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Spatial and temporal variation in yield of rainfed lowland rice in inland valley as affected by fertilizer application and bunding in North-West Benin

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ABSTRACT

Rainfed lowlands in inland valleys present a high potential for rice (*Oryza* spp.) production in West Africa. However, rice yield in the lowlands is, in general, low due to various constraints such as poor soil fertility, drought, iron (Fe) toxicity, and poor crop management practices. The objective of this study was to evaluate the efficiency of bunding and fertilizer application for improving rice productivity in the two toposequential positions (upslope and downslope positions) in an inland valley. The experiment was conducted in a researcher-managed on-farm trial located in the North West of Benin Republic over four wet seasons (2007–2010). In addition to the toposequential positions, the experiment included two treatments: (1) fertilizer inputs: no fertilizer and fertilizer (60 kg N and 40 kg P ha^{-1}) and (2) water control: with and without bunds (without drainage). Effect of bunding on rice yield was consistent across four seasons, two fertilizer application treatments, and two toposequential positions, and bunding increased rice yield by 29%. Rice yield was higher in upslope than in downslope, except for 2010. In upslope, high ponded water level in 2010, due to higher rainfall than in other years, increased Fe toxicity, resulting in lower yield in 2010. Year-to-year variation in yield response to fertilizer application was related to differences in N uptake at 38 days after sowing. When Fe concentration in leaves was lower, N uptake was higher. Thus, Fe toxicity at early stage could contribute to yield response to fertilizer application. These results indicate that while bunding is essential for improving rice productivity, improving yield response to fertilizer application requires drainage systems in the areas where risk for Fe toxicity is high.

1. Introduction

Inland valleys constitute over 38% of the total wetlands in the sub-Saharan Africa and are cropped extensively with rainfed lowland rice in the wet season (WARDA, 2008). Rainfed lowland rice is grown on level to slightly sloping, unbunded or bunded fields, which are flooded by rains and groundwater for part of the rice-growing season, although in some seasons fields may not be flooded due to lack of rainfall. Rainfed lowland rice is also grown in flash-flood areas, where water level is suddenly increased during the rice-growing season, causing short-term submergence. On-farm yield level is generally low due to various biophysical constraints and poor crop management practices (Becker and Johnson, 2001; Touré et al., 2009). Furthermore, in inland valleys, natural resources (particularly water and soil resources) are strongly correlated with their position in the toposequence (Homma et al., 2003; Tsubo et al., 2006; Haefele et al., 2006). Thus, better understanding of the yield determining factors in rainfed lowland rice cropping is prerequisite for developing good agricultural practices.

Major difference between Asia and West Africa in rainfed lowland rice cropping is that most of fields in West Africa have no water control such as bunds or drainage system. It has been demonstrated that bunds could improve productivity by 30–100% of yield increase in Tanzania (Raes et al., 2007). Applied nitrogen efficiency of rainfed lowland rice is improved by the bund with gain due of 10–12 kg grain kg^{-1} in Cote d'Ivoire (Becker and Johnson, 2001; Asubonteng, 2001; Touré et al., 2009). In field experiments, bunds

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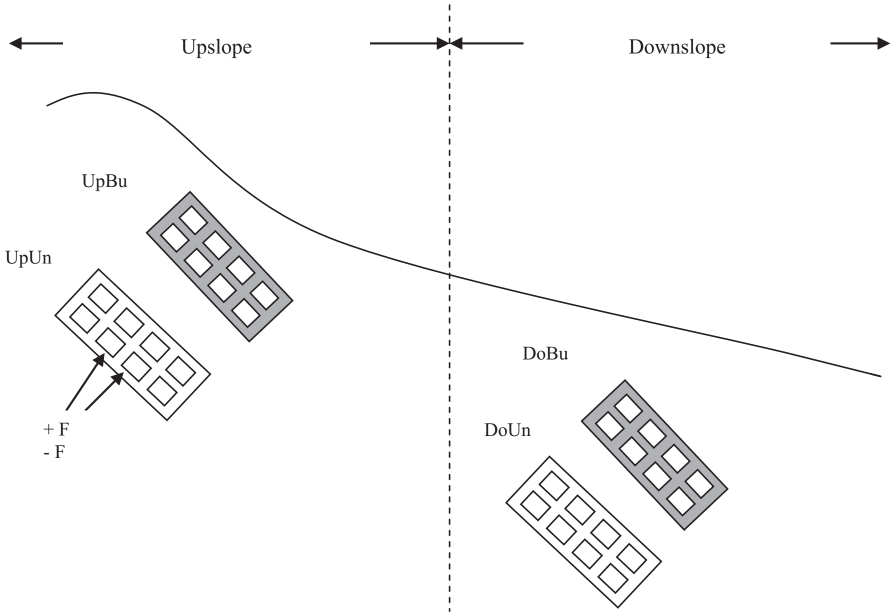

