J. ISSAAS Vol. 25, No. 2: 31-44 (2019)

NUTRIENT DYNAMICS AND UPTAKE OF RICE IN IRRIGATED LOWLAND SOILS OF AGUSAN DEL NORTE SUBJECTED TO EPISODIC FLOODING

[1]Genevive A. Nemeño[1], Pearl B. Sanchez[2], Erlinda S. Paterno[2],
Rodrigo B. Badayos[2], and Pompe C. Sta Cruz[3]
PhilRice Agusan, Basilisa, RTRomualdez, Agusan del Norte, 8611, Philippines
[2] Agricultural Systems Institute and [3] Crop Science Cluster, University of the Philippines Los Baños, College, Los Baños, Laguna 4031, Philippines,
Corresponding author: ga.nemeno@philrice.gov.ph

(Received: November 19, 2018; Accepted: October 12, 2019)

ABSTRACT

The dynamics of N, P, K, Ca and Mg in irrigated lowland soils subjected to episodic flooding and uptake of these nutrients at different growth stages were evaluated in Agusan del Norte, Philippines to address the recurring and persistent problems of nutrient deficiencies resulting in poor crop growth and subsequently low yield. The study was conducted at PhilRice – Agusan Experiment Station for two cropping seasons from June 2017 to March 2018. Five fertilizer treatments were laid out in randomized complete block design and crops were managed following the PalayCheck® system. Nutrients such as N, P, K, Ca and Mg both in soil and plant tissue were collected at various growth stages and analyzed in the laboratory. Unlike N and P, K is the most dynamic in the soil when subjected to flooding. The medium to high level of exchangeable K inherent in the soil can drop to a critical level during flooding but could rise to optimum level after the flooding episodes. Soil total N and available P are high and less affected by flooding incidents. The exchangeable Ca and Mg are very high and resulted in a very wide (Ca + Mg):K ratio of 176:1 and Mg:K ratio of 86:1. The wide exchangeable Mg:K ratio and very low exchangeable Ca:Mg ratio in the soil significantly reduced Mg content at all growth stages, far below the critical limit for rice. Discovering K – induced Mg deficiency in irrigated lowland rice in Agusan del Norte is the breakthrough of this study. Thus, further study on soil K and Mg interactions and their management should be prioritized.

Keywords: nutrient management, nutrient absorption, flooding episodes, imbalanced cations

INTRODUCTION

Rice is grown in bunded fields or paddies that are flooded either from rainwater or through irrigation canals. However, flooding the soil can lead to both increase and decrease in soil nutrient content; thus, soil nutrient dynamics in lowland rice ecosystems are highly complex. During flooding, soil becomes highly reduced or can cause hypoxia, resulting to a decrease in pH of alkaline soils that leads to an increase in the mobility of soil nutrients such as N, P, K, Mg, Ca and Na. The overall effect of submergence is to increase the pH of acid soils and to depress the pH of sodic and calcareous soils. Thus, submergence makes the pH values of acid soils (except those low in iron) and alkaline soils converge to 7. Furthermore, the organic matter decomposition rate is reduced, leading to low soil nutrient content release to plants, thus affecting crop growth and productivity (Ponnamperuma 1972).

In the lowland rice areas of Agusan del Norte for instance particularly in the Philippine Rice Research Institute – Agusan Experiment Station where episodic flooding has been regularly experienced, previous soil analysis indicated that K and S are at sufficient levels while Ca and Mg are at very high levels. However, with the Minus – One Element Technique (MOET) test revealed that K and S are the most deficient based on the growth of the test plants (Nemeño and Paculba 2012). Thus, it is hypothesized that K may be present in the soil at a sufficient level but may be less available for plant uptake due to nutrient imbalance or antagonistic effect with the Ca and Mg level in the soil and presence in the flood water.

Previous studies found that high Ca levels in soils suppress Mg and K uptake by crops because of the competition between Ca, Mg and K (Marschner 1995). An imbalance between plant available Mg, Ca and K ions may lead to Mg and/or K deficiencies to crops. Thus, abundance of soil Ca, Mg, or K may compete uptake of one of the others as recorded by Bergmann (1992). In many lowland rice areas in the region that experience episodic flooding, it has been observed that about two weeks after flood occurrence, the leaves of the rice crops turn dark green, while those at the lower level become yellowish, spotted and brownish and with stunted growth, and poor root development which could be most likely due to K deficiency (Mabayag and Sobrevilla 2012). It is presumed that N and S deficiencies indicated by MOET test, and Ca and Mg toxicities found in soil laboratory analyses aggravate K deficiency due to the flooding event. Until now, the real causes of these abnormalities in crop growth are not yet clear since there is no sufficient data to pinpoint the real and specific cause. No documentation and characterization study have been conducted yet to determine the impact of episodic flooding on nutrient dynamics, availability and uptake in irrigated lowland rice soils in the station.

