ha^{-1} in the wet season. In both seasons, K application did not cause a significant yield increase. The almost linear response to P in the DS and the high yield level achieved suggests that the fixed P-dose chosen for the N-response curve was too low at high N application rates. Highest grain yield achieved in the experiment were 7.5 t ha^{-1} in the DS and 4.7 t ha^{-1} in the WS.

IS was estimated based on the N, P and K omission plots and empirical factors for N, P and K (Dobermann et al., 2003b). Using these factors (13.4 / 2.9 / 15.8 kg N / P / K per ton grain yield) and DS yields, the experimental field had an INS of 35 kg N ha^{-1}, an IPS of 18 kg P ha^{-1} and an IKS of 100 kg K ha^{-1}. Segda et al. (2004) estimated average N uptake in unfertilized plots in farmers' fields during the 2000 wet season at 37 kg N ha^{-1}, which is very close to the estimated INS in this trial.

RIDEV simulations

Table 2 shows optimal practices according to RIDEV for rice cultivar TOX 728-1. Mean values for simulations conducted at 7-days intervals over a period of 10 years are presented. The simulations address the dominant crop establishment techniques in each season, which is direct seeding in the dry season and transplanting in the wet season (Segda et al., 2004). The table shows best timing of crop management interventions as a function of sowing date (or transplanting) and indicates the risk of temperature induced yield losses. Transplanting after August 3 must be avoided. Assuming a preparation phase of about one month for the wet season and a dry season crop duration of 120 days, the dry season crop should be established by mid February latest to avoid dangerous delays of the onset of the WS. The wet season crop could then be harvested beginning of December.

Alternative fertilizer recommendations

To derive alternative fertilizer recommendations (AFR), FERRIZ_F simulations were conducted based on the indigenous supply of 35 kg N ha^{-1}, 18 kg P ha^{-1} and 100 kg K ha^{-1}, obtained from the nutrient-omission trial; fertilizer recovery rates of 0.45 kg kg^{-1} for N, 0.25 kg kg^{-1} for P, 0.45 kg kg^{1} for K, and Y_{pot} of 8.0 and 9.0 t ha^{-1}. Urea (46 % N) and "cotton" fertilizer (12% N, 10.5% P and 10% K) were used in the simulations (Tables 3 and 4), as these fertilizers are commonly used by farmers in the region.

Maximum target yields were set to 80% of potential yield as beyond that level, internal efficiencies of nutrients in the rice plant decline (Witt et al., 1999). About 80% of potential yield seems also to represent a ceiling for what can be achieved by best farmers under field conditions (Dobermann et al., 2002).

For the same target yield, higher fertilizer doses have to be applied when Y_{pot} is lower (Table 3). For high target yields, N, P and K have to be applied, whereas only N application is needed for low target yields. For optimal profit (marginal rate of return = 0), up to 135,000 FCFA must be invested in fertilizer in the dry season, which is above the investment made by most farmers. According to the field survey, farmers in Bagré spend on average 95,000 FCFA (maximum 125,000 FCFA) for total fertilizer costs (Segda et al., 2004). The comparison of applied N, P and K and aboveground plant uptake at the target yield indicates negative P and K balances for all simulation scenarios, when complete grain and straw removal is assumed (Table 3).

The outcome of the FERRIZ_F simulations illustrates the importance of N fertilizer as compared to P and K in Bagré. AFR were then derived based on estimated yield, NPK balance, costs and simplicity. We decided to reduce the NPK fertilizer dose as compared to existing fertilizer recommendations by 100 kg ha^{-1} and to increase the urea dose by 100 kg ha^{-1}. This does not entail increased costs but gives extra weight to N as compared to P and K.

AFR for the wet season were, therefore, defined as: 116 kg N ha^{-1}, 21 kg P ha^{-1}, and 20 kg K ha^{-1} and for the dry season: 139 kg N ha^{-1}, 21 kg P ha^{-1}, and 20 kg K ha^{-1}.

