

NUTRIENT DEFICIENCIES AND THEIR SYMPTOMS IN UPLAND RICE

Jerome Jonathan Mghase, Hironobu Shiwachi, Hisamitsu Takahashi and Kenji Irie

Graduate School of Agriculture, Tokyo University of Agriculture
Sakuragaoka 1-1-1, Setagaya -ku, Tokyo, 156-8502, Japan

(Received: August 15, 2010; Accepted: November 27, 2010)

ABSTRACT

Four upland rice varieties namely Norin 26 (Japonica type), Yar 2 (Indica type) and NERICA 1 and NERICA 4 were grown in nutrient solutions separately deficient of one of the following elements: N, P, K, Ca and Mg, to examine deficiency symptoms as well as the effects on growth and grain yield. All varieties showed similar response to any of the deficient nutrient element at different levels. P and N deficiencies were the most growth limiting factors at the early growth period of all varieties. NERICA 1 and NERICA 4 varieties recorded the lowest yield reduction due to nutrient deficiencies. The results indicate that NERICA varieties which are interspecific hybrids of *Oryza sativa* L. and *Oryza glaberrima* Steud. have relative advantage over their cultivated rice parent *O. sativa* L., which was represented by Norin 26 and Yar 2, for cultivation under nutrient deficient low fertile soil of the upland ecosystems.

Key words: Deficiency symptoms, growth, nutrient composition, yield components

INTRODUCTION

Rice cultivation has become the principal activity and source of income for millions of households around the world, and several countries of Asia and Africa are highly dependent on rice as a source of foreign exchange earnings and government revenue. It is the most important crop grown in the agricultural countries of Southeast (SE) Asia given its political, economic, and social significance (Mutert and Fairhurst, 2002). Upland rice is grown on both flat and sloping fields that are not banded, that were prepared and seeded under dry conditions, and depend on rainfall for moisture (De Datta, 1975). About 3 million ha out of 42 million ha of land under rice in SE Asia (approximately 7%) is upland systems (Mutert and Fairhurst, 2002). In Africa, upland rice ecosystems accounts for about 75% of the area planted to rice (De Datta, 1975).

Soil-fertility depletion in smallholder farms is the fundamental cause of declining food production (Sanchez et al. 1997; Shepherd and Soule, 1998). For instance, an estimated annual nutrient depletion rate of 41 kg N, 4 kg P and 31 kg K per hectare has been reported in East African region (Bekunda et al., 2004). Poor rice productivity is also reported in upland systems of Asia where yields are small and only one crop is grown per year (Mutert and Fairhurst, 2002). Upland rice systems are especially most vulnerable to low soil fertility because upland rice is usually grown without fertilizer, and a long fallow period is required to generate soil fertility. Due to the increased population pressure, such lengthy fallow periods are no longer feasible and upland rice is thus a major cause of land degradation and nutrient mining in many parts of Africa and Southeast Asia (Mutert and Fairhurst, 2002; Oteng and Sant Anna, 1999). One of the measures to sustain rice productivity in these marginal lands is the use of improved varieties such as NERICA and its nutrient management.

Extensive research has been conducted on nutrient deficiency symptoms in rice (De Datta, 1981; Marschner, 1986; Dobermann and Fairhurst, 2000; Fairhurst et al. 2007). However, information on responses of NERICA to the nutrient deficiency is limited. This study aimed at comparing the effect of N, P, K, Ca and Mg deficiencies on growth and yield between upland NERICA 1 and NERICA 4 varieties, and Norin 26 (Japonica) and upland Yar 2 (Indica), both belonging to cultivated rice species *Oryza sativa*, one of the parents of NERICA. The results obtained will serve as a useful diagnostic tool in nutrient management of upland rice in Asia and Africa where nutrient deficiency is common.