Thus, the study was conducted to evaluate the impacts of episodic flooding and fertilizer management on nutrient dynamics and uptake of major nutrients in irrigated lowlands of Agusan del Norte. Specifically, it aimed to (1) investigate the effects of episodic flooding on the soil chemical properties, dynamics and levels of N, P, K, Ca and Mg in the soil; and (2) examine the variation in N, P, K, Ca and Mg uptake as influenced by nutrient management at various growth stages.

MATERIALS AND METHODS

Field study. A field experiment was conducted at Philippine Rice Research Institute – Agusan Experiment Station (125°34.951' E 09°03.935'N) in Barangay Basilisa, municipality of Remedios T. Romualdez, Agusan del Norte province, Philippines for two cropping seasons from June 2017 to March 2018. One cropping during wet season (WS) or relatively drier season was conducted on June to October 2017 (2017 WS) and one cropping for very wet season (VWS) was conducted from December 2017 to March 2018 (2018 VWS).

Site description. The experimental area is a very flat (0 – 1 % slope) alluvial fan which is elevated at 14 masl. The soils were developed from the shale-sandstone, either old or new alluvium, and limestone as parent materials (Fernandez and Clar de Jesus 1980). Recent soil survey conducted identified the soils as Butuan series which developed from the older alluvial terraces (Collado and Obico 2007). The Caraga region, situated in the northern part Mindanao, has Type II climatic condition. It is characterized as having no distinct dry season with very pronounced rainfall during the months of November to April and wet during the rest of the months. Total rainfall peaked in the month of November and remained continuously high in December and January ranging from 120 to 280 mm wherein episodic floods occurred at least twice during this period. Lowest total rainfall or relatively drier months were observed in the months of March to April (45 – 70 mm) and August to September (85 – 90 mm).

Treatments. Four fertilizer treatments were laid out in randomized complete block design and replicated four times (Gomez and Gomez, 1984). The following treatments were imposed in each bunded plot measured at 5 x 5 m (25 m^2):

T1 – No fertilizer (Control);

T2 – 76-30-60 kg NPK ha^{-1} (2 splits, K) for 2017WS; 53-30-60 kg NPK ha^{-1} (2 splits, K) for 2018 VWS (Recommended NPK fertilizer rate for irrigated rice in the area) N applied based on Leaf Color Chart (LCC) reading, P was applied at 14 days after transplanting (DAT), K applied in 2 splits (50% at 14 DAT; 50% at 5 days before panicle initiation);

T3 – 76-30-60 kg NPK ha^{-1} (3 splits, K) for 2017WS; 53-30-60 kg NPK ha^{-1} (3 splits, K) for 2018 VWS
N applied based on LCC reading, P was applied at 14 DAT, K applied in 3 splits (50% at 14 DAT, 25% at 5 days before panicle initiation, and 25% applied at early flowering stage);

T4 – 53-7-37 kg NPK ha^{-1} (NPK fertilizer applied based on the documented farmers' best practice in the municipality wherein N and K fertilizers were applied in two equal splits (50% at 20 DAT, and 50% at panicle initiation stage or 35 DAT), and all P was applied at 20 DAT).

Cultural management practices. All cultural management practices and key checks recommended in the PalayCheck® System (PhilRice and FAO 2007) were strictly followed except for fertilizer management as earlier detailed. High quality seeds of a commonly planted in the area and early maturing variety - PSB Rc82 (Peñaranda) was planted for two cropping seasons.