In order to compare the performance of the alternative recommendations versus the existing fertilizer recommendations (EFR), FERRIZ_Y was used to simulate yield and plant uptake with the same input data as above. Simulation results are given in Table 4. Existing fertilizer recommendations differ for the dry and wet season (105 kg ha^{-1} N, 31 kg ha^{-1} P, and 30 kg ha^{-1} K in the DS; 82 kg ha^{-1} N, 31 kg ha^{-1} P, and 30 kg ha^{-1} K in the WS), assuming a lower yield potential in the WS, but reduces only the N dose. Simulated yields with the higher dose were about 6.5 t ha^{-1}, whereas the lower dose resulted in yield estimates of about 6.0 t ha^{-1}. Nitrogen and P uptake were always below the applied amount, whereas K uptake was more than three times higher.

AFR increased estimated yields by 0.4 to 0.5 t ha^{-1} as compared to EFR. The balance between nutrients applied and plant uptake became more positive for N, balanced for P and even more negative for K. Simulations were also conducted for DS growing conditions, using the AFR developed for the WS as farmers were reluctant to accept the 'high' AFR doses, they preferred to use AFR developed for the WS for both seasons (see below). In this case AFR yields were comparable to EFR yields, but at substantially lower costs.

Validation experiments

The performance of existing and alternative fertilizer recommendations and farmers' practice were compared during the dry and wet seasons of 2003 and 2004 (Table 5). Farmers decided to test only the AFR developed for the WS in both seasons; AFR developed for the DS was considered not within financial reach of most farmers. The amount of fertilizer applied by the farmers themselves was indeed considerably lower than AFR and EFR rates. Farmers applied about 80 kg N ha^{-1}, 16 kg P ha^{-1} and 16 kg K ha^{-1}, but there was a large variability among farmers in terms of timing and dosage used (details not shown). Total fertilizer cost (TFC) was about 30,000 CFA ha^{-1} higher for AFR as compared to FP. TFC for AFR was substantially lower than EFR in the DS and about the same in the wet season. Gross returns above fertilizer cost (GRF) were most interesting for AFR, with differences between AFR and EFR ranging from 54,600 to 111,700 CFA per season, and between AFR and FP ranging from 34,400 to 147,300 CFA per season. Over the four seasons, EFR increased gross returns above fertilizer costs by an average of about FCFA 90,000 or about US$ 160 per season as compared to both farmers' practice and actual recommendations.

DISCUSSION

Fertilizer trials constitute an important tool to determine fertilizer doses, which help farmers to optimize the agro-economic returns to mineral fertilizer use and to maintain the natural resource base. In order to give sound advice, they should be conducted at several sites within a homogenous region and over several seasons to capture the effect of spatial soil variability and of temporal weather variability. Due to the African conditions of often limited financial means, both conditions can rarely be fulfilled. Further constraints are that most fertilizer trials in the region are conducted on-station where continuous high doses cause considerable residual effects not typical for farmers' fields. The approach used in this study allows using different data sources and employs simulation tools to circumvent some of these shortcomings.

The fertilizer trial used in this study was conducted in a farmer's field, thereby reflecting the influence of farmer crop management practices on soil fertility. Significant fertilizer responses were only observed for N and P (Figure 1). Clear yield increases due to N and P application and no or little effects of K application were observed repeatedly in several irrigation schemes in the West African Sahel and Savanna regions (Wopereis et al., 1999;

Haefele, 2001, Haefele et al., 2003a). Buri et al. (1999) reported high soil K levels for most flood plains in the same region. Considerable soil K reserves and little effect of farmer's fertilizer management (largely without K application) on extractable soil K in a Sahelian flood plain were shown by Haefele (2001). Highest yields in the trial were achieved with 120 kg N ha^{-1} and 39 kg P ha^{-1} in the DS and 120 kg N ha^{-1} and 26 kg P ha^{-1} in the WS.

Based on the NPK omission plots in the trial and empirical factors for NPK uptake in such plots (Dobermann et al., 2003b), IS for NPK was estimated. Indigenous N supply estimated for the trial site was very close to the average INS measured in the 1999-2000 survey for farmers' fields (Segda et al., 2004). No survey measurements for IPS and IKS were available.

