Toposequnential Variation in Soil Fertility and Limiting Nutrient for Rice Growth in the White Volta Floodplain of Northern Ghana

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Abstract

Integrated floodplain resource management for rice cultivation is imperative to satisfy the growing demand of rice in West Africa. Irrigated pot experiments were conducted with different fertilizer treatments to identify toposequential variation in soil fertility and limiting nutrient for rice growth within the White Volta floodplains in Ghana. Eighteen experimental soils were examined across a riverside to upland gradient, ranging from 898 to 4200 m in distance from the main riverside, from 73 to 106 m in elevation, and from 0.7 to 2338.1 m in distance from water sources. The soil analysis revealed close correlation between N-mineralization rates and carbon contents of the soils, which were exponentially decayed with distance from water sources. In the non-fertilized treatments, plant N uptakes at maturity also decreased along the same transect from the water sources. However, the dry matter production was little relevant to this toposequential factor. Various fertilizer treatments identified remarkable effect of sulfur on rice growth, which was more significant on soils closer to waster sources. NPK application without S increased only N concentration and N: S ratio in plant tissues but not biomass production. The results indicated that sulfur is the primary limiting element for rice growth, and its supplementation would be more beneficial as closer to water sources so as to effectively utilize greater N-supplying capacity of this agro-environmental soils.

Keywords: rice, sulfur deficiency, floodplain, soil carbon, water source

Introduction

River floodplains, consisting of wide and flat plain of alluvium bordering rivers, are expected to support a large expansion in rice cultivation area and production in Africa, of which the major share is currently unexploited. Major constraints to expand agricultural activities into river floodplains include difficulty in water control, risk of complete submergence of plants, occurrence of water-borne diseases, and disadvantage in access to the road and market (Balasubramanian *et al*. 2007). On the other hand, this geographical environment can provide water resources as well as relatively fertile alluvial soils compared to uplands (Buri *et al*. 1999). Moreover, the use of river floodplains for rice cultivation should not cause spatial competition with the other crops due to the risk of periodic flooding.

In the traditional lowlands in Asia, large variance in cultivation conditions and rice productivity are commonly recognized within relatively small areas, and farmers' management practices are adapted to this variance according to the sequential changes in soil fertility and water availability (Fukai *et al*. 1998). However, either quantitative data or farmers' practical adoption on the toposeqential distribution of environmental resources are scarce for rice cultivation within river floodplains in West Africa.

Primary objectives of this study were, therefore (1) to quantify the rice productivity of soils in relation to small-scale toposequence and (2) to identify deficient nutrient for rice growth, which results can help effective use of soil nutrient resources and development of toposequence-specific fertilizer management practices within a target environment. To achieve these objectives, phytometry experiments with rice were conducted under various fertilizer treatments by using multiple soils collected within a Whiter Volta floodplain in the northern Ghana. In addition to the major macronutrients of N, P and K, target nutrients included Zn, Si and S which deficiency have been previously reported in the region and in the similar hydromorphic soils in the other parts of the sub-Sahara Africa (Buri *et al*. 2000; Tsujimoto *et al.* 2010).

Materials and Methods

Sampling of experimental soils

Experimental soils were collected from the top 0-15 cm at 18 points across a riverside to upland gradient in the White Volta floodplains of northern Ghana at the beginning of rainy season in June, 2010. The sampling points ranged from 898.7 to 4200.0 m in distance from the main Volta riverside, from 73 to 106 m in elevation (ASTER-GDEM), and from 0.7 to 2338.1 m in distance from water sources. The average slope angle was 0.86 % between the closest and furthest sampling points from the riverside. Distance from water sources were calculated after extracting rivers and back-swamps by the image analysis of Quickbird imagery. Experimental soils were air-dried for a week in a screen house at the Savanna Agricultural Research Institute (9˚ 26' N, 0˚ 59' W, 183 m asl.). Thereafter, the soils at the air-dry equivalent weight (4.2 kg) were put into 7-l plastic pots followed by flooding and puddling with different fertilizer treatments.