Soil characteristics. Composite soil samples were collected before planting (initial), during active tillering, panicle initiation, flowering, and at physiological maturity stage of the crop using PVC pipe with 4" diameter and 10" long, and analyzed at Region 13 Soils Laboratory and University of the Philippines – Agricultural Systems Institute, Analytical Soils Laboratory. For the initial soil samples, soil analysis for pH was prepared in 1:1 soil to water ratio and measured with a glass electrode, organic matter was determined using Walkley and Black method, total N was analyzed using Kjeldahl method, available P was measured using the Olsen P method. The exchangeable K, Ca, and Mg were extracted by 1N ammonium acetate (NH_4OAc) and determined using a flame photometer (K) and EDTA titration for Ca and Mg. The available Zn and Cu were extracted with DTPA extracting solution and determined using the atomic absorption spectrophotometer (AAS). For soil samples taken during active tillering, panicle initiation, flowering, and at physiological maturity stage, only N, P, K Ca and Mg were analyzed following the same methods mentioned above.

Plant tissue concentration and uptake. Plant tissue samples were collected in four hills per plot during active tillering, panicle initiation, flowering, and at physiological maturity stage of the crop. Samples were oven-dried at 60 - 70°C for two to three days, weighed and grinded. Plant tissues were treated with nitric and sulfuric acid, and dry ashing was done in the furnace at 500ºC for 4-8 hours. The total N of the plant tissue both the grains and rice straw samples were determined using Kjeldahl method. The total P was determined through the Vanadomolybdate method and measured in spectrophotometer at 460 nm. The total K was determined using a flame photometer (Model No. 410, Sherwood) while Ca and Mg were measured using an atomic absorption spectrophotometer (Model No. 400, Perkin Elmer) (Perkin-Elmer 1996).

Nitrogen, P, K, Ca and Mg uptake in straws or grains (kg ha^{-1}) were computed using the formula:

$$\frac{\text{Nutrient conc in grain or straw (\%) x dry matter of grain or straw (kg ha}^{-1}\text{)}}{100}$$

Data analysis and interpretation. All data gathered were subjected to ANOVA (Gomez and Gomez 1984) using Statistical Tool for Agricultural Research software developed by the International Rice Research Institute and treatment means were compared using LSD at 5 % level of significance.

RESULTS AND DISCUSSION

Soil characteristics. The experimental area had a clay loam soil texture with slightly acidic pH (6.60). The soil is considered fertile with very high organic matter content (3.7%) and medium total N content (0.35%). Exchangeable K is high for irrigated rice at 0.44 $\text{cmol}_c\ \text{kg}^{-1}$ and available Olsen phosphorus is very high for acid soils with 25 mg kg^{-1}. Both Ca and Mg are very high at 37.97 and 37.79 $\text{cmol}_c\ \text{kg}^{-1}$, respectively. Micronutrients such as Cu and Zn are below average and very low, at 3.66 and 0.48 mg kg^{-1}, respectively (Table 1).

Table 1. Particle size distribution and chemical characteristics of the soil in the experimental area before planting

Soil Properties	Butuan Soil Series	Critical Level/ Range*
Particle size distribution		
% sand	22.1	
% silt	49.4	
% clay	28.2	
Texture	Clay loam	
pH	6.6	5.5-6.5
Organic matter content (%)	3.7	2.0-3.0
Total Nitrogen (%)	0.35	0.1-0.15
Available Olsen P (mg kg^{-1})	25	5.0 (acid soils) >25.0 (calcareous soils)
Exch. K ($\text{cmol}_c\ \text{kg}^{-1}$ soil)	0.44	0.20 $\text{cmol}_c\ \text{kg}^{-1}$
Calcium ($\text{cmol}_c\ \text{kg}^{-1}$ soil)	37.97	< 1 $\text{cmol}_c\ \text{kg}^{-1}$
Magnesium ($\text{cmol}_c\ \text{kg}^{-1}$ soil)	37.79	< 1 $\text{cmol}_c\ \text{kg}^{-1}$
Zinc (mg kg^{-1})	0.48	0.6 – 0.8 mg kg^{-1}
Copper (mg kg^{-1})	3.66	0.2 – 0.3 mg kg^{-1}

* *Source: Dobermann, A. and T. Fairhurst. 2000. Rice Nutrient Disorders and Nutrient Management. 1st Ed. International Rice Research Institute, Los Baños, Laguna, Philippines. 191 pp.*