MATERIALS AND METHODS

The green house experiment was conducted in Tokyo University of Agriculture (TUA) Setagaya, Tokyo, Japan from June to October 2009. Two upland NERICA varieties (NERICA 1 and 4) and upland Norin 26 (Japonica) and upland Yar 2 (Indica) were used. Seeds were treated with fungicide Benomyl –Thiram (Benlate-T) one gram per litre solution for 24 hours and washed with running tap water for 24 hours to pre-germinate. Pre-germinated seeds were seeded in seedling boxes and left to grow for three weeks to attain 3-4 leaf stage. Five seedlings per pot were transferred into ten-litre rectangular pot filled with tap water without nutrient solution for seven days. Seedlings were suspended into the solution through slots made in the pieces of sponge foam and fixed in 5-cm diameter slots made on a board floating on the solution. After seven days seedlings were subjected to nutrient solutions having one of N, P, K, Ca and Mg nutrient elements missing and one solution with full supplement of the five nutrient elements (Arnon and Hoagland, 1996). The micro elements Fe, Mo, Mn, Cu, B and Zn were applied in all pots (Table 1). Sulphur was supplied as a component of potassium, magnesium, manganese, copper and zinc sulphate. The pH of the solutions was adjusted to 5.8 by HCl and NaOH. The nutrient solution was changed weekly. The experiment was laid in a complete randomized block design with six treatments, four varieties and three replications.

Table 1. Composition of nutrient solution.

Reagent	Amount (mg L ⁻¹)	Treatment					
		Control	- N	- P	- K	- Ca	- Mg
Ca(NO ₃) ₂ .4H ₂ O	147.00	+ ^{1/}	-	+	+	-	+
K ₂ SO ₄	112.00	+	+	+	-	+	+
KH ₂ PO ₄	178.00	+	+	-	-	+	+
NH ₄ NO ₃	44.00	+	-	+	+	+	+
MgSO ₄ .7H ₂ O	489.00	+	+	+	+	+	-
CaCl ₂ .2H ₂ O	92.00	-	+	-	-	-	-
NaH ₂ PO ₄ .2H ₂ O	210.00	-	-	-	+	-	-
EDTA.Fe	60.30	+	+	+	+	+	+
Na ₂ MoO ₄ .2H ₂ O	0.02	+	+	+	+	+	+
MnSO ₄ .5H ₂ O	2.00	+	+	+	+	+	+
CuSO ₄ .5H ₂ O	0.14	+	+	+	+	+	+
H ₃ BO ₃	1.14	+	+	+	+	+	+
ZnSO ₄ .7H ₂ O	0.22	+	+	+	+	+	+

Source: Arnon and Hoagland, 1996.

^{1/}plus sign (+) and the minus sign (-) indicates that reagent applied and not applied, respectively.

Sampling and data collection

Three plants from each pot were sampled randomly from which the following data were recorded: plant height, number of tillers per plant, SPAD value (Minolta SPAD 502), fresh and dry weight of roots and aerial part of the plant. Plant height of N and P-deficient plants were taken at 35 days after transplanting which marked the end of N and P treatments. The number of panicles per plant, grains per panicle, percent filled grains and 1000-grain weight were determined at harvest.

Determination of nutrient composition in the plants

One plant sample per replication was taken at five weeks after transplanting and at harvest oven-dried for three days at 70 °C ground finely. About 0.1 g of ground plant tissue was digested by 8 ml of concentrated nitric acid (HNO₃) in a High Performance Microwave Labstation MG Ver. 3.0. (Milestone General). The digest was made to 100 ml volume with deionized water and filtered through filter paper No. 5C, followed by a second filtration using RC 0.20 µm (Toyo Roshi Co. Ltd). The samples were then analysed for P, K, Ca, and Mg by inductively coupled plasma emission spectroscopy - ICPS 7000 Ver. 2 (Shimadzu Corporation). Custom Assurance Standard (10 mg L⁻¹) was used to make standards with 0.1, 0.5, 10, 5.0 and 10.0 mg L⁻¹ concentrations. About 20 mg of the ground plant tissue samples were analysed for total N and total C by using an Automatic High Sensitive NC-Analyzer (NC - 22F Sumigraph) (Sumika Co. Ltd) using hippuric acid (C₉H₉O₃N) as standard.

Varietal differences on the influence of nutrient deficiency

In comparing the relative performance of varieties with respect to the measured parameters, respective values were computed as percent of the control values since varieties differ in their potentials.