Fig. 1. Experimental layout and treatments in the Dogué field trial in 2007, 2008, 2009 and 2010. Bund and without bund blocks are located at the same slope position. UpUn: upslope without bund, UpBu: upslope with bund, DoUn: downslope without bund, DoBu: downslope with bund; +F: with fertilizer, −F: without fertilizer application; Each main plot of UpUn, UpBu, DoUn and DoBu contains 4 replicates of each fertilizer application level (with and without fertilizer).

on the slope were used as runoff trapping. If rainfall is too abundant or too intense to be absorbed by the soil, it has to be collected in order to trap the runoff water before it gathers enough energy to run downslope (Roose, 1996). Given the roughness of the soil surface, the micro relief of the land and the risk of damage by excess rainfall, a bund height of 0.3 m is recommended for plots of maximum 0.10 ha. However, little information is available on the effects of bunding and fertilizer application on rice yield in Benin Republic, where the major part of rainfed lowland rice is grown with traditional practices without bunds in inland valleys and flood plains and the development of bunds has been promoted recently (MAEP, 2011).

Furthermore, iron (Fe) toxicity in the soil is considered as one of the major constraints to rice production in rainfed lowlands in West Africa (Becker and Asch, 2005). The reductive conditions found in lowland soils are a prerequisite for the development of iron toxicity through the solubilization of virtually all iron compounds in the soil into its ferrous form (Fe^{2+}). Two levels of toxicity can be observed in the wetland system: the primary iron toxicity explained by an apparent sensitivity of rice seedlings to high amounts of Fe^{2+} accumulated just after flooding, while secondary iron toxicity may be described by the excessive Fe^{2+} uptake caused by an increased root permeability and enhanced microbial iron reduction in the rizosphere (intensive exudation) during the physiologically active phase between heading and flowering (Prade et al., 1986). Fe toxicity can be also linked to nutritional imbalances due to low availability of P, K, Zn, Ca or Mg rather than to a high content of soluble iron in the soil solution. Therefore, iron concentration in the leaf tissue is a much better indicator for the occurrence of iron toxicity than extractable iron in collected soil samples.

High iron can reduce the uptake of other minerals such as nitrogen (N) and phosphorus (P) by rice plants (Yoshida, 1981; Diatta and Sahrawat, 2005), and consequently reduce rice yield (Chérif et al., 2009). Increased ponded water level due to development of bunds to avoid water stress may increase risk for Fe toxicity, resulting in reduced rice yield or fertilizer use efficiency. However, it is little known about the effects of bunding and fertilizer application on rice yield in the areas where Fe toxicity is one of major constraints. Therefore, the objectives of this study were to quantify the effects of toposequential position, bunding and fertilizer application and their interactions on growth and yield of rainfed lowland rice in an inland valley in North-West Benin, and to examine if year-to-year variation in climate condition impacted the results.

2. Materials and methods

The experiment was conducted in a researcher managed on-farm trial over 4 years (2007–2010) and located in Dogué village (latitude 9°05′ N, longitude 01°55′ E), in southern Donga district, North West of Benin Republic. The site is characterized by ferruginous tropical soils in the well-drained areas. The slope with an inclination of 3% is situated between an upland with sandy loams overlying ironstone and the valley bottom with more hydromorphic and loamy soils. According to FAO soil classification the soils at the upslope are Lixisols and at the lower slopes Gleysols.