Mg content in the soil was 13 times higher than the normal level of 1 $\text{cmol}_c\ \text{kg}^{-1}$. The excess Mg level derived from ultrabasic rocks of Mt. Hilong-hilong resulted in a Ca:Mg ratio of 1:1. The normal Ca:Mg ratio in the soil is between 3 – 4:1 (Dobermann and Fairhurst 2000). Calcium concentration in the soil was 37 times higher than the normal level of 1 $\text{cmol}_c\ \text{kg}^{-1}$ soil. The combined high levels of Ca and Mg in the irrigated lowland soils in Agusan del Norte resulted in wide (Ca + Mg):K ratio of 176:1. The ideal soil should be one with an exchangeable cation distribution of 65% Ca^{2+}, 10% Mg^{2+}, 5% K^+, and 20% H^+ (13:2:1 Ca^{2+}:Mg^{2+}:K^+ ratio; 6.5:1 Ca^{2+}:Mg^{2+} ratio) (Bear and Prince 1945). A ratio greater than 100 will result in stronger K adsorption to cation exchange sites and reduce the concentration of K in the soil solution (Dobermann and Fairhurst 2000). Moreover, the abundance of soil Ca and Mg may compete uptake of K and other cations in the exchange sites. Thus, this unbalanced cation ratio is believed to be the one of the major causes of soil nutrient problem in Agusan del Norte.

The soils grown with irrigated rice in the north east and mid-east part of Agusan del Norte province developed from the shale-sandstone, either old or new alluvium, and limestone as parent materials (Fernandez and Clar de Jesus 1980). The high concentration of Ca and Mg in Butuan soil series is inherent in soils derived from ultrabasic and/or ultramafic rocks. This condition is further aggravated by the continuous deposition of these cations carried by the floodwaters every flooding events. The pH of flood water slightly increased to 8.10 which could be attributed to the presence of calcium, magnesium and bicarbonate in the irrigation water. If this trend will continue with each flooding event, the accumulation of sediments could further increase the water pH, making many nutrients less available.

Soil nutrient dynamics. The soil NPK dynamics recorded at various soil conditions and growth stages of rice are summarized in Table 2.

Table 2. Nitrogen, P and K dynamics in the soil as influenced by NPK fertilizer application at various growth stages of rice for two cropping seasons

Fertilizer Management	**Nitrogen (%)**		**Phosphorus (mg kg^{-1})**		**Potassium (cmol$_c$ kg^{-1} soil)**	
	2017 WS	2018 VWS	2017 WS	2018 VWS	2017 WS	2018 VWS
Active Tillering	***ns***	***ns***	***ns***	***ns***	*	**
T$_1$: Control	0.36	0.38	26	26	0.46ab	0.30a
T$_2$: 76-30-60 kg NPK ha^{-1} (2 splits, K)	0.33	0.34	26	34	0.49a	0.14b
T$_3$: 76-30-60 kg NPK ha^{-1} (3 splits, K)	0.35	0.33	24	27	0.34bc	0.13b
T$_4$: 53-7-37 kg NPK ha^{-1}	0.34	0.33	23	30	0.26c	0.12b
Mean	**0.35**	**0.35**	**25**	**29**	**0.39**	**0.17**
Panicle Initiation	***ns***	***ns***	***ns***	***ns***	**	**
T$_1$: Control	0.34	0.34	29	22	0.23b	0.33b
T$_2$: 76-30-60 kg N$^{\pm}$PK ha^{-1} (2 splits, K)	0.34	0.34	29	23	0.21b	0.41a
T$_3$: 76-30-60 kg N$^{\pm}$PK ha^{-1} (3 splits, K)	0.34	0.34	30	23	0.30a	0.40a
T$_4$: 53-7-37 kg NPK ha^{-1}	0.35	0.33	29	23	0.32a	0.39a
Mean	**0.34**	**0.34**	**29**	**23**	**0.27**	**0.38**
Flowering	***ns***	**	***ns***	***ns***	***ns***	***ns***
T$_1$: Control	0.30	0.33b	28	21	0.14	0.32
T$_2$: 76-30-60 kg N$^{\pm}$PK ha^{-1} (2 splits, K)	0.35	0.35a	29	25	0.14	0.40
T$_3$: 76-30-60 kg N$^{\pm}$PK ha^{-1} (3 splits, K)	0.35	0.35a	27	22	0.13	0.35
T$_4$: 53-7-37 kg NPK ha^{-1}	0.34	0.34a	26	20	0.12	0.35
Mean	**0.33**	**0.34**	**27**	**22**	**0.13**	**0.35**
Physiological Maturity	***ns***	**	***ns***	***ns***	***ns***	***ns***
T$_1$: Control	0.30	0.34b	28	22	0.12	0.28
T$_2$: 76-30-60 kg N$^{\pm}$PK ha^{-1} (2 splits, K)	0.33	0.33c	30	25	0.14	0.35
T$_3$: 76-30-60 kg N$^{\pm}$PK ha^{-1} (3 splits, K)	0.33	0.36a	29	21	0.14	0.29
T$_4$: 53-7-37 kg NPK ha^{-1}	0.32	0.36a	27	21	0.11	0.29
Mean	**0.30**	**0.35**	**29**	**22**	**0.13**	**0.30**

* In a column, means followed by the same letter are not significantly different at 5% level of significance by LSD.