RESULTS AND DISCUSSION

Nutrient deficiency symptoms

Plates 1-4 shows the nitrogen (N), phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg) deficiency symptoms. Nitrogen deficient plants of all varieties were characterized by stunting and yellowing. Phosphorus deficiency resulted in dark green plants with narrow, short and very erect leaves. Tillering was very poor in N and completely lacking in P deficient plants. Symptoms of potassium deficient plants were leaf rolling starting from the older leaves and dark brown necrotic spots at 49 DAT. Calcium deficient plants showed chlorosis and rolling of tips of younger leaves which later turned brownish. Magnesium deficiency symptoms were small orange-yellow interveinal chlorosis first appearing on the older leaves. Symptoms of Ca deficiency appears first on young leaves because Ca is less mobile and is not retranslocated to new growth unlike K and Mg which are mobile and readily retranslocated to new growth. Therefore symptoms appearing first on older leaves (Dobermann and Fairhurst, 2000). The manifestation of these deficiency symptoms in both Japonica and Indica, and NERICA rices is an indication of the need for fertilizer in order to increase productivity of the poor soils of upland rice ecosystems of Asia and Africa. Oikeh et al. (2008) reported a strong response to fertilizers by NERICA and considered 120 kg N, 26 kg P and 25 kg K per ha, the appropriate rate for high input farmers. This produces 145% more grain yield compared to no NPK fertilizer application. The application of 60 kg N, 13 kg P and 25 kg K per ha, appropriate for low to moderate input (smallholder) farmers, has proved to double grain yield as compared to zero fertilizer application. Basal application of P and K at sowing and top dressing with one-third urea at the beginning of tillering, and the remaining two-thirds urea at about panicle initiation is recommended.

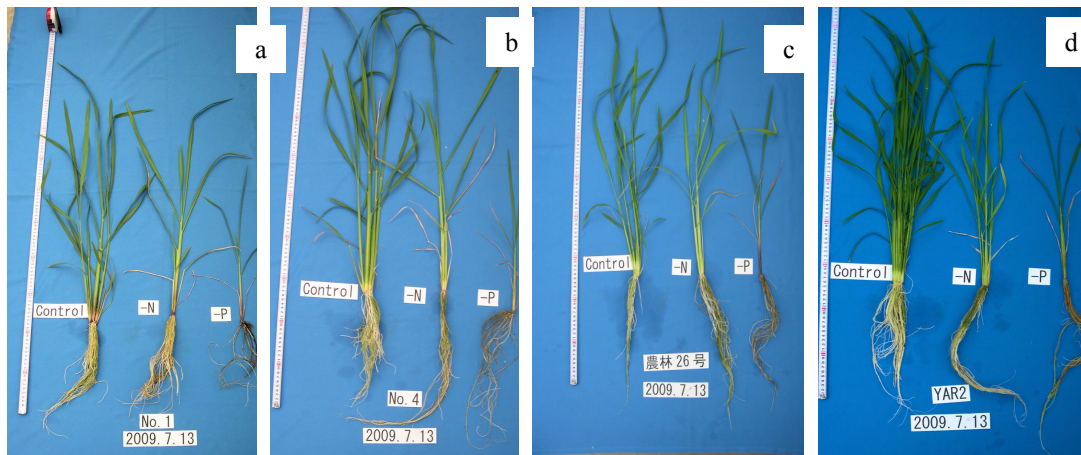


Plate 1. N and P deficiency symptoms at 38 days after transplanting: (a) NERICA 1, (b) NERICA 4, (c) Norin 26 (d) Yar 2.