The experiment was conducted in two toposequential positions: upslope (up) and downslope (down). In each toposequential position, there were two water control treatments: with and without bund (Fig. 1). In this study, we did not install drainage system in the bunded plots. Then, in each water control treatment, fertilizer treatments were arranged with split plot design with four replications, and the same layout was used for the four years. Fertilizer treatments included no fertilizer application and mineral fertilizer at a rate of 60 kg N and 40 kg P ha^{-1}. Plot size was 5 m × 5 m including the bunds. In the bund treatment, bunds of 0.2–0.3 m height were built around each plot, thus preventing water to runoff. Bunds were re-built every year or repeatedly during the rainy season when necessary.

Rice was grown in every rainy season (June–November) and every cropping cycle was separated by a fallow period during the dry season (December–May). After clearing and removing the fallow vegetation grown in the dry season, the land was hand ploughed. The lowland rice variety 'NERICAL-26' was dibble seeded at hill density of 0.2 m × 0.2 m and thinned to 2 plants per hills. The sowing date varied between years: 18, 1, 7 and 3 July in 2007, 2008,

Table 1
Soil physical and chemical properties of the 0–20 cm layer in Dogué experimental field trial (*n* indicates the number of samples, SD is the standard deviation).

Soil properties	Unit	Upslope ($n = 16$)		Downslope ($n = 16$)	
		Mean	SD	Mean	SD
Physical properties					
Fine earth (elements < 2 mm)	%	96	4.0	90	7.0
Sand	%	39	–	25	–
Clay	%	4	–	19	–
Chemical properties					
pH (H_2O)	–	5.4	0.27	5.6	0.34
C_{org}	%	0.65	0.07	0.93	0.27
Total N	%	0.039	0.005	0.064	0.015
Bray P	ppm	1.2	0.64	1.8	0.98
CEC	cmol kg^{-1}	4.2	0.56	5.5	1.36
K^+	cmol kg^{-1}	1.64	0.53	2.36	1.41
Ca^{2+}	cmol kg^{-1}	0.19	0.17	0.23	0.13
Mg^{2+}	cmol kg^{-1}	0.56	0.08	0.69	0.18
Na^+	cmol kg^{-1}	0.00	0.00	0.03	0.04

2009 and 2010, respectively. Weeding was carried out when necessary. Harvest was carried out on 17, 7, 6 and 19 November in 2007, 2008, 2009 and 2010, respectively. All crop residues were removed from the plots after harvest.

Rice plants were cut at the ground level after maximum tillering period at 38 days after sowing (DAS) from randomly selected two areas of 1 m × 1 m in each plot. The samples were weighed after 72 h oven drying. Then, they were extracted for analyses of Fe and N concentration with one bulk sample over all repetitions per treatment for Fe and two bulk samples for N in 2007, with two repetitions for both Fe and N in 2008, whereas in 2009 and 2010, Fe and N analysis was performed on all 4 repetitions. Fe concentration was determined by atomic absorption spectrometry and the total N with a CNS auto-analyzer. At maturity, rice plants were harvested at two randomly selected 1 m × 1 m areas in each plot. The grain weight was determined after 72 h oven drying.

Soil samples for each plot were collected in 2006 during the fallow period from 0 to 0.2 m depth. Soil texture was determined using pipette method (Gee and Or, 2002). Organic carbon estimation was made using Walkley and Black method (1934). The total N in the soil was measured with the Kjeldahl method (1883). The exchangeable bases were extracted with ammonium acetate and measured by spectro-photometry with atomic absorption. Cation exchange capacity (CEC) was determined by an extraction with barium chloride followed by leaching, exchange with Na^{2+} and measurement by atomic absorption. Available phosphorus was determined by the Bray method (Bray and Kurtz, 1945). The contents of clay, organic carbon, and total nitrogen in the soil were lower in upslope than in the downslope. CEC and available P were not largely different between the two positions (Table 1).