The chemical and physical properties of the experimental soils were analyzed after air-dried and sieved. Total C and N were determined by automatic high sensitive NC analyzer, Sumigraph NC-220F (SCAS, Japan). Mineralizable nitrogen was determined by a 4-week anaerobic incubation at 30°C as the amount of NH_4^+-N extracted with 10% KCl solution. Available phosphorus content was measured by Bray No.2 method. Extractable sulfate was determined by extraction with KH_2PO_4 solution containing 500 mg l^{-1} P. CEC was measured by the ammonium acetate extract method at pH 7.0. Exchangeable bases were determined by plant atomic emission spectrometer, ICPE-9000 (Shimadzu, Japan). Soil texture was determined by sieving and pipetting method.

Experiment design and measurements

Two pot experiments were conducted. In the Experiment 1, rice was grown with no fertilizer inputs, using all the 18 experimental soils. In the Experiment 2, three of the 18 experimental soils were selected in a wide range of the distance from water sources (*Bottom*: 40 m; *Middle*: 501 m; *Top*: 1870 m), for which ten different fertilizer treatments were established including no fertilizer treatment in the Experiment 1: 1. Control (no fertilizer); 2. +N; 3. +P, 4. +K, 5. +NP; 6. +NK; 7. +NPK, 8. +NPKSi, 9. +NPKZn, 10. +NPKS. The chemical forms and application rates for each nutrient were 0.70 g N, 0.22 g P, 0.36 g K, 1.87 g Si, 0.05 g Zn, and 0.23 g S per pot as Urea, NaH_2PO_4, KCl, SiO_2, $ZnCl_2$, and Na_2SO_4, respectively. Both experiments had three replicates, followed by the same cultivation management and measurements. Two 21-day old seedlings of a local cultivar, *Jasmine85*, were transplanted at a rate of one hill per pot on June 26 in 2010, and were subsequently harvested on October 8 in 2010. The water level was kept above 2 cm throughout the rice growing period. Weeds were removed manually. No specific pest management was conducted.

The plants were harvested from each pot at maturity. The dry weights of the plant samples were determined after oven drying at 80˚C to a constant weight. The plant N concentration was determined by using automatic high sensitive NC analyzer, Sumigraph NC-220F (SCAS, Japan). The plant nutrient concentrations of P, K, S, Mg, Ca, Zn, Fe, Mn, Cu, and B were analyzed by plant atomic emission spectrometer, ICPE-9000 (Shimadzu, Japan), after digesting each sample with HNO_3 and H_2O_2 in microwave digestion system (MLS-1200 MEGA, Milestone Inc.). The plant nutrient uptakes were calculated as the product of the dry weight and the nutrient concentration of each plant tissue. Statistic analysis was performed by using JMP 8 software (SAS Institute Inc.).

Results and Discussion

Toposequential variation in soil fertility and plant growth (Experiment 1)

The results of soil analysis revealed large variances in soil properties within the gently sloping floodplain area (Table 1). The total carbon (TC) and total nitrogen (TN) contents ranged from 3.48 to 30.15 g kg^{-1} and from 0.28 to 2.25 g kg^{-1}, respectively. Although differing among the locations, available P and extractable S were both below the critical deficiency levels shown by Dobermann and Fairhurst (2000). This was in accordance with the previous studies conducted in the same agro-ecological zones of West Africa (Buri *et al.* 1999, 2000).

Table 1. Soil properties and its correlation with the total carbon contents (n=18).