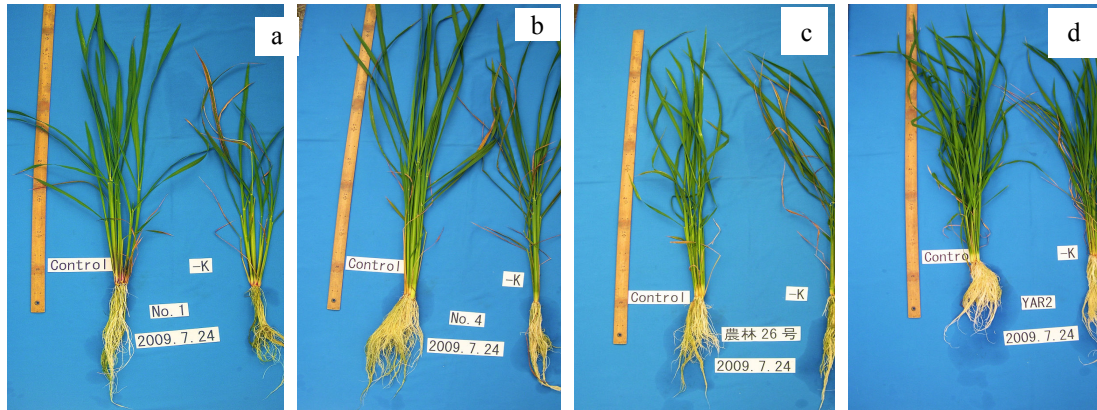


Plate 2. K deficiency symptoms at 49 DAT: (A) NERICA 1 (b) NERICA 4 (c) Norin 26 (d) Yar 2

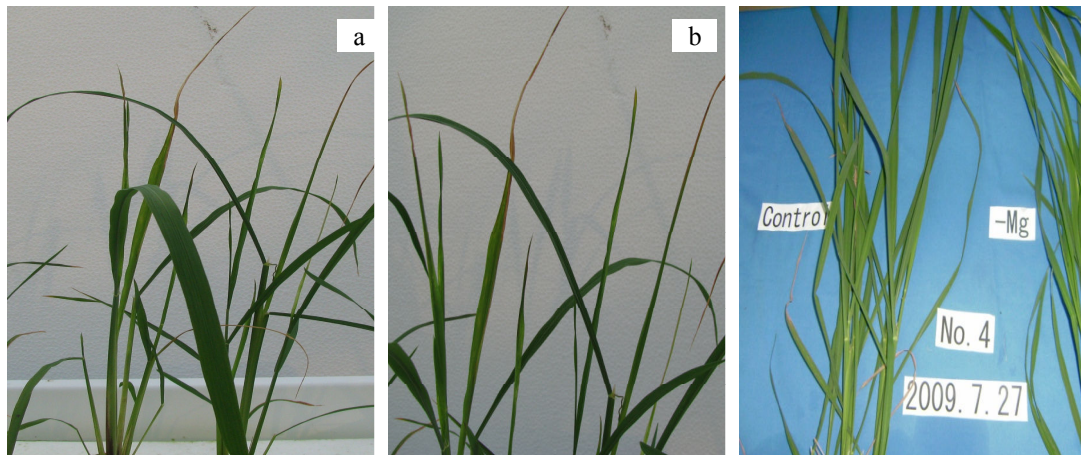


Plate 3. Ca deficiency symptoms: (a) NERICA 1 and (b) NERICA 4

Plate 4. Mg deficiency NERICA 4

Growth characteristics

With the exception of SPAD value in Yar 2, plant height, number of tillers, leaf age, chlorophyll content and dry matter were significantly higher in plants with full supply of nutrients (control), followed by nitrogen deficient plants and lastly phosphorus deficient plants (Table 2). Phosphorus is particularly important in early growth stages. It promotes root development, tillering, early flowering, and ripening. Hence, low P levels lead to poor root development and therefore poor nutrient uptake for proper plant growth. Phosphorus also stores and transfer energy required for photosynthetic activity. Thus, low P level implies impaired functions and ultimately poor growth. Under severe P deficiency the role of N i.e. promoting rapid growth (increased plant height and number of tillers), and increased leaf size, spikelet number per panicle, percentage filled grains, and grain protein content, as well as those of other nutrient elements could not be fully realised. This makes P the most limiting nutrient element at the early growth stages of rice.

Table 2. Effect of N and P deficiency on early growth and dry matter production.