Ponding of water occurred in both bunded and unbunded plots due to the low slope inclination and constant flow of run off water from the uplands after longer rainfall periods. During the appearance of ponded water level was recorded 1–3 times per week during the rice growing season. Daily climate data were collected from a nearby research climate station at about 1 km from the field.

Data were analyzed with PROC mixed procedure using the restricted maximum likelihood (SAS Institute Inc., 2001) for variance estimation for slope. The Tukey test was used for mean separation, when the analysis of variance showed a significant factorial effect. The significance level was fixed at $p < 0.05$. Regression analysis was applied to identify the causes for variation in rice yield.

3. Results and discussion

The rainfall pattern in the study site was characterized by monomodal distribution (Fig. 2). Total rainfall during the growing period from July–November was 793, 833, 690 and 1191 mm in 2007, 2008, 2009 and 2010, respectively. Monthly rainfall was higher in 2010 in all the rice growing seasons, except for November. Although rainfall was very low in September in 2009, the onset of the dry season was a bit later. Average ponded water level over all the growing

Table 2
Effects of position (P), bund (B), fertilizer (F) and year variation (Y) on grain yield, N leaf content (N plant) and Fe concentration for 4 years combined. d.f.: degree of freedom; DDF: denominator degree of freedom of covariance parameters.

Factors	d.f.	DDF	*F* ratio			
			Grain yield	N concentration of rice plants at 38 DAS[a]	Fe concentration of rice plants at 38 DAS	Mean water table (cm) before 38 DAS
Y	3	84	0.03	<0.0001	<0.0001	0.0001
P	1	12	ns[*]	0.03	<0.0001	0.02
B	1	12	0.03	0.002	ns	0.03
F	1	84	0.0001	ns	ns	ns
YxP	3	84	<0.0001	ns	<0.0001	0.0002
YxB	3	84	ns	ns	0.04	<0.0001
YxF	3	84	0.03	ns	ns	ns
PxB	1	12	ns	ns	0.01	ns
BxF	1	84	ns	ns	ns	ns
FxP	1	84	ns	ns	<0.0001	ns
BxPxF	1	84	ns	ns	ns	ns
PxBxY	3	84	ns	ns	ns	0.008
FxBxY	3	84	ns	ns	ns	ns
PxFxY	3	84	ns	ns	0.02	ns
FxBxPxY	3	84	ns	ns	ns	ns

[a] Days after sowing.
[*] Not significant at the <0.05 probability level.

Table 3
Main factors effect on mean grain yield, mean N content and Fe concentration by year in Dogué field trials. Main effect means (year, slope position, water control and fertilizer) followed by different letters are significantly different within the main effect at $p < 0.05$.

Factors	Grain yield ($Mg\,ha^{-1}$)	N concentration of rice plants at 38 DAS (%)	N uptake of rice plants at 38 DAS ($kg\,ha^{-1}$)	Biomass at 38 DAS ($Mg\,ha^{-1}$)	Fe concentration of rice plants at 38 DAS (ppm)	Mean ponded water level growing season (cm)	Mean ponded water level before 38 DAS (cm)
Year effect							
2007	3.8b	1.7c	0.38d	0.02c	670a	1.5c	0.9c
2008	4.1ab	2.1b	0.75b	0.03b	411b	1.7bc	1.5b
2009	4.4a	2.4a	1.26a	0.05a	206b	2.9b	1.8 ab
2010	4.4a	2.1 b	0.50c	0.02c	648a	2.5a	2.1 a
Position effect							
Upslope	4.56a	2.17a	0.81a	0.03a	379.47b	0.99b	0.85b
Downslope	3.66a	1.97b	0.61b	0.02a	588.07a	2.81a	2.33a
Water control effect							
Bund	4.63a	2.23a	0.74a	0.03a	479.47a	2.93a	2.66a
No bund	3.59b	1.92b	0.68b	0.03a	488.08a	0.86b	0.51b
Fertilizer effect							
Fertilizer	4.62a	2.14a	0.92a	0.04a	479.62a	1.62a	1.55a
No fertilizer	3.6b	2.01a	0.50a	0.02b	487.93a	1.95a	1.62a