$^{\pm}$ LCC-based N rate applied in T$_2$ and T$_3$ plots during 2018 VWS was 53 kg N ha-^{1} only

Total nitrogen. Nitrogen dynamics in the soil recorded at various growth stages during 2017 WS (no episodic flooding) was not affected by fertilizer management. However, during the 2018 VWS, the combined effects of episodic flooding and fertilizer management were significant particularly during flowering and physiological maturity stage of rice. Nitrogen content in the soil ranging from 0.30 to 0.36 % was considered above the critical level for irrigated rice at 0.10 - 0.15% set by Dobermann and Fairhurst (2000). In unfertilized plots (T1), N level markedly decreased from 0.36 to 0.30% and from 0.38 to 0.34% during 2017 WS and 2018 VWS, respectively. The decrease observed in unfertilized plots was more rapid and continuous during 2017 WS (0.30%) which was relatively drier season compared to the 2018 VWS (0.35%).

The combined effects of episodic flooding and fertilizer management were significant at flowering and physiological maturity stage of rice in 2018 VWS. The soil N concentration was significantly higher in plots applied with LCC-based N (T3: 53 kg ha^{-1} plus 3 splits of K) and in farmers best practice plots (T4: 53 kg N ha^{-1} and 37 kg K_2O ha^{-1}). On the other hand, increasing the rate of N fertilizer application up to 76 kg N ha^{-1} (T2 and T3) applied based on LCC reading did not improve the level of soil N compared to the unfertilized plot (T1) throughout the 2017 WS. Although the observed soil N level during 2018 VWS was higher and the trend was decreasing towards crop maturity, but the recorded change was more or less steady compared to the previous cropping (2017 WS). This trend is generally observed in rice crops because N is equally important in the grain formation, grain filling, and protein synthesis at reproductive stage (Dobermann and Fairhurst 2000), thus ensuring N availability for plant uptake using LCC is vital.

In general, results indicated that both the indigenous N supply in the soil and the applied N were utilized by the plants to support the nutrient needs for plant growth and development. In untreated plots, since there was no other fertilizer supplied to the soil, the rapid decrease in soil N was expected as rice crop needs to take up at least 15-20 kg N to produce one ton of grain per hectare (Dobermann and Fairhurst 2000). It was observed that N level in the unfertilized plots could already support at least 4.6 t ha^{-1} grain yield both in wet and very wet cropping seasons. The results revealed that the indigenous N supply in the soils of Agusan del Norte is still very high, ranging from 65 to 90 kg ha^{-1}.

Available Olsen phosphorus. Generally, the dynamics of P in the soil was not affected by episodic flooding events and different P fertilizer rates applied (Table 2). Soil P recorded at various crop growth stages during the 2017 WS showed an increasing trend starting at panicle initiation to physiological maturity stage. Although P containing fertilizer was applied at 15 DAT or at early tillering stage, soil P concentration remained at 25 mg kg^{-1}. This trend is expected since P is needed by the crop at early stage to extend and strengthen the root anchorage into the soil system so that it could take up more nutrients to produce more tillers. On the contrary, soil P showed a decreasing trend during 2018 VWS. The P concentration in the soil continuously declined from the initial value of 25 mg kg^{-1} observed after fallow period or before planting to 22 mg kg^{-1} at flowering to physiological maturity stage. The decreasing trend observed in 2018 VWS where solar radiation and temperature were low was consistent with the observations of Dobermann and Fairhurst (2000). They observed that P is mobile in the plant and promotes tillering, root development, early flowering and ripening especially where the temperature is low. Furthermore, the results revealed that P fertilizer application did not influence P concentration in the soil even when applied at 30 kg ha^{-1} (T2 and T3). This is because inherent P content of irrigated lowland soils of Agusan del Norte is already high. Rice grain yield in unfertilized plot (T1) was 4.6 t ha^{-1}, which implies that the crop was able to take up at least 9 to 14 kg of P, which is lower than the available P in the soil. Even when P was not applied, the P level in the soil was high at 28 and 22 mg kg^{-1} during 2017 WS and 2018 VWS, respectively. Therefore, P fertilizer application could only be applied as maintenance fertilizer only to avoid nutrient mining in the soil.

