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Original Research Article

Yields and Nutrient Concentrations in Above ground Dry Matter of Rain-Fed Rice as Affected by Nutrient Deficiencies

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Declining yields in continuous cropping are a serious threat to rain-fed rice (*Oryza* spp.) production. Yields are affected by ecological stress, including soil nutrient deficiencies as well as plant mineral nutrition. However, there is a limited diagnosis of soil nutrients and rice mineral nutrition in the humid forest zone of West Africa. Therefore, a nutrient-omission trial was conducted in the humid forest in Côte D'Ivoire on a Ferralsol of foot slope during the cropping seasons in 2007, 2008, and 2009. The effect of the complete fertilizer (Fc: N, P, K, Ca, Mg, and Zn) and other treatments (Fc–N, Fc–P, Fc–K, Fc–Ca, Fc–Mg, Fc–Zn, and unfertilized plot) with the exclusion of a specific nutrient from Fc were evaluated on rice grain and straw yields coupled with mineral concentrations in rice leaves and grains. Significant decline of grain and straw yields was observed after the first cropping season. Effects of P and K deficiencies differed respectively between cropping seasons, while N and Mg deficiencies induced reduction of the overall mean of grain yield by 17% and 26%, respectively. Except for treatment Fc–Mg that had an antagonistic effect on rice P nutrition, the effect of other treatments involved could be related to a significant depletion of soil Zn content. Sequential application of basal fertilizer composed of P, PK, and the PKMg according cropping season is recommended for sustaining rain-fed rice production with high yield in continuous cropping.

Keywords Côte D'Ivoire; Rain-fed rice; Soil nutrient deficiencies; Declining yield; Grain quality

INTRODUCTION

Rice (*Oryza* spp.) currently sustains the livelihoods of about 100 million people in sub-Saharan Africa (FAO, 2009). It is an important crop in attaining food security and poverty reduction in many low-income, food-deficit African countries. However, the demand for rice far outstrips its production in Africa, which has increased mainly due to land expansion since the 1970s, with only 30% being attributable to an increase in productivity (Fagade, 2000). Because of land shortage due to demographic growth (Amadji et al., 2013), improvement of the production systems should be the preferred option for meeting the shortfall in rice production of West Africa (Oikeh et al., 2008). This strategy will require intensification including maximizing continuous cropping (Beets, 1989).

However, the declining yield of upland rice has been observed in continuous cropping even with fertilizer applications in the humid forest zone, including that of Côte D'Ivoire (Gupa and O'Toole, 1986; Koné et al., 2010). Sequential cropping and mixed cropping were advised to address this threat, but they did not achieve much (George et al., 2002; Melendez et al., 2003; Assigbé et al., 2012). Hence, there is still need to understand rice yield decline in the upland rice-growing environment of sub-Sahara Africa.

Wide range of literatures (Adepetu and Corey, 1977; Melendez et al., 2003) is limited to the investigation of soil N and P contents, contrasting with soil contents of K, Ca, Mg, and Zn in spite of their importance to rice production (Yao et al., 2000; Roy et al., 2006). Such approach may have occulted knowledge generation in rice soil fertility management because of existing multiple nutrient interactions for nutrient uptake (Ranade-Malvi, 2011) and partitioning into the leaves and grains (Yoshida, 1981) resulting quantitative or/and qualitative grain production according to nutrient availabilty (Koné et al., 2014).

This study was therefore initiated to assess the effects of soil deficiency in N, P, K, Ca, Mg, and Zn on upland rice grain and straw yields, and their respective content in grains and

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leaves. The study was carried out on a Ferralsol of foot slope in the humid forest zone of Côte D'Ivoire (West Africa). Nutrient-omission trials were conducted for 3 years to improve knowledge of a rice yield decline in order to identify the composition of basal fertilizer to sustain upland rice production.

MATERIAL AND METHODS

Site Location

The experiment was conducted at Guéssihio (6°06' N, 6°00' W, 180 m), located in the center western part of Côte D'Ivoire. This is a forest zone with a bimodal rainfall pattern of about 1200 mm annually (Figure 1). The study was preceded by a 3 years bush fallow dominated by *Chromolaena odorata* (L.) King & H.E.Robins on a Hyper Dystric Ferralsol of foot slope position. It was a deep (>1 m) sandy-clay soil having a moderate gravel content of less than 30% within 60 cm.