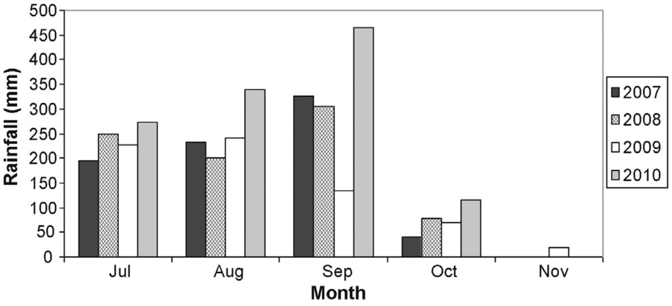

Fig. 2. Monthly rainfall in 2007, 2008, 2009, 2010 during the rice growing period in Dogué village.

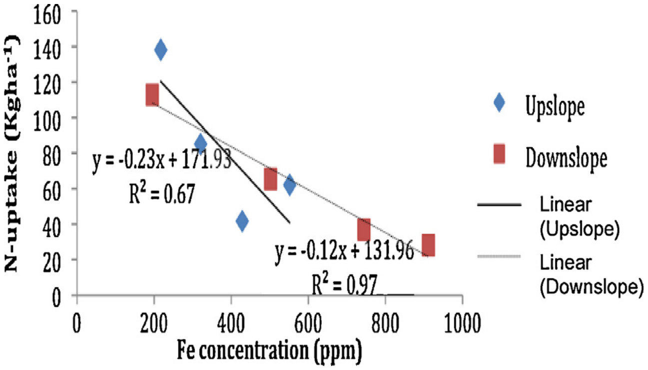

Fig. 3. Relationship between N-uptake and Fe concentration in rice leaves at 38 DAS at Upslope and downslope position.

season was 0.009, 0.015, 0.018, and 0.021 m in 2007, 2008, 2009 and 2010, respectively (Table 3). Higher ponded water level in 2010 was associated with the highest amount of total rainfall.

Results of analyses of variance combined for the four seasons for grain yield at maturity, and N uptake and Fe concentration of rice plants are shown in Table 2. The effects of fertilizer, bunding, season, year-by-position and year-by-fertilizer on rice yield were highly significant, whereas position effect on rice yield was not significant. For N concentration, the main effects of bunding, position, and season were significant. Various interaction effects on Fe concentration of the rice plants were observed (Table 2).

Variation in grain yields across two toposequential positions, two fertilizer treatments, and two water control treatments in the four seasons was relatively small and the yields ranged from 3.8 in 2007 to 4.4 $Mg\,ha^{-1}$ in 2010 (Table 3). In combined analysis over four seasons, bunding increased rice yield by 29%. Bunding increased ponded water level during rice growing season (Table 3). Positive effect of bunding on rice yield in this study agreed to previous studies in Cote d'Ivoire and Tanzania (Touré et al., 2009, Raes et al., 2007). Touré et al. (2009) also reported that ponded water level and N accumulation of rice plants at maturity were increased by bunding.