Estimates of IS for N, P and K and other input parameters (potential yield, fertilizer recovery fractions and input prices) allowed to calculate economically optimal yields and determine fertilizer doses for specific target yields with FERRIZ_F (Table 3). The dominant N limitation is showing clearly in the simulations, but they also indicate that at current IS levels no P or K application would be necessary up to target yields of 6.5 t ha^{-1}. Such a strategy would be highly beneficial in the short term (low costs and high target yield), but comparison of nutrient input and plant uptake shows that this would result in negative P and K balances.

Knowing the low soil P reserves and their rapid depletion in West African flood plains (Buri et al., 1999; Haefele et al., 2004), a balance between P application and plant uptake was targeted for the site-specific nutrient management recommendations (Table 3). In comparison to existing recommendations, this can be achieved with lower compound fertilizer doses, allowing an increased N dose at identical cost levels.

A relative increase of N was repeatedly recommended and successfully tested in West African irrigated rice-based systems (Wopereis et al., 1999; Donovan et al., 1999, Haefele et al., 2000, 2002), and the simulations show that this strategy increases profits over the existing recommendation especially at higher Y_{pot}. The simulations also show that mainly N needs to be adjusted to Y_{pot}, whereas P and K doses can be maintained stable. This opens the way to real-time N management strategies. Adjustment of N doses to rice crop appearance (i.e. leaf color chart) was successfully tested in Asia (Balasubramaniam et al., 1999) and has high potential in African environments too. Even though the compound fertilizer dose was reduced, the P dose is still high and close to the dose achieving optimal responses in the fertilizer trial (Figure 1).

As average farmers' yield increases from the current level of about 3.6 (WS) to 4.9 t ha^{-1} (DS) to the simulated yield of 6.5 to 6.9 t ha^{-1}, actual P balances will still remain positive. The K balance based on K input and plant K uptake became more negative as compared to the existing recommendation, but it assumes complete straw removal, no other K inputs and average yields close to 6.5 to 6.9 t ha^{-1}. Considerable K inputs can be expected from dust deposition (Hermann, 1996), and remaining stubbles as well as straw application (in the form of compost or manure) can reduce the negative balance considerably. Together with the high soil K reserves discussed above and the current absence of K response, a strategy of slow soil K mining seems more adequate than a soil K maintenance strategy. Saving the investment for soil K maintenance in the near future might help African rice farmers to compete better with cheap imports. Higher K doses would become adequate when K responses can be observed and when farmers reach a higher productivity level.

The simulated yield and profitability gains were more than confirmed in farmers' fields during four consecutive growing seasons. In all seasons, AFR yields were considerably higher than EFR or FP yields, and yield gains were significant ($p<0.05$) in 2004 (Table 5). Yield gains from AFR were larger than simulated, probably because for AFR, fertilizer N was applied in three splits, ensuring better balanced crop nutrition as compared to farmer practice and EFR where only two N splits were used. Similar results were obtained by Wopereis-Pura et al. (2002). Monitoring INS, IPS and IKS every five to ten years with omission plots in farmers fields as proposed by Dobermann et al. (2003a) and the here presented framework may serve to readjust AFR in the future.

Segda et al. (2004) found low economic returns to investment in fertilizer, particularly in the wet season (Segda et al., 2004). It was concluded that sub-optimal timing of crop management practices and sub-optimal fertilizer management were the most important single factors contributing to the observed low efficiency. This is especially true for the WS sowing date as can be seen from Table 2. Relatively small delays in crop establishment can cause significant yield losses. Sowing after the first week in August increased the risk of cold sterility tremendously. The RIDEV simulation results were confirmed by the low yields of farmers with late sowing in the WS (Segda et al., 2004), and cold sterility due to late sowing date might be the main reason for low economic returns of many farmers in the WS. This confirms results reported by Nebié (1995), who set August 15 as a threshold date for transplanting. Without knowledge of these processes, it is extremely difficult for farmers to relate the occurrence of low minimum temperatures around panicle initiation with spikelet sterility. With a tight cropping calendar for rice double cropping and additional activities in surrounding rainfed fields, delays in establishment are easy to understand. Since such delays can have tremendous effects, farmers must understand the consequences of a late start in the WS in order to react adequately. The frequent occurrence of cold damage in the simulations over ten years indicate that in the case of a delay, not to grow rice seems the better alternative. Spikelet sterility due to high daily maximum temperatures in the DS as reported from irrigated schemes further north (e.g. the Office du Niger in Mali; Dingkuhn and Sow, 1997) does not seem to be an important problem in the region. Nevertheless, farmers should establish the DS crop in January or until mid February latest since delayed start of the DS is in most cases directly related to a late start of the WS. RIDEV derived recommendations on optimal timing of crop management practices during the season (Table 2) can further contribute to higher fertilizer efficiency and should be part of integrated crop management options. Such approaches were successful in similar rice-based systems in West Africa (Kebbeh and Miézan, 2003).