Field Experiment

In 2007, 2008, and 2009, the land was cleaned and tilled manually in early March. Simple fertilizers composed of nitrogen (urea, 46% N), phosphorus (super triple phosphate, 22% P), potassium (potassium chloride, 50% K), calcium (calcium sulfite, 40% Ca), magnesium (magnesium sulfite, 17% Mg), and zinc (zinc sulfite, 36% Zn) were applied as the complete fertilizer (Fc) treatment and a specific nutrient was excluded for the other treatments (Fc–N, Fc–P, Fc–K, Fc–Mg, Fc–Ca, and Fc–Zn). No fertilizer treatment (0) was the control. Rice variety WAB 56-104 (*O. sativa* L.) was sown at three grains per hill spaced at 20 cm in a randomized complete block design. The subplots were 3 m × 5 m, spaced by 0.5 m apart in a block. Four replications spaced by 1.5 m were laid for a total of 32 subplots. The fertilizers were applied at 30 kg N ha^{-1}, 100 kg P ha^{-1}, 50 kg K ha^{-1}, 50 kg Ca ha^{-1}, 50 kg Mg ha^{-1}, and 10 kg Zn ha^{-1} as basal fertilizer. At rice tillering and panicle initiation, additional applications of 35 kg N ha^{-1} were applied.

Soil and Plant Sampling and Analyses

In 2007 and 2008, before the application of the fertilizers, the soil was sampled at 0–20 cm depth on each subplot using an augur. The samples were dried, broken, and sieved (2 mm) before the laboratory analysis. Soil pH_{water} and its contents of organic carbon (C), total N, available P, and exchangeable K, Ca, Mg, and Zn were determined as described by ASA and SSSA (1982). In 2003, two-thirds of mature leaves were sampled by plant from a 1 m^2 during the flowering period. A sample of grain was also taken after harvest. Leaf and grain concentrations of N, P, K, Ca, Mg, and Zn were analyzed as described by TSBF (Anderson and Ingram, 1993).

Yield Data Collection

At rice grain maturity (about 100 days after emergence), the rice was harvested from 8 m^2 of each subplot leaving two seeding lines in the border. After threshing, the grains were sun-dried, sieved, and weighed for a specific moisture content measured. The grain yield (GY) was determined for standard moisture content of 14%. The straw was also weighed for yield (SY) determination.

Statistical Analysis

By linear model procedure, the treatment effect was evaluated in soil nutrient contents and GY per year of the experiment. Nutrient contents of rice leaves and grains were also analyzed per treatment by the same procedure. Mean values were separated by least significant difference (LSD) test for α = 0.05. The mean value of the difference between nutrient contents in soil (2008–2007) was determined by mixed model analysis and α was 0.10. Analyses were performed with SAS software (SAS, 2002).

RESULTS

Soil Nutrient Contents and Rice Yields

Soil chemical characteristics determined before the experiment are presented in Table1. The soil acidity was moderate (pH > 5.5) except for treatments Fc–P, Fc-Mg and Fc–Ca, which showed high acidity (pH < 5.5). Almost the plots had low soil C content (<10 g kg^{-1}), while moderate (Fc, Fc–K, and Fc–Zn) to low soil P contents were observed. The critical level of soil P (4.2 mg kg^{-1}) was determined for treatment Fc–P, as was soil K content in Fc–K (0.10 cmol kg^{-1}). There was low content of Ca and Mg in the soil of all the studied plots, while treatments Fc, Fc–N, and Fc–Zn had sufficient (>1 mg kg^{-1}) soil Zn content.

The grain and straw yields were differently affected by the treatments (Table 2): in year 2007, lowest GY (1.65 t ha^{-1}) was observed in treatment Fc–P,while no significant difference was observed for SY except for the control treatment (0). In the subsequent year (2008), both GY and SY were significantly decreased in treatments Fc–P and Fc–K,while Fc–N had significantly reduced SY compared with Fc-Ca. However, only the treatment Fc–P induced significant decrease of GY in 2009 similarly for SY. The overall GY was decreased by about 45% (Fc–P), 32% (Fc–K), 25% (Fc–Mg), and 16% (Fc–N) compared with the highest yield (2.23 tha^{-1}) recorded for treatment Fc-Zn.