In combined analysis over four seasons, fertilizer application increased rice yield by 28% (Table 3). No significant bunding-by-fertilizer interaction on rice yield indicates that fertilizer application effect was similar to both non-bunded and bunded fields in this study (Table 2). When data on rice yield were analyzed for each season, the effect of fertilizer application on rice yield reach significance at $p < 0.05$ in 2009 and 2010 with the highest response in 2009 (Table 4). As rice yields in 2009 and 2010 under non-fertilized treatment were at the same level as in 2007 and 2008, the higher response in 2009 and 2010 is not likely to be due to drastic soil degradation. Higher yield response to fertilizer application in 2009 was associated with higher N uptake and lower Fe concentration of rice plants at 38 DAS. There was significant negative relationship between Fe concentration and N uptake of rice plants (Fig. 3). This result is supported by previous reports, which indicated that the high Fe^{2+} concentration of the rice plants could reduce the N uptake (Yoshida, 1981; Diatta and Sahrawat, 2005). Furthermore, low rainfall on September 2009 could indicate higher solar radiation, which could contribute to response (Table 4). In the year, ponded water during rice growing season was similar to 2007, in spite of lower rainfall. Thus, water stress did not occur in the year. As solar radiation is often negatively related to rainfall, higher solar radiation may have contributed to higher yield response, as indicated by Islam and Morison (1992).

The mean of N concentration in leaves of 2.07% denoted that the plants were nitrogen-deficient in comparison with the standard critical concentrations for rice plants of 2.5% (Yamauchi, 1989; Tanaka and Yoshida, 1970. N-uptake and N% at 38 DAS was correlated with fertilizer response (Table 4). Plots with lower N-uptake in 2007 presented higher iron in leaves indicating that the occurrence of iron toxicity in plots created a nutrient disorder limiting the response to fertilizer application. With higher fertilizer efficiency, the application of nutrients such as P, Zn and K strengthens the rice plant, "dilutes" toxic Fe2+ via enhanced biomass growth, and especially bivalent cations may also act as competing ions. Previous studies provided further evidence that the application of P, K and Zn in conjunction with N is an effective way of reducing iron toxicity (Yamauchi, 1989; Yoshida, 1981). Yamauchi (1989)

Table 4
Effect of year and fertilizer interaction on grain yield, N in plant, N uptake, Fe concentration and ponded water level. Fertilizer effect means followed by different letters are significantly different at $p < 0.05$.

Year		2007	2008	2009	2010
Grain yield (Mg ha^{-1})	Fertilizer	3.9a	4.4a	5.4a	4.9a
	None	3.3a	3.9a	3.3b	3.9b
N plant (%)	Fertilizer	1.7a	2.3a	2.6a	2.1a
	None	1.6a	2.0b	2.2b	2.2a
N uptake (kg ha^{-1})	Fertilizer	0.41a	0.94a	1.69a	0.65a
	None	0.29a	0.56b	0.82b	0.34b
Fe concentration (ppm)	Fertilizer	656a	461a	198a	605a
	None	684a	362a	215a	691a
Ponded water level at 38DAS (cm)	Fertilizer	0.7a	1.3a	1.4a	1.9a
	None	0.8a	1.2a	1.5a	1.9a
Ponded water level from 39DAS until harvest (cm)	Fertilizer	2.1a	1.7a	2.0a	2.6a
	None	2.0a	1.7a	1.9a	2.5a

Table 5
Effect of year and position interaction on grain yield, N in plant, N uptake, Fe concentration and ponded water level. Position effect means followed by different letters are significantly different at $p < 0.05$.

Year		2007	2008	2009	2010
Grain yield (Mgha^{-1})	Upslope	4.2a	5.3a	5.1a	3.6b
	Downslope	2.90b	2.96b	3.66a	5.12a
N plant (%)	Upslope	1.71a	2.27a	2.51a	2.19a
	Downslope	1.56a	1.99b	2.31a	2.04a
N uptake (kg ha^{-1})	Upslope	0.41a	0.85a	1.38a	0.62a
	Downslope	0.28b	0.65a	1.12a	0.36b
Fe concentration (ppm)	Upslope	428.50a	320.56a	217.29a	551.55a
	Downslope	911.25b	501.87b	195.08a	744.10b
Ponded water level at 38 DAS (cm)	Upslope	0.84a	0.86a	0.59a	1.66a
	Downslope	1.24b	2.14b	3.07b	2.87a
Ponded water level from 39DAS until harvest (cm)	Upslope	1.07a	0.85a	0.57a	1.61a
	Downslope	2.84b	2.55b	3.53b	3.47b

indicated that there is rather a strong relationship between an increase of iron and a decrease of potassium.