Variety	Treatment	Plant height (cm)	Number of tillers	Leaf age	Shoot dry weight (g)	Root dry weight (g)	SPAD value
NERICA 1	Control	85.5 a	2.8 a	10.1 a	3.2 a	0.7 a	41.5 a
	-N	69.6 b	0.3 b	8.9 b	1.4 b	0.7 a	30.9 b
	-P	49.9 c	0.0 b	7.4 c	0.5 b	0.3 b	31.8 b
NERICA 4	Control	99.2 a	4.2 a	9.8 a	4.6 a	1.3 a	45.7 a
	-N	71.7 b	1.0 b	8.8 b	1.3 b	0.7 b	33.4 b
	-P	51.0 c	0.0 b	7.5 c	0.6 b	0.5 b	34.3 b
Norin 26	Control	92.7 a	4.9 a	10.0 a	4.9 a	0.8 a	40.2 a
	-N	71.7 b	1.1 b	8.9 b	1.5 b	0.7 a	23.4 c
	-P	52.1 c	0.0 c	8.1 c	1.3 b	0.4 b	30.7 b
Yar 2	Control	77.0 a	14.8 a	12.0 a	2.7 a	1.1 a	38.3 a
	-N	58.2 b	4.3 b	10.5 b	1.3 b	1.1 a	24.1 b
	-P	57.4 b	1.9 b	9.5 b	0.4 c	0.6 b	36.2 a

Means in columns followed by the same letters are not significantly different at $p < 0.05$.

Effect of K, Ca and Mg deficiency on growth and yield components

Plant height was significantly reduced under K deficiency while no significant difference was observed between Ca and Mg deficiency, and control (Table 3). Shoot dry weight was significantly reduced due to K deficiency followed by Ca and lastly Mg deficiency. Low K arrested the process of accumulation and translocation of carbohydrates thereby impacted negatively the growth and biomass yield of shoots. No significant difference was observed between Ca and Mg deficiency in NERICA 1, and Ca, Mg deficiency and control in Norin 26. Varieties differed significant in the shoot dry weight due to Ca and Mg deficiencies (Fig. 1).

The number of panicles per plant and grains per panicle of all varieties were significantly low under K followed by Ca and Mg deficiency. Percentage of ripened grains was reduced significantly in NERICA 1, NERICA 4 and Yar 2 due to K deficiency. Ca and Mg did not influence the percentage of ripened grains significantly. Dobermann and Fairhurst (2000) also reported one of the functions of potassium as to increase the yield components in rice.

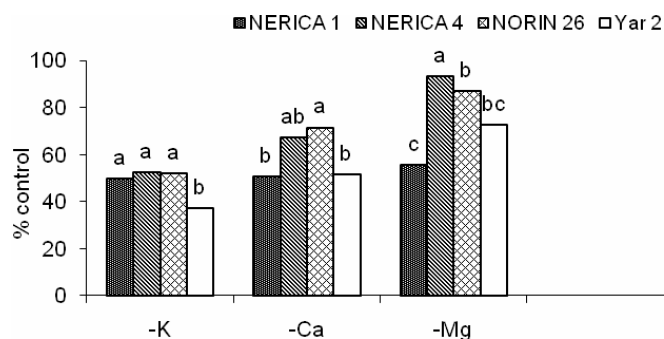


Fig. 1. Influence of nutrient deficiencies on shoot dry weight across varieties.
Bars indicated by the same letters are not significantly different at $p < 0.05$.

Table 3. Effect of K, Ca and Mg deficiency on yield components and grain yield of rice varieties.