	Mean	Max	Min	coefficiency of variation (%)	correlation coefficient to Total C
pH 1:2.5 (H_2O)	6.29	7.56	5.42	10.8	-0.43
Clay (%)	13.65	30.96	5.60	54.2	0.80***
Total C (g kg^{-1})	11.91	30.15	3.48	64.4	-
Total N (g kg^{-1})	0.89	2.25	0.28	65.3	0.91***
Mineralizable N (mg kg^{-1})	43.53	141.10	1.42	104.5	0.96***
Available P (mg kg^{-1})	11.26	31.85	1.98	79.5	0.58*
Extractable S (mg kg^{-1})	8.72	14.48	6.09	24.4	0.50*
CEC (cmol kg^{-1})	6.97	15.10	3.07	56.8	0.80***
Exchangeable cation (cmol kg^{-1})					
Na	0.75	1.54	0.33	50.3	0.57*
K	0.35	0.47	0.24	23.3	0.64**
Mg	1.05	2.65	0.40	68.9	0.80***
Ca	1.89	4.21	0.80	59.6	0.78***

The total carbon (TC) contents of the soils correlated to most of the other soil properties, exponentially decreased as the distance from water sources (Figure 1a). This toposequential gradient in the TC, SOC or clay contents of the soils was also observed in the other rice-growing lowlands of Asia (Homma *et al.* 2003; Tsubo *et al.* 2006). The accumulated TC contents in the lower parts of the toposequence were most likely attributable to greater deposition of clay minerals, and to longer periods of submergence that alleviates the decomposition of organic substrates (Sahrawat 2004).

The total N uptakes of rice plants also showed exponential reduction along the same transect from the water sources (Figure 1b). This could be explained by large differences in soil mineralizable N, that were highly correlated with the TC contents (Table 2). Soil mineralizable N was regarded as a good index of soil N-supplying capacity, and sufficiently correlated with plant N uptakes under non-N fertilized conditions in previous studies (Russell *et al.* 2006; Tsujimoto *et al.* 2010). However, top dry matter (TDM) yield was less relevant to this toposequential factor (Figure 1b). The TDM production highly fluctuated within a 100 m radius of water sources, and one had a relatively high yield level at upper area of the floodplain. This discrepancy in responses with rice production to N-supplying capacity of the soils indicated that there existed other limiting elements apart from N.

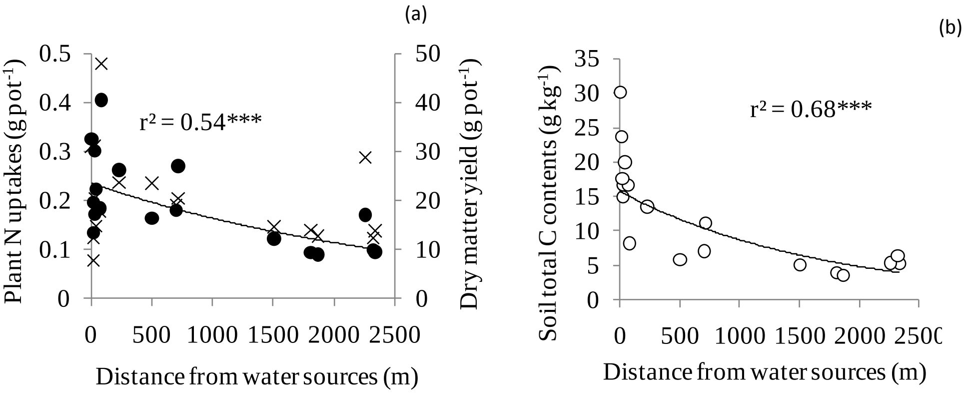

Figure1. Relationship between distance from water sources and (a) soil TC contents and (b) plant N uptakes (closed circles: ●) and top dry matter yield (cross marks: X).

Effects of fertilizer treatment and soil type on rice growth (Experiment 2)

The results of ANOVA showed significant F-values for the main and interactive effects of fertilizer treatment and soil type on the TDM production. The application of NPKS demonstrated stunningly higher TDM yields compared to the Control plots (Table 2). The differences in TDM yields between NPKS and Control plots were greater as closer to water sources (80.5; 40.7; and 29.7 g pot^{-1} on the *Bottom*, *Middle*, and *Top* soils, respectively). On the other hand, the application of N, P, and K or combinations of these elements without S showed no effects on the TDM yields for any of the experimental soils.

Table 2. Top dry matter yields and N: S concentration ratio at maturity as affected by different fertilizer treatments for the three experimental soils.