Figure 2 shows significant ($P < 0.05$) decrease of annual GY and SY from 2007 to 2009. This trend was more pronounced for SY than for GY. But, GY were more stable in treatments Fc, Fc-Ca and somewhat for Fc-N across the year (Table 2). However, only soil Zn content decreased significantly from 2007 to 2009 in the treatments Fc–N, Fc–P, and Fc–K. The negative balances observed for soil C, P, and Mg were not statistically significant except for soil P in treatment Fc-Zn (Table 3).

Nutrient Concentrations in Plant Dry Matter

Table 4 shows the concentrations of the studied nutrients in the rice grain and leaf according to the treatments. Leaf N concentrations (15.6–21.1g kg^{-1}) were significantly greater (almost double) than that of the grain (10.5–12.7 g kg^{-1}) except for treatment Fc–N, which showed no significant difference between the mean values of the two organs. There were also significant differences between mean values of K (2.7–3.6 g kg^{-1} cf.16.8–19.5 g kg^{-1}), Ca (0.20–0.32 g kg^{-1} cf. 7.8–9.7 g kg^{-1}), and Mg (0.22–0.47 g kg^{-1} cf. 2.67–4.6 g kg^{-1}) concentrations in the grains and leaves. No significant difference was observed between the mean values of P and Zn in the grains and leaves, except for Zn concentration in the treatment Fc–Ca.

Table 1. Chemical characters determined in the 0–20 cm depth of the soil before the experiment per plot.

Trial	pH_{water}	C ($g\ kg^{-1}$)	P ($mg\ kg^{-1}$)	K ($cmol\ kg^{-1}$)	Ca ($cmol\ kg^{-1}$)	Mg ($cmol\ kg^{-1}$)	Zn ($mg\ kg^{-1}$)
Fc	5.7 (0.08)†	12.2 (4.8)	8.0 (2.16)	0.15 (0.04)	0.94 (0.17)	0.41(0.14)	6.80 (6.00)
Fc–N	5.7 (0.58)	8.30 (1.3)	3.2(1.25)	0.30 (0.30)	0.70 (0.20)	0.31(0.10)	1.40 (0.69)
Fc–P	5.3 (0.34)	5.10 (4.1)	4.2(2.63)	0.54 (0.94)	0.40 (0.04)	0.22(0.80)	0.70 (0.35)
Fc–K	5.7 (0.58)	9.40 (3.3)	6.5(7.10)	0.10 (0.01)	0.78 (0.25)	0.32(0.13)	0.70 (0.35)
Fc–Ca	5.2 (0.05)	6.15 (4.0)	4.0 (0.25)	0.11(0.04)	0.78 (0.17)	0.35(0.04)	0.95 (0.28)
Fc–Mg	5.4 (0.29)	8.55 (2.7)	4.5(0.57)	0.09 (0.02)	0.50 (0.23)	0.20(0.04)	0.35 (0.05)
Fc–Zn	5.8 (0.85)	9.55 (2.6)	18.5(2.16)	0.41(0.52)	0.69 (0.25)	0.30(0.07)	1.10 (0.17)
0	5.8 (0.40)	10.70 (4.1)	4.5(3.11)	0.15 (0.07)	0.81 (0.05)	0.41(0.27)	0.60 (0.17)

† Standard deviation given in parentheses (n=4)

Table 2. Grain and straw yields in 2007, 2008, and 2009, and respective overall average value of these parameters per treatment

Treatment	2007		2009		2009		Mean	
	GY†	SY	GY	SY	GY	SY	GY	SY
				($t\ ha^{-1}$)				
Fc	2.63abA	3.47aA	1.66abA	2.93abA	2.03aA	2.00Aa	2.10ab	2.80a
Fc–N	2.25abcA	3.27abA	1.75aA	2.49bcA	1.59abA	1.57abA	1.85abc	2.44ab
Fc–P	1.65cA	3.15abA	0.84bcB	2.28bcAB	1.14bAB	1.13bB	1.21d	2.19ab
Fc–K	2.49abcA	3.29aA	0.74cC	2.53bAB	1.27abB	1.24abB	1.50abc	2.35ab
Fc–Ca	2.83abA	3.92aA	2.07aA	3.40aA	1.71abA	1.70abA	2.20a	2.97a
Fc–Mg	2.29abcA	3.35aA	1.33abcB	2.73abA	1.30abB	1.30abA	1.64abcd	2.45ab
Fc–Zn	3.07aA	3.58aA	1.63abB	3.42aA	2.00aAB	1.95abA	2.23a	2.98a
0	1.94bcA	2.31bA	0.85bcB	1.75cAB	1.25abAB	1.23abB	1.34cd	1.76b
$LSD_{0.05}$	0.95	0.97	0.83	0.75	0.88	0.88	0.172	1.59
$P > F$	0.07	0.98	0.02	0.56	0.79	0.29	0.172	0.001