Variety	Treat- ment	Plant height (cm)	Shoot dry weight (g per plant)	Number of panicles per plant	Number of grains per panicle	Percentage of ripened grains	1000 grain weight (g)	Grain yield per plant (g)
NERICA 1	Control	132.5 a	30.4 a	6.3 a	150.7 a	79.2 a	22.6	16.1 a
	-K	107.1 b	14.4 b	3.8 b	97.3 cb	68.8 b	21.7	5.7 c
	-Ca	119.1 ab	15.3 b	4.2 b	122.7 ba	78.4 a	22.3	9.0 b
	-Mg	119.5 ab	16.7 b	5.1 ab	125.7 b	76.6 a	21.5	10.4 b
NERICA 4	Control	118.9 a	18.2 a	6.8 a	129.4 a	74.0 ab	21.8	14.1 a
	-K	94.4 b	9.2 d	4.1 b	72.0 b	74.3 ab	20.7	4.6 c
	-Ca	102.9 ab	12.0 c	4.7 b	121.3 a	67.3 b	21.6	8.3 bc
	-Mg	116.6 a	15.3 b	5.2 ab	130.1 a	81.6 a	21.5	11.8 ab
Norin 26	Control	125.3 a	14.3 a	5.8 a	173.3 a	91.4	23.0 a	20.0 a
	-K	95.6 b	7.4 b	4.0 b	69.7 d	93.1	17.6 b	4.7 c
	-Ca	117.7 a	10.3 a	4.9 ab	104.4 c	92.7	22.7 a	10.8 b
	-Mg	120.7 a	14.8 a	5.9 a	132.7 b	90.7	21.4 a	16.0 ab
Yar 2	Control	105.7 a	33.7 a	17.4 a	139.7 a	71.4 ab	18.9 a	32.1 a
	-K	76.0 b	13.2 cd	9.7 b	47.0 c	58.4 b	16.2 b	5.1 c
	-Ca	95.6 a	17.4 c	11.6 b	124.9 b	65.6 ab	18.0 a	14.7 bc
	-Mg	104.6 a	24.4 b	13.7 ab	117.7 b	75.5 a	18.5 a	22.9 ab

Means in columns followed by the same letters are not significantly different at $p < 0.05$.

Effect of K, Ca and Mg deficiency on grain yield

Deficiency of K and Ca reduced significantly grain yield of all varieties compared to the control. Significant yield reduction due to magnesium deficiency was only observed in NERICA 1. Yield reduction due to Mg in all varieties was lowest but did not differ significantly with those due to Ca. Across varieties, NERICA 4 had the least grain yield reduction due to K, Ca and Mg deficiencies compared with Norin 26, NERICA 1 and Yar 2 (Figure 2). In the multi-location yield adaptability trials conducted in Tanzania, NERICA 4 was reported to yield higher amongst the five recently registered NERICA varieties which include NERICA 1, NERICA 2, NERICA 7 and WAB 450-12-2-

BL1-DV4 (Kibanda, KATRIN, unpublished). Dobermann et al., (1998) and Dobermann and Fairhurst (2000) also reported that K increases the yield components in rice especially the number of grains per panicle, percentage of filled grains and grain weight. The high yield of Yar 2 was attributed to the higher number of panicles per plant. In general, deficiency of K highly reduced grain yield of all varieties with Yar 2 most affected.

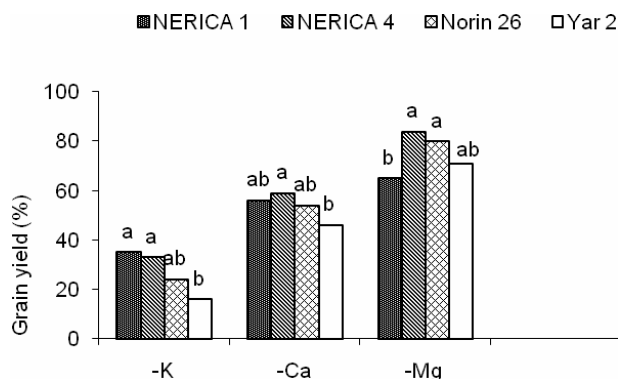


Fig. 2. Influence of K, Ca and Mg nutrient deficiency on grain yield across varieties.

Nutrient composition of rice plants

Total N and total C were significantly lowest in N deficient plants (Table 4). Except NERICA 4, total N in P deficient plants did not differ significantly compared to the control. Total Carbon in P deficient plants was significantly low in NERICA 1 and NERICA 4. Phosphorus content in control and N deficient plants in NERICA 1, NERICA 4 and Yar 2 plants was not significantly different. Plant uptake of K, Mg and Ca was lowest in P deficient plants. This is due to the impaired root development resulted from low P supply and hence inefficient nutrient uptake. The K and Mg content was significantly low in plants without P and N for all varieties. There was no significant difference in the Ca content between control and plants without N for Norin 26 and Yar 2.