CONCLUSIONS

Surveys conducted in irrigated rice-based systems in West Africa have demonstrated that considerable potential exists to improve rice productivity in these systems through improved crop management, with improved soil fertility management as a key factor. Low productivity not only threatens the economic survival of individual farmers, but also puts at risk the sustainability of entire irrigation schemes. However the need to work with farmers on alternatives to current, often out-dated, fertilizer recommendations collides with African reality, where limited financial means do not allow large scale research activities. The presented case study used a framework of simulation models and available field data to develop improved nutrient and crop management recommendations for increased agro-economic productivity at current input levels. This approach is, in principle, relatively cheap but requires skills that are unfortunately still relatively rare in West Africa.

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CAPTIONS OF FIGURES

Figure 1: Grain yields in the nutrient omission trial at Bagré during the dry and wet seasons 1999. In (**a**) N doses applied varied, in (**b**) P doses and in (**c**) K doses. Fixed mineral fertilizer doses were 120 kg N ha^{-1} in (b) and (c), 13 kg P ha^{-1} in (a) and (c) and 25 kg K ha^{-1} in (a) and (b). Fertilizer response curves based on quadratic functions (a and b) or linear function (c) are included for data sets with significant yield response to fertilizer application.

Table 1. Fertilizer treatments and nitrogen splits at early tillering (ET), panicle initiation (PI) and booting (B) in the fertilizer trial in farmers' field during the dry season 1999 and the wet season 1999 in Bagré, Burkina Faso.

Treatment	Total N dose (kg ha^{-1})	N applied at ET (kg ha^{-1})	N applied at PI (kg ha^{-1})	N applied at B (kg ha^{-1})	Total P dose (kg ha^{-1})	Total K dose (kg ha^{-1})
T1	0	0	0	0	13.1	24.9
T2	60	25	25	10	13.1	24.9
T3	90	40	40	10	13.1	24.9
T4	120	40	40	40	13.1	24.9
T5	150	50	50	50	13.1	24.9
T6	120	40	40	40	0	24.9
T7	120	40	40	40	6.5	24.9
T8	120	40	40	40	13.1	24.9
T9	120	40	40	40	26.2	24.9
T10	120	40	40	40	39.2	24.9
T11	120	40	40	40	13.1	0
T12	120	40	40	40	13.1	24.9
T13	120	40	40	40	13.1	49.8

Table 2. RIDEV estimated cropping calendars using 7 days intervals for direct-seeded (dry season) or transplanted (wet season) rice, cultivar TOX 728-1, Bagré (Burkina Faso). DAS = days after sowing.

Sowing date	Transplanting date	First weeding (DAS)	First urea split (DAS)	Second urea split (DAS)	Third urea split (DAS)	Flowering Date (DAS)	Date of last drainage (DAS)	Harvest date (DAS)	Spikelet sterility (%)	Risk of sterility > 20% (No. of years/10 years)
Direct seeding										
01 Jan		29	32	58	78	88	103	117	2.7	0
08 Jan		29	32	56	76	87	101	115	3.7	0
15 Jan		28	31	54	74	85	99	113	6.8	0
22 Jan		25	28	53	73	83	98	112	7.8	0
29 Jan		25	28	52	72	82	97	111	8.5	0
05 Feb		22	25	50	70	81	95	110	6.2	0
12 Feb		21	24	50	70	80	95	109	2.3	0
19 Feb		20	23	49	69	79	94	109	0.6	0
	*Transplanting**									
25 June	20 July	39	42	73	93	97	118	133	0.9	0
02 July	27 July	39	42	72	92	97	117	134	6.1	1
09 July	03 August	39	42	72	92	97	117	134	22.5	4
16 July	10 August	39	42	71	91	97	116	136	37.7	6
23 July	17 August	36	39	67	87	98	112	137	48.8	10
30 July	24 August	39	42	70	90	101	115	140	71.7	10
06 Aug.	31 August	39	42	71	91	104	116	143	72.9	10
13 Aug.	07 September	39	42	72	92	108	117	146	84.4	10