Letters a, b and c are indicating mean values with significant difference in column for specific values of Lsd and P; A and B are related to mean values difference in row; GY, grain yield; SY, straw yield.

Table 3. Difference in soil contents in C, P, K, Mg, Ca, and Zn in 0–20 cm depth of each treatment before the experimentation in 2007 and 2008

Treatment†	C (g kg^{-1})	P (mg kg^{-1})	K (cmol kg^{-1})	Ca (cmol kg^{-1})	Mg (cmol kg^{-1})	Zn (µg kg^{-1})
Fc	0.402*	2.750	0.042	0.675	0.035	0.475
Fc–N	–0.255	–2.250	0.187	0.215	–0.055	–1.375**
Fc–P	–0.653	1.500	0.450	0.162	–0.072	–1.400**
Fc–K	0.077	0.500	0.067	0.122	–0.087	–2.225**
Fc–Ca	–0.137	–3.750	–0.187	0.352	–0.065	–1.100
Fc–Mg	–0.017	–1.000	–0.037	0.112	–0.075	–1.250
Fc–Zn	–0.687	–3.250*	0.287	0.397	0.080	–0.250
0	0.090	2.500	0.030	0.412	0.015	–0.375

* Significant at $P \leq 0.05$; ** significant at $P \leq 0.10$; † Fc, complete fertilizer; 0, no fertilizer.

Table 4.Comparison of nutrient (N, P, K, Ca, Mg, and Zn) mean values in rice leaf and grain under effect of different treatments

Nutrient		Treatment†							
		Fc	Fc–Ca	Fc–K	Fc–Mg	Fc–N	Fc–P	Fc–Zn	0
N	Leaf	20.0a	20.7a	19.8a	20.2a	15.6a	21.1a	20.5a	19.0a
(g kg^{-1})	Grain	12.4b	12.7b	11.5b	10.8b	10.5a	11.4b	10.6b	11.1b
P	Leaf	1.62a	1.47a	1.61a	1.62a	2.65a	1.25a	1.82a	1.37a
(g kg^{-1})	Grain	1.87a	1.92a	2.10a	2.17a	2.22a	1.20a	2.07a	1.50a
K	Leaf	17.0a	18.1a	16.9a	17.1a	19.5a	17.0a	16.8a	19.2a
(g kg^{-1})	Grain	3.30b	3.2b	2.7b	3.02b	3.6b	3.3b	3.07b	2.8b
Ca	Leaf	9.35a	9.5a	9.7a	8.42a	8.7a	7.8a	9.7a	7.9a
(g kg^{-1})	Grain	0.27b	0.32b	0.30b	0.25b	0.20b	0.25b	0.27b	0.27b
Mg	Leaf	4.6a	4.40a	4.02a	3.5a	2.7a	3.4a	4.5a	2.67a
(g kg^{-1})	Grain	0.42b	0.47b	0.47b	0.42b	0.45b	0.22b	0.52b	0.25b
Zn	Leaf	0.023a	0.034a	0.024a	0.021a	0.023b	0.025a	0.017a	0.023a
(g kg^{-1})	Grain	0.0315a	0.021b	0.030a	0.032a	0.033a	0.032a	0.024a	0.026a

Mean values followed by the same letter are not significantly different in column at α = 0.05; † Fc, complete fertilizer; 0, no fertilizer.