Table 4. Nutrient composition of rice plants under N and P deficiency.

Variety	Treatment	Total N	Total C	mg 100 g ⁻¹			
		%	%	P	K	Mg	Ca
NERICA 1	Control	3.2 a	40.2 a	178.6 a	3706.9 a	405.0 a	420.5 a
	- N	1.4 b	36.6 c	171.3 a	2502.8 b	340.8 b	330.4 b
	- P	3.0 a	38.6 b	147.0 b	2012.4 c	270.7 c	312.4 b
NERICA 4	Control	3.0 a	40.2 a	179.7 a	3954.9 a	581.3 a	453.3 a
	- N	1.6 b	36.6 c	169.1 a	2841.9 b	479.7 b	654.5 a
	- P	1.9 b	38.6 b	152.2 b	2135.0 c	272.5 c	290.9 a
Norin 26	Control	3.1 a	40.1 ab	176.9 a	3645.2 a	433.6 a	342.5 a
	- N	1.9 b	38.2 b	169.1 b	2436.7 b	349.0 b	320.6 a
	- P	2.3 ab	40.6 a	156.0 c	1971.4 c	187.0 c	215.4 b
Yar 2	Control	2.8 a	40.5 a	169.4 a	3797.3 a	501.9 a	372.0 a
	- N	1.3 b	37.7 b	169.4 a	2572.9 b	310.8 b	317.4 ab
	- P	2.8 a	40.1 a	150.2 b	2446.0 b	228.8 c	282.8 b

Means in columns followed by the same letters are not significantly different at $p < 0.05$.

There was no significant difference in total N between plants deficient of K, Mg and Ca (Table 5). However, all showed a significant difference with control. Total carbon did not differ significantly in NERICA 1 but in NERICA 4, Norin 26 and Yar 2 where Ca deficiency recorded the lowest total Carbon. Uptake of K, Mg and Ca is influenced by the ratio of one nutrient to the other. It has been reported that the ration of exchangeable K: Mg greater than 1:1 causes decreased Mg uptake (Dobermann and Fairhurst, 2000). When Mg is low, K uptake by plant becomes high and vice versa. Similar observation exists between Ca and Mg, and Ca and K.

Table 5. Nutrient composition of straw under K, Ca and Mg deficient environments.

Variety	Treatment	Total N	Total C	P	K	Mg	Ca
		%					
NERICA 1	Control	2.2 a	40.0 a	270.9 a	6032.9 a	898.0 a	565.1 a
	- K	2.0 b	39.4 a	270.0 a	3256.5 b	961.1 a	580.9 a
	- Ca	1.4 b	40.0 a	239.6 a	5903.1 ab	447.1 b	341.2 b
	- Mg	1.6 b	40.5 a	159.3 a	7187.1 a	308.9 b	616.8 a
NERICA 4	Control	2.5 a	39.0 ab	415.6 b	6854.3 a	823.7 a	654.0 a
	- K	2.0 b	38.8 ab	322.0 b	2436.1 b	1026.5 a	486.4 ab
	- Ca	1.8 b	38.7 b	1463.1 a	3099.9 b	921.1 a	451.8 b
	- Mg	2.0 b	40.2 a	1506.2 a	3676.9 b	815.4 a	605.1 a
Norin 26	Control	5.0 a	41.1 a	1129.1 a	3353.3 b	737.8 a	586.0 bc
	- K	1.9 b	39.3 b	998.1 ab	2653.5 c	681.3 a	666.4 b
	- Ca	1.5 b	37.1 c	723.5 b	3797.9 ab	561.6 a	482.7 c
	- Mg	1.5 b	41.1 a	726.8 b	3866.4 a	472.5 a	838.5 a
Yar 2	Control	2.8 a	41.3 a	773.8 b	3756.8 a	693.8 b	935.7 b
	- K	1.9 b	39.3 b	1229.3 b	1398.8 c	1083.5 a	830.0 b
	- Ca	1.7 b	38.9 b	2005.6 a	2857.8 b	1012.5 a	843.0 b
	- Mg	2.2 b	40.6 a	789.2 b	4048.2 a	451.8 b	1226.6 a

Means in columns followed by the same letters are not significantly different at $p < 0.05$.