Table 5 shows season-by-position interaction effect on rice yield. There was no significant position effect in 2009. Rice yield was higher in upslope than downslope position in 2007 and 2008. In contrast, rice yield in 2010 was higher in downslope compared with the upslope positions (Table 5). This result for 2010 is similar to Touré et al. (2009), reporting that rice yield increased from the valley fringe towards the valley centre. In this study, as N uptake at 38 DAS was lower in downslope than in upslope in 2010, rice growth was improved after 38 DAS and longer crop duration may also have contributed to higher yield (140 days in 2010 vs. 124 to 130 days in 2007–2009).

In upslope, rice yield was lower in 2010 than in others. Ponded water and Fe concentration of rice plants were higher in 2010 than others. Thus, Fe toxicity may have caused low yield in 2010. Ferrous iron (Fe^{2+}), when abundantly taken up by the plant, becomes concentrated in the leaves, causing limb discoloration, reduced tillering, stunted growth and substantially reduced yields (Chérif et al., 2009). At the critical iron mass of 500 mg kg^{-1} in leaves, yield loss occurs (Marschner, 1995).

In this study, higher yield in upslope than in downslope in three seasons (Table 5) were in contrast with Touré et al. (2009) who observed an increase of mean grain yield from the valley fringe towards the valley centre from 0.5 to 1.0 Mg ha^{-1} in the drier year and from 0.3 to 1.3 Mg ha^{-1} in the wetter year. Tsubo et al. (2006) found grain yield was 6–43% greater at the bottom than the top position on the toposequence at one out of 4 sites and at 2 out of the four sites higher in upslope position.

The reasons for difference between previous studies and ours are not clear. But, in this study, we did not observe severe water stress confirmed by tensiometer measurements (data not shown) in both toposequential positions for all the seasons, although ponded water level was relatively lower in upslope. Fe concentration of rice plants at 38 DAS tended to be higher in downslope (Table 5), indicating that Fe toxicity could make the major difference between previous studies and ours.

4. Conclusions

This study assessed spatial and temporal variability in growth and yield of lowland rice cropping in an inland valley with special attention to two crop management options: bunding and fertilizer application. Bunding improved rice yield up to 1 Mg ha^{-1}. Season-by-position and season-by-fertilizer application interactions on rice yield were associated with Fe toxicity and climatic conditions, through its effect on ponded water level, N uptake and Fe concentration of rice plants. Although this study did not install drainage system in the bunded plots, improving yield response to fertilizer application may require drainage system in the areas where risk for Fe toxicity is high. However, it is noted that where drought risk is high, drainage may give negative effect on rice yield, when drought occurs after removing water in the fields. Thus, better understanding of local rainfed lowland rice growing environment and in particular local hydrological processes through dynamic modelling approaches is essential for recommending optimal agricultural practices to farmers.

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References

Asubonteng, O.K., 2001. Characterization and evaluation of inland valley watersheds for sustainable agricultural production: case study of semi-deciduous forest zone in the Ashanti Region of Ghana. Tropics 10, 539–554.

Becker, M., Asch, F., 2005. Iron toxicity in rice – conditions and management concepts. Journal of Plant Nutrition and Soil Science 168, 558–573.

Becker, M., Johnson, D.E., 2001. Improved water control and crop management effects on lowland rice productivity in West Africa. Nutrient Cycling in Agroecosystems 59, 119–127.

Bray, R.H., Kurtz, L.T., 1945. Determination of total, organic and available forms of phosphorus in soils. Soil Science 59, 39–45.

Chérif, M., Audebert, A., Fofana, M., Zouzou, M., 2009. Evaluation of iron toxicity on lowland irrigated rice in West Africa. Tropicultura 27, 88–92.

Diatta, S., Sahrawat, L.K., 2005. Iron toxicity of rice in West Africa: screening tolerant varieties and the role of N, P, K and Zn. In: Audebert, A., Narteh, L.T., Kiepe, P., Millar, D., Beks. (Eds.), Iron Toxicity in Rice-Based Systems in West Africa. Africa Rice Center (WARDA), Cotonou, Benin, p. 75.