Table 5. Nutrient contents in rice aboveground organs in the first year of trial

Organ	Treatment†	Nutrient concentrations					
		N ($g\ kg^{-1}$)	P ($g\ kg^{-1}$)	K ($g\ kg^{-1}$)	Ca ($g\ kg^{-1}$)	Mg ($g\ kg^{-1}$)	Zn ($g\ kg^{-1}$)
Leaf	**Fc**	20.0a	1.62b	17.0a	9.3a	4.6a	0.023a
	Fc–N	15.6a	2.65a	19.5a	8.7a	2.7b	0.024a
	Fc–P	21.1a	1.25b	17.0a	7.8a	3.4ab	0.025a
	Fc–K	19.8a	1.65b	17.0a	9.7a	4.0ab	0.024a
	Fc–Ca	20.7a	1.47b	18.1a	9.5a	4.4a	0.021a
	Fc–Mg	20.2a	1.62b	17.1a	8.4a	3.5ab	0.021a
	Fc–Zn	20.5a	1.82ab	16.8a	9.7a	4.5a	0.018a
	0	19.0a	1.37b	19.2a	7.9a	2.7b	0.018a
$LSD_{0.05}$		6.01	0.83	3.3	2.14	1.70	0.011
Grain	**Fc**	12.4a	1.87ab	3.3a	0.30ab	0.42a	0.031ab
	Fc–N	10.5a	2.23a	3.6a	0.20b	0.45a	0.033ab
	Fc–P	11.4a	1.20c	3.3a	0.25ab	0.22b	0.032ab
	Fc–K	11.5a	2.10ab	2.7a	0.30ab	0.47a	0.030abc
	Fc–Ca	12.7a	1.92ab	3.2a	0.32a	0.47a	0.034a
	Fc–Mg	10.8a	2.17a	3.0a	0.25ab	0.42a	0.032ab
	Fc–Zn	10.6a	2.07ab	3.0a	0.27ab	0.52a	0.024c
	0	11.1a	1.50bc	2.8a	0.27ab	0.25b	0.026bc
$LSD_{0.05}$		2.41	0.63	0.94	0.11	0.11	0.07

Mean values followed by the same letter are not significantly different in column at $\alpha = 0.05$; † Fc, complete fertilizer; 0, no fertilizer.

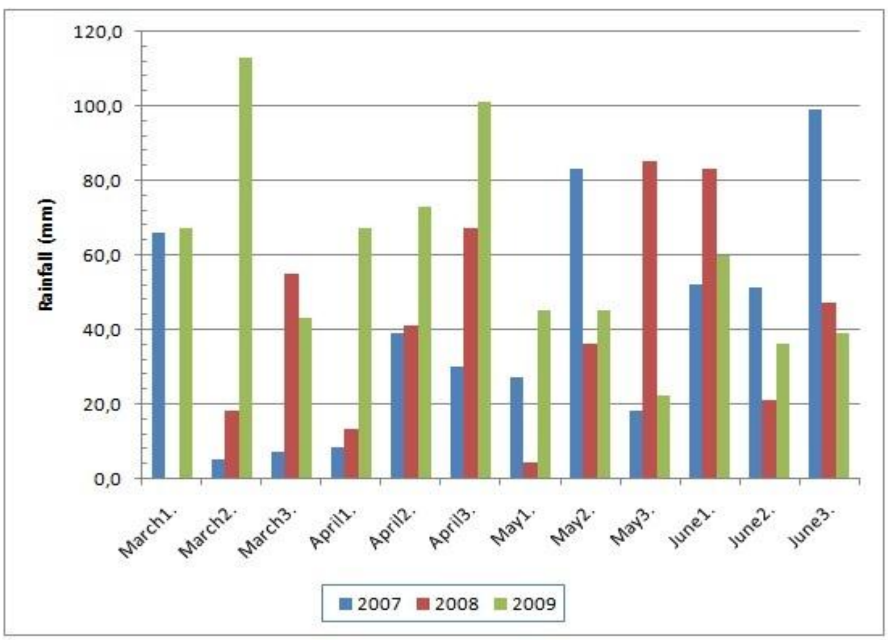

Figure 1. Monthly 10-day average rainfall during the cropping period (1, 2, and 3 = period of 10-days)