* Transplanting is recommended 25 days after sowing.

Table 3. Simulated N, P and K requirements to reach specific target yields in the Bagré plain, depending on potential yield (Y_{pot}). Included are yield levels (Y_{pot}). All data are based on simulations with FERRIZ_F using indigenous supply of 35 kg N ha^{-1}, 18 kg P ha^{-1} and 100 kg K ha^{-1} and fertilizer recovery rates of 0.45 kg kg^{-1} for N, 0.25 kg kg^{-1} for P, and 0.45 kg kg^{-1} for K. Average fertilizer prices are used for 2003-2004.

Y_{pot} (t ha^{-1})	Target yield (t ha^{-1})	Urea dose (kg ha^{-1})	NPK dose (kg ha^{-1})	NPK applied (kg ha^{-1})			Nutrient uptake at target yield (kg ha^{-1})			Fertilizer costs (1000 FCFA ha^{-1})
				N	P	K	N	P	K	
9.0	8.0	425	275	229	28.2	27.4	139	25.5	116	175.7
	7.5	400	150	202	15.7	14.9	127	22.2	111	137.4
	7.0	350	50	167	5.2	5.0	111	19.6	106	99.3
	6.5	275	0	127	0.0	0.0	93	18.3	104	67.9
	6.0	200	0	92	0.0	0.0	77	18.3	104	49.4
8.0	7.0	370	150	188	15.7	14.9	121	22.2	111	129.9
	6.5	300	50	144	5.2	5.0	101	19.6	106	87.0
	6.0	225	0	104	0.0	0.0	83	18.3	104	55.6
	5.5	175	0	81	0.0	0.0	72	18.0	104	43.2
	5.0	125	0	58	0.0	0.0	62	18.0	104	30.9

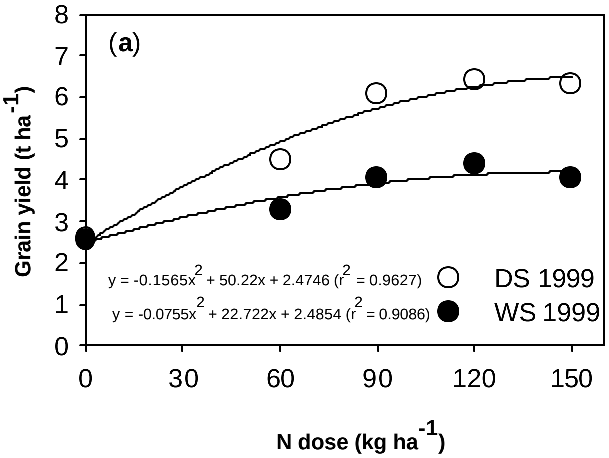
Table 4. Simulated yields, yield gains and NPK uptake using alternative (AFR) and existing fertilizer recommendations (EFR) for the Bagré plain during the dry season (DS) and the wet season (WS). Target yields were simulated using FERRIZ_Y and average indigenous soil nutrient supply of the nutrient omission trial. Estimated total fertilizer costs were calculated using average prices in 2003-2004. Simulations were based on: indigenous supply of 34.6 kg N ha^{-1}, 17.6 kg P ha^{-1} and 99.7 kg K ha^{-1}: fertilizer recovery rates of 0.45 kg kg^{-1} for N, 0.25 kg kg^{-1} for P, 0.45 kg kg^{-1} for K.