Gee, G.W., Or, D., 2002. Particle-size analysis. In: Dan, J.H., Topp, G.C. (Eds.), Methods of Soil Analysis. Part 4. Physical Methods. Soil Science Society for America, Madison, WI, pp. 255–293.

Haefele, S.M., Naklang, K., Harnpichitvitaya, D., Jerakongman, S., Skulkhu, E., Romyen, P., Phasopa, S., Tabtim, S., Suriya-arunroj, D., Khunthasuvon, S., Kraisorakul, D., Youngsuk, P., 2006. Factors affecting rice yield and fertilizer response in rainfed lowlands of Northeast Thailand. Field Crops Research 98, 39–51.

Homma, K., Horie, T., Shiraiwa, T., Supapoj, N., Matsumoto, N., Kabaki, N., 2003. Toposequential variation in soil fertility and rice productivity of rainfed lowland paddy fields in mini-watershed (Nong) in Northeast Thailand. Plant Production Science 6, 147–153.

Islam, M.S., Morison, J.I.L., 1992. Influence of solar radiation and temperature on irrigated rice grain yield in Bangladesh. Field Crops Research 30, 13–28.

Kjeldahl, J., 1883. A new method for the estimation of nitrogen in organic compounds. Zeitschrift Fur Analytische Chemie 22, 366.

MAEP, 2011. Strategie nationale pour le developpement de la riziculture au Benin. Ministry for Agricultre, Lifestock and Fishery, Cotonou, Benin.

Marschner, H., 1995. Mineral Nutrition of Higher Plants. Functions of Mineral Nutrients: Micronutrients: Iron. Academic Press, London, pp. 313–323.

Prade, K., Ottow, J.C.G., Jacq, V.A., 1986. Excessive iron uptake (iron toxicity) by wetland rice (*O. sativa* L.) on an acid sulfate soil in the casamance/Senegal. In: Proc. 3rd Int. Symp. Acid Sulphate Soils, Dakar, Senegal.

Raes, D., Kafiriti, E.M., Wellens, J., Deckers, J., Maerten, A., Mugogo, S., Dondeyne, S., Descheemaeker, K., 2007. Can soil bunds increase the production of rain-fed lowland rice in South Eastern Tanzania? Agricultural Water Management 89, 229–235.

Roose, E., 1996. Land husbandry – components and strategy. FAO Soils Bulletin, vol. 70. Food and Agriculture Organization, Rome, Italy.

SAS Institute Inc., 2001. SAS System Version. SAS Institute Inc., Cary, NC, USA.

Tanaka, A., Yoshida, S., 1970. Nutritional disorder of rice plant in Asia. Int. Rice Res. Inst. Tech. Bull., vol. 10.

Touré, A., Becker, M., Johnson, D.E., Koné, B., Kossou, D.K., Kiepe, P., 2009. Response of lowland rice in agronomic management under different hydrological regimes inland valley of ivory coast. Field Crops Research 114, 304–310.

Tsubo, M., Basnayake, J., Fukai, S., Sihathep, V., Siyavong, P., Sipaseuth Champhengsay, M., 2006. Toposequential effects on water balance and productivity in rainfed lowland rice ecosystem in southern Laos. Field Crops Research 97, 209–220.

Walkley, A., Black, I.A., 1934. An examination of the Degtjareff method for determining organic carbon in soils: effect of variations in digestion conditions and of inorganic soil constituents. Soil Science 63, 251–263.

WARDA, 2008. Africa Rice Trends, 2007. The Africa Rice Center, Cotonou, Benin, 74 pp.

Yamauchi, M., 1989. Rice bronzing in Nigeria caused by nutrient imbalances and its control by potassium sulfate application. Plant and Soil 117, 275–286.

Yoshida, S., 1981. Fundamentals of Rice Crops Science. International Rice Research Institute (IRRI), Manila, Philippines.