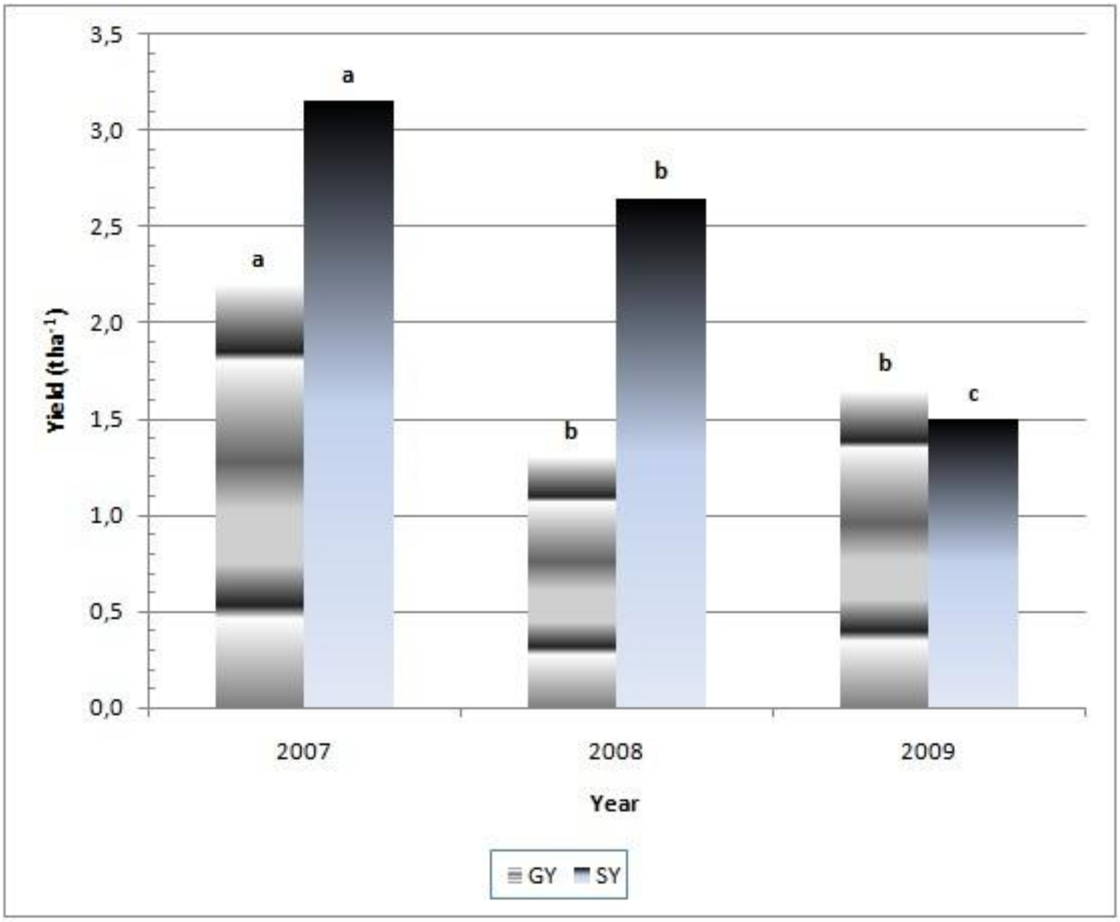

Figure 2. Grand means of Yields according to grain (GY) and straw (SY) in 2007, 2008, and 2009
(Columns for the same factor (grain yield or straw yield) bearing the same letter are not statistically significantly different (α = 0.05)).

Moreover, no significant difference between the treatments was observed for the concentrations of N, K, Ca, and Zn in the leaf (Table 5), contrasting with that of P concentration (highest in treatment Fc–N) and Mg in treatments Fc (4.6 g kg^{-1}), Fc–Zn (4.5 g kg^{-1}), and Fc–Ca (4.4 g kg^{-1}). The concentration of P in the leaves was significantly reduced in the treatments Fc, Fc–P, Fc–K, Fc–Ca, and Fc–Mg including the control plot. No significant difference of N (10.5–12.7 g kg^{-1}) and K (2.7–3.6 g kg^{-1}) concentrations were observed for rice grain, contrasting with the mean concentrations of P, Ca, Mg, and Zn according to the treatments. The concentration of P in grain ranged from 1.20 g kg^{-1} (Fc–P) to 2.23 g kg^{-1} (Fc–N). Meanwhile, Fc–N induced a depressive effect on Ca (0.20 g kg^{-1}) concentration in the rice grain. Reductions were also observed for Mg (0.20 g kg^{-1}) concentration in treatment Fc–P and for Zn (0.0024 g kg^{-1}) in treatment Fc–Zn.