Exchangeable potassium. Among the macronutrients, K is the most dynamic in the soil system and was significantly influenced by the fertilizer management and episodic flooding occurrence specifically during active tillering to panicle initiation stage (Table 2). During 2017 WS, highest K of 0.49 cmol$_c$ kg^{-1} (tillering stage) was obtained in plots applied with 60 kg K_2O ha^{-1} added in two splits (T2) but the level significantly decreased to 0.21 cmol$_c$ kg^{-1} at panicle initiation stage. For the 2018 VWS, it was noted that at active tillering stage, high level of soil K at 0.30 cmol$_c$ kg^{-1} was obtained from the unfertilized plots (T1) compared in the soils applied with K_2O fertilizer (15 to 30 kg K_2O ha^{-1} per split) (T2 and T3). The application of K-containing fertilizer at early tillering stage or at 15 DAT wherein flooding episodes occurred temporarily decreased the availability of K in the soil. The recorded decrease of 40 - 47 % was obtained causing the reduction drops below the critical level of < 0.20 cmol$_c$ kg^{-1}. It was markedly observed that K fertilizer added at 15 DAT negatively affects the K concentration level in the soil, ranging from 0.12 to 0.14 cmol$_c$ kg^{-1} only. The results revealed that episodic flooding events impacted the soil K level during flooding events from fallow period up to the tillering stage possibly due to the imbalanced levels of other nutrients deposited during flooding as well as the sediments, particularly Ca and Mg which could inhibit K availability.

Potassium is the most affected macronutrient required by plants when soil is subjected to episodic flooding. The medium to high exchangeable K inherent in the soil can drop to critical levels during flooding but could rise to optimum level after the flooding episodes. Between the two cropping seasons, soil K dynamics was more stable in 2018 VWS when episodic floods occurred as compared to 2017 WS which was a relatively drier season. The soil K concentration during 2017 WS markedly decreased during flowering to crop maturity stage ranging from 0.12 to 0.14 cmol$_c$ kg^{-1} which is already below the critical limit for rice at 0.20 cmol$_c$ kg^{-1} (Dobermann and Fairhurst 2000). The significant K declined in the soil could be due to high absorption of K from transplanting and continued till the dough stage and in some cases, up to maturity as observed in the previous researches (Ishizuka and Tanaka 1952; Mohanty and Patnaik 1974). The results also suggested that at flowering stage K is most needed by the rice plant and this is the critical stage of the crop where K should be managed properly. Among the major macronutrients, K is the most depleted nutrient in the soil since rice can take up K in luxury consumption. This could be the reason why there is a very low soil K balance for the next cropping or 2018 VWS. However, high soil K balance ranging from 0.28 to 0.40 cmol$_c$ kg^{-1} after harvest of the second crop (2018 VWS) regardless of rate and time of application. This could further be improved during fallow period when rice straws are recycled and incorporated back into the soil particularly when there is no episodic flooding event.

In general, episodic flooding occurring as early as during fallow period until maximum tillering stage of rice in the area, inhibits the availability of K. Supposedly, K is expected to increase as rice straws, stubbles and other organic materials decompose and undergo mineralization during fallow period. Although a slight increase was observed from 0.13 to 0.17 cmol$_c$ kg^{-1} soil, it was still below the critical limit (20 cmol$_c$ kg^{-1}). This could be the reason why severe K deficiency symptom was observed around 2-3 weeks after episodic flooding or during tillering stage of rice in affected fields (Nemeño and Paculba 2012). Like N, rice plants need at least 15 – 20 kg K to yield one t ha^{-1}. The results also revealed that inherent K status in the soil is very high ranging from 65 to 90 kg ha^{-1}. Thus, K fertilizer application is needed only to maintain the K balance in the soil and avoid K mining.

Exchangeable calcium and magnesium. Results of laboratory analysis during 2018 VWS showed that Ca and Mg concentration in Agusan soils (Butuan clay loam) are very high (Table 3).