CONCLUSION

The growth of rice is constrained under nutrient deprivation, especially of N, P and K. Nutrient deficiency symptoms expressed by the rice plant throughout the growth period serves as an important diagnostic tool for soil fertility and plant nutrient management. Visual symptoms can be manifested in foliar parts or in the roots. The symptoms differ from one nutrient to another, but in some cases, similar symptoms can be shown by more than one nutrient or causes other than nutrient deficiency, such as diseases. Unbalanced fertilizer use may also reduce yield, as in the case where the response of N and P is constrained by insufficient K. Under such circumstances, knowledge of differential diagnosis supported by tissue analysis is necessary. In this study, visual symptoms related to the absence of major elements were similar in upland NERICA and their Indica and Japonica ancestors. Nutrient deficiencies were also reflected in the tissue analysis. The yield data from these experiments showed NERICA out yielding Norin 26 and Yar 2 under nutrient deficient conditions, suggesting that NERICA can be grown in low fertility upland soils in Southeast Asia or Africa where soil fertility amendment options are not practical due to farmers' poor access to fertilizers resulting in their low purchasing power.

REFERENCES

- Arnon, D.J. and D.R.Hoagland. 1996. In: Encyclopedia on soil. Fertilizer and Plant Nutrition Hakuyudo, Tokyo p 225.
- Bekunda, M.A., Ebanyat, P., Nkonya, E., Mngendi, D and J.J. Msaky. 2004. Soil fertility status, management and research in East Africa. East Africa Journal of Rural Development. 20(1) 94-112.
- De Datta, S.K. 1975. Upland rice around the world. In: Major research in upland rice. International Rice Research Institute Los Banos, Philippines pp 1-11.
- De Datta, S.K. 1981. Principles and Practices of Rice Production. John Wiley and Sons. New York. pp 618.
- Dobermann A, Cassman K.G., Mamaril C.P. and J.E. Sheehy. 1998. Management of phosphorus, potassium and sulphur in intensive, irrigated lowland rice. Field Crops Res. 56: 113-138
- Dobermann, A. and T. Fairhurst. 2000. Rice Nutrient Disorders and Nutrient management. International Rice Research Institute (IRRI) p 191.
- Fairhurst, T.H., Witt, C., Buresh, R.J. and A. Dobermann (Eds). 2007. *Rice: A Practical Guide to Nutrient Management (2nd edition)*. International Rice Research Institute (IRRI), Philippines, p 89.
- Marschner, H. 1986. Mineral Nutrition of Higher Plants 4th ed. Academic Press Inc., San Diego. p 674.
- Mutert, E. and T.H. Fairhurst. 2002. Developments in Rice Production In Southeast Asia In Better Crops International Vol. 15, Special Supplement pp 12-17.
- Oikeh S, Diatta S and T. Tsuboi (2008) Soil fertility and NERICA rice nutrition. In: NERICA: the New Rice for Africa – a Compendium. Somado EA, Guei RG and Keya SO (Eds.) Africa Rice Center (WARDA) Cotonou, Benin p 75-82.
- Oteng J.W. and R. Sant'Anna (1999) Rice production in Africa: current situation and issues. International Rice Commission Newsletter Vol. 48.
- Sanchez, P.A., Shepherd, K.D., Soule, M.J., Place, F.M., Mokwunye, A.U., Buresh, R.J., Kwesiga, F.R., Izac, A.N., Ndiritu, C.G. and P.L. Woomer. 1997. Soil fertility replenishment in Africa: An investment in natural resource capital. In: Replenishing soil fertility in Africa. Buresh RJ, Sanchez PA (Eds.). (Spec. Publ. No. 51, Soil Science Society of America, Madison, WI, pp 1-46.
- Shepherd, K.D. and M. J. Soule. 1998. Soil fertility management in West Kenya: Dynamic simulation of productivity, profitability and sustainability at different resources endowment levels. Agric. Ecosystem, Environment 71:133-147.