DISCUSSION

The highest grain yield observed during the trial was 3.07 t ha^{-1} in 2007 for the treatment Fc–Zn, reflecting sufficient soil Zn content (> 1 mg kg^{-1}) before the experiment. Productivity remained high in this treatment throughout the duration of the study with no significant difference compared with that of the treatments Fc and Fc–Ca. However, soil Ca content was low (< 2 cmol kg^{-1}) in all the treatments including treatment Fc–Ca in the normal range for highly weathered acidic soil (Juo and Wilding, 1996).

However, this deficiency didn't affect rice grain yield significantly. The similar effect of Ca exclusion of basal fertilizer was observed by Koné et al. (2008) in a derived savannah zone of West Africa. Moderate availability of Ca^{2+} can reduce the reception of environmental stress signal by plant regarding to the physiological function of this cation, considered as a signal transducer (Cvetkovska et al., 2005). Thus, exclusion of Ca could have mitigated intermittent drought effects that occurred during the trial (Figure 1). Consequently, we do not recommend lime amendment in this agroecosystem. However, the omission of Ca^{2+} can decrease Zn^{2+} translocation into the grain, resulting in degradation of grain nutritional quality regarding for Zn^{2+} lower concentration in grain compared with that of the leaf (Table 4).

In year 2007, only the grain yield was affected by soil P deficiency in the treatment Fc–P, but, over the course of the study, in combination with the effect of soil Zn content depletion (Table 3) and antagonistic effect in Mg translocation into the grain (Table 5), it also affected the straw yield. Similar effect on straw yield as observed for Fc–N and Fc–K may also have resulted from Zn depletion in the soil. This result is in contrast with the synergistic effect described between N and

Zn^{2+} on one hand, and K^{+} and Zn^{2+} on the other (Ranade-Malvi, 2011).

However, the depletion of soil Zn content as induced by the treatments Fc–N and Fc–K could have provoked the reduction of straw yield through tiller abortion and premature leaf fall (Roy et al., 2006). This consequence of soil Zn content depletion could have increased the reduction of rice tillering ability in the treatment Fc-P (Koné et al., 2011). Regarding to the effect of one year cropping on soil Zn content, we assume that the accumulative effect during the 3 years cropping can explain the grain yield reduction of 45%, 32%, and 16% for the treatments Fc–P, Fc–K, and Fc–N, respectively. In fact, reduction in vegetative growth can impair rice grain production (Zhao et al., 2007).

The grain yield reduction (25%) observed for treatment Fc–Mg could have been attributable to the negative balances observed for almost all the studied soil nutrients (Table 3) even though these were not statistically significant. Furthermore, P concentration in rice leaf was similarly low in treatments Fc-Mg and Fc-P while the lowest concentration of Mg in the grain accounted for treatment Fc-P and the control plot (Table 5). In fact, poor Mg supply can impair the physiological process of P nutrition (Mengel and Kirkby, 2001) resulting in depression of rice grain yield. Although not deficient in the studied soil, Mg and Zn were strongly involved in rice nutrition and yield stabilization depending to soil Zn balance, which was particularly depleted in low N-, P-, and K-supplying conditions, whereas Mg effect was recorded in P-nutrition. Therefore, N, P, K, and Mg fertilizers are required for yield stabilization in the studied agroecosystem. Nitrogen fertilizer should be recommended for split applications at tillering and panicle-initiation stages.

CONCLUSION

Our study revealed that P, K, Mg, and N were the most limiting nutrients for rain-fed rice production in a Ferralsol of foot slope in the humid forest zone of West Africa. The annual application of all these nutrients can induce positive balance of soil Zn, enhancing P nutrition for greatest and stable straw and grain yields in continuous cropping. An alternative and economical option for basal fertilizer is the application of P in the first year of cropping, P and K in the second year, and P, K, and Mg in the following year to sustain rice production. However, grain nutritional quality could be altered because of low Zn concentration as a consequence of Ca exclusion from the basal fertilizer.

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