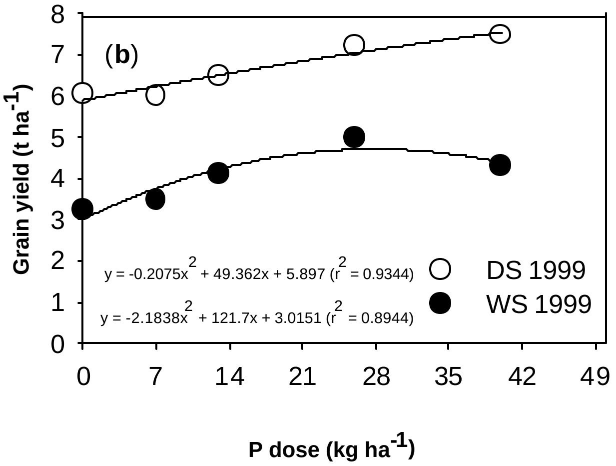
Season *	Fertilizer recom.	Y_{pot}	Urea dose	NPK dose	N dose	P dose	K dose	Yield estimate	NPK uptake	Fertilizer costs	Yield gain (AFR-EFR)
		t ha^{-1}	-----------------kg ha^{-1}----------------					--t ha^{-1}--	-----kg ha^{-1}-----	1000 FCFA ha^{-1}	----t ha^{-1}----
DS	EFR	9.0	150	300	105	31.4	29.9	6.52	82/23.0/108	114.2	
WS	EFR	8.0	100	300	82	31.4	29.9	6.00	72/22.3/105	101.8	
DS	AFR	9.0	250	200	139	20.9	19.9	6.92	96/21.7/106	113.2	0.40
DS	*	9.0	200	200	116	20.9	19.9	6.56	86/21.3/105	100.8	0.04
WS	AFR	8.0	200	200	116	20.9	19.9	6.46	86/21.3/105	100.8	0.46

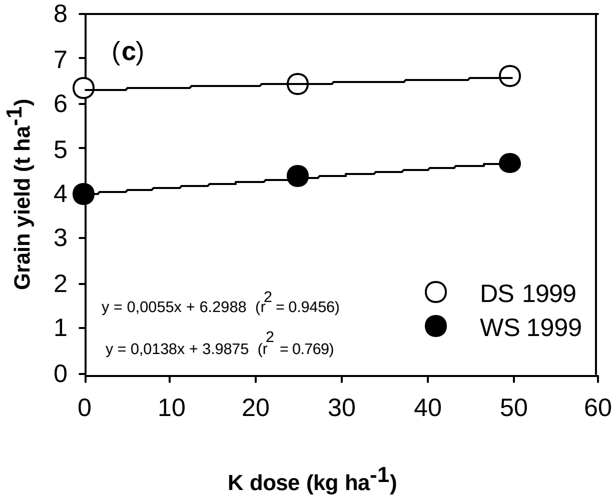
* AFR for wet season applied to dry season to save on fertilizer costs – as preferred by farmers in the validation trials

Table 5. Effect of farmers' practice in terms of fertilizer use (FP), existing fertilizer recommendations (EFR) and alternative fertilizer recommendations (AFR) on paddy yield, total cost of fertilizer (TFC) and gross return above fertilizer cost (GRF) during the dry and wet seasons of 2003 and 2004 (DS03, DS04, WS03, WS04), Bagré, Burkina Faso. N/P/K fertilizer use for EFR in DS: 105/31/30 kg ha^{-1}, in WS: 82/31/30 kg ha^{-1}; for AFR regardless of season: 116/21/20 kg ha^{-1}. See text for prices of fertilizer and paddy per season. Yield and GRF data followed by a common letter are not significantly different (Newman-Keuls test, p = 0.05, tests per season).