Fertilizer	Top dry matter yield (g pot^{-1})			N: S ratio		
	Bottom	*Middle*	*Top*	*Bottom*	*Middle*	*Top*
C	14.7 $^{fghijkl\#}$	23.5 ^{def}	12.7 ^{hijkl}	29.2 ^{f}	13.0 ^{hi}	12.9 ^{hi}
N	12.4 ^{ghijklm}	27.0 ^{d}	10.1 ^{jklm}	51.6 ^{ab}	25.4 ^{fgh}	47.9 ^{ab}
P	14.6 ^{fghijkl}	22.2 ^{defg}	12.8 ^{hijkl}	27.8 ^{fg}	11.3 ^{i}	14.7 ^{ghi}
K	18.6 ^{defghij}	17.1 ^{defghijk}	11.5 ^{hijklm}	26.9 ^{fgh}	12.5 ^{hi}	14.9 ^{ghi}
NP	10.7 ^{ijklm}	24.5 ^{def}	9.3 ^{ijklm}	45.0 ^{abcd}	31.6 ^{ef}	50.4 ^{ab}
NK	14.6 ^{fghijkl}	20.3 ^{defgh}	7.9 ^{klm}	57.1 ^{a}	34.0 ^{cdef}	50.8 ^{ab}
NPK	16.5 ^{fghijkl}	16.5 ^{efghijk}	5.9 ^{lm}	51.8 ^{ab}	43.8 ^{bcde}	47.1 ^{abc}
NPKSi	18.9 ^{defghij}	25.2 ^{de}	12.0 ^{hijklm}	49.6 ^{ab}	33.6 ^{def}	48.3 ^{ab}
NPKZn	19.5 ^{defghi}	12.0 ^{hijklm}	3.2 ^{m}	33.7 ^{def}	44.6 ^{abcde}	56.5 ^{ab}
NPKS	95.2 ^{a}	71.2 ^{b}	42.4 ^{c}	13.4 ^{hi}	6.6 ^{i}	7.1 ^{i}
	df	F-values		df	F-values	
Soil type (S)	2	166.1***		2	98.7***	
Fertilizer (F)	9	319.2***		9	159.8***	
S x F	18	24.4***		18	11.1***	

#Values within the next three columns followed by the same letter do not differ significantly at $P<0.05$ by Tukey's HSD multiple range test. ***Significant at $P<0.001$.

The high N: S ratio, notably on the *bottom* soil, and the increased values by the N application without S also implies the unbalanced supplies between N and S (Table 2). The ratios reduced only by adding S as a result of the substantial increases in biomass production. In a conventional study, Yoshida and Chaudhry (1979) suggested a critical N: S ratio for S deficiency at 14 in straw, and they demonstrated 50% of biomass reduction at the value of 40. The other study also indicated the similar value as a critical N: S ratio, and slightly higher value for grains (Islam and Ponnamperuma, 1982). Our results indicated that sulfur shortage severely hampers rice growth as well as maximum efficiency of N from either inherent soils or fertilizers in the target floodplain. The limiting S supply was also apparent in the S concentration values, that were all below the critical deficiency level at 0.06% (Dobermann and Fairhurst, 2000), among the rice plants in the Experiment 1. The other macro- and micro- nutrient concentration values were above the critical deficiency level except four of the 18 plots for the P level (data not shown).

Conclusions

This study revealed steep gradients in soil fertility within a gentle slope of a river floodplain in the northern Ghana. The phytometrical experiments suggested that the spatial variances in soil fertility for rice growth were mainly represented by the N- and S- supplying capacity of the soils. Once the limit of S is lifted, rice production is expected higher as closer to water sources due to exponentially greater amounts of N-supplying capacity of the soils. A further study requires identifying spatial distributions in S-supplying capacity of the soils, so that efficient fertilizer management practices can be developed on a basis of balancing N and S applications. The development of toposequence-specific fertilizer management will certainly help effective extension of rice production within the target floodplain environments.

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