Variable	**Season**	**Treatment**	**Cases**	**Average**	**SD**	**Min**	**Max**
Yield (t ha^{-1})	DS03	FP	7	4.03 a	1.93	1.10	6.50
		EFR	7	5.35 a	1.70	3.17	7.00
		AFR	7	5.77 a	1.58	3.50	7.67
	WS03	FP	13	5.92 a	1.05	4.04	7.17
		EFR	13	5.90 a	0.89	4.17	6.83
		AFR	13	6.50 a	0.96	4.50	7.29
	DS04	FP	17	6.33 a	1.27	4.17	8.67
		EFR	17	6.43 a	14.30	3.92	8.83
		AFR	17	7.48 b	1.15	5.00	9.50
	WS04	FP	12	4.53 a	0.94	2.92	4.53
		EFR	12	5.02 a	1.31	2.54	7.17
		AFR	12	6.01 b	0.95	4.17	7.46
N fertilizer (kg ha^{-1})	DS03	FP	7	78.7	13.6	64.0	104.0
	WS03	FP	13	80.2	17.4	58.0	110.0
	DS04	FP	17	83.6	17.0	58.0	116.0
	WS04	FP	12	72.2	12.7	58.0	93.0
P fertilizer (kg ha^{-1})	DS03	FP	7	14.2	4.0	10.5	21.0
	WS03	FP	13	17.5	5.5	10.5	31.4
	DS04	FP	17	16.3	3.6	10.5	21.0
	WS04	FP	12	16.2	3.5	10.5	21.0
K fertilizer (kg ha^{-1})	DS03	FP	7	13.5	3.8	10.0	19.9
	WS03	FP	13	16.7	5.2	10.0	29.9
	DS04	FP	17	15.5	3.5	10.0	19.9
	WS04	FP	12	15.4	3.3	10.0	19.9
TFC (1000FCFA ha^{-1})	DS03	FP	7	64.3	9.3	53.3	77.0
		EFR	7	106.7	0	106.7	106.7
		AFR	7	94.8	0	94.8	94.8
	WS03	FP	13	71.9	17.0	48.0	109.5
		EFR	13	98.0	0	98.0	98.0
		AFR	13	96.0	0	96.0	96.0
	DS04	FP	17	78.8	14.0	53.0	106.0
		EFR	17	120.0	0	120.0	120.0
		AFR	17	106.0	0	106.0	106.0
	WS04	FP	12	72.0	12.0	53.0	93.0
		EFR	12	107.0	0	107.0	107.0
		AFR	12	106.0	0	106.0	106.0
GRF (1000FCFA ha^{-1})	DS03	FP	7	346.6 a	188.6	58.9	592.0
		EFR	7	439.3 a	173.0	216.4	607.4
		AFR	7	493.9 a	161.6	262.2	687.2
	WS03	FP	13	532.3 a	103.6	334.0	646.5
		EFR	13	503.5 a	91.0	327.0	599.0
		AFR	13	566.7 a	97.6	363.0	648.0
	DS04	FP	17	471.8 a	104.7	283.5	661.0
		EFR	17	439.4 a	113.5	220.8	648.5
		AFR	17	544.5 b	99.9	329.0	720.5
	WS04	FP	12	431.2 a	103.1	243.8	576.0
		EFR	12	449.8 a	145.0	175.1	688.5
		AFR	12	561.5 b	105.4	356.5	721.9


(a)
Grain yield (t ha-1)
N dose (kg ha-1)
0
1
2
3
4
5
6
7
8
0
30
60
90
120
150
y = -0.1565x2 + 50.22x + 2.4746 (r2 = 0.9627)
y = -0.0755x2 + 22.722x + 2.4854 (r2 = 0.9086)
○ DS 1999
● WS 1999


(b)
Grain yield (t ha-1)
P dose (kg ha-1)
0
1
2
3
4
5
6
7
8
0
7
14
21
28
35
42
49
y = -0.2075x2 + 49.362x + 5.897 (r2 = 0.9344)
y = -2.1838x2 + 121.7x + 3.0151 (r2 = 0.8944)
○ DS 1999
● WS 1999


(c)
Grain yield (t ha-1)
K dose (kg ha-1)
0
1
2
3
4
5
6
7
8
0
10
20
30
40
50
60
y = 0,0055x + 6.2988 (r2 = 0.9456)
y = 0,0138x + 3.9875 (r2 = 0.769)
○ DS 1999
● WS 1999