At panicle initiation or after the flooding events, exchangeable Ca ranged from 25.68 to 28.14 cmol$_c$ kg^{-1}, and exchangeable Mg ranged from 21.30 to 24.30 cmol$_c$ kg^{-1}. High exchangeable Mg in the soil resulted in imbalanced Ca:Mg ratios of 1.1:1 and 1.2:1 at panicle initiation and at flowering stage, respectively. The ratio of Ca, Mg and K (Ca+Mg:K, K:Mg, Ca:Mg and Ca:K) in the soil is the most important because in case of excess concentration of one element, the uptake of the other elements is inhibited. The ideal ratio of Ca:Mg in the soil should be 3-4:1 for normal plant growth and the correct ratio of K, Ca and Mg in the soil is important because excessive concentrations of either element can affect negatively plant growth (Dobermann and Fairhurst 2000). Thus, Ca and Mg ratio in the soil should be improved and kept at the ideal ratio by increasing available Mg through fertilizer management or integrated crop management.

At physiological maturity stage, application of 60 kg K_2O ha^{-1} fertilizer (T3) applied in three splits decreased significantly Mg concentration in the soil with 15.33 $cmol_c$ kg^{-1} compared with the control (21.42 $cmol_c$ kg^{-1}). In contrast, this application resulted in increased Ca level in the soil. Moreover, the ratio of Ca:Mg increased ranging from 1.4:1 to 1.8:1 when K fertilizers were applied (T2 – T4) in two to three splits compared to 1.1:1 in unfertilized plots (T1). The increased Ca level observed in the soil could be attributed to the inhibition of Mg with K application. K^+ competes with Mg^{2+} in the apoplast binding sites, and possibly competes for transporters (Grauer and Horst 1992). Some Mg transporters may also transport other cations like K. As a consequence, a high plant available K concentration in the soil/rhizosphere blocks these unspecific Mg transporters for Mg uptake.

Table 3. Ca and Mg concentration (cmolc kg^{-1} soil) and ratio in the soil at various growth stages of rice as influenced by NPK fertilizer application in 2018 VWS

Fertilizer Application	**Calcium**	**Magnesium**	**Mg:K Ratio**	**Ca:Mg Ratio**	**(Ca+Mg):K Ratio**
	($cmol_c$ kg^{-1} soil)				
Panicle Initiation	**ns**	**ns**			
T1: Control	27.34	22.5	68 :1	1.2:1	151 :1
T2: 76-30-60 kg NPK ha^{-1} (2 splits, K)	27.14	24.3	59 :1	1.1:1	125 :1
T3: 76-30-60 kg NPK ha^{-1} (3 splits, K)	25.89	22.64	57 :1	1.1:1	121 :1
T4: 53-7-37 kg NPK ha^{-1}	25.68	22.91	59 :1	1.1:1	125 :1
Mean	*26.5*	*23.1*	*61 :1*	*1.1:1*	*131 :1*
Flowering	**ns**	**ns**			
T1: Control	28.09	21.38	67 :1	1.3:1	155 :1
T2: 76-30-60 kg NPK ha^{-1} (2 splits, K)	28.14	22.48	56 :1	1.3:1	127 :1
T3: 76-30-60 kg NPK ha^{-1} (3 splits, K)	27.98	23.08	66 :1	1.2:1	146 :1
T4: 53-7-37 kg NPK ha^{-1}	27.07	23.68	68 :1	1.1:1	145 :1
Mean	*27.8*	*22.7*	*65 :1*	*1.2:1*	*144 :1*
Physiological Maturity	**	*			
T1: Control	24.20b	21.42a	77 :1	1.1:1	163 :1
T2: 76-30-60 kg NPK ha^{-1} (2 splits, K)	24.88b	17.65ab	50 :1	1.4:1	122 :1
T3: 76-30-60 kg NPK ha^{-1} (3 splits, K)	27.48a	15.33b	53 :1	1.8:1	148 :1
T4: 53-7-37 kg NPK ha^{-1}	26.80a	18.23ab	63 :1	1.5:1	155 :1
Mean	*25.84*	*18.16*	*61 :1*	*1.4:1*	*147 :1*

* In a column, means followed by the same letter are not significantly different at 5% level of significance by LSD.

Crop Nutrient Uptake

Nitrogen uptake. The effect of fertilizer management on the total N uptake of rice plant was significant at the active tillering and flowering stage during 2017 WS. But in 2018 VWS, the combined effects of episodic flooding and fertilizer management statistically differed from panicle initiation to physiological maturity stage of rice (Fig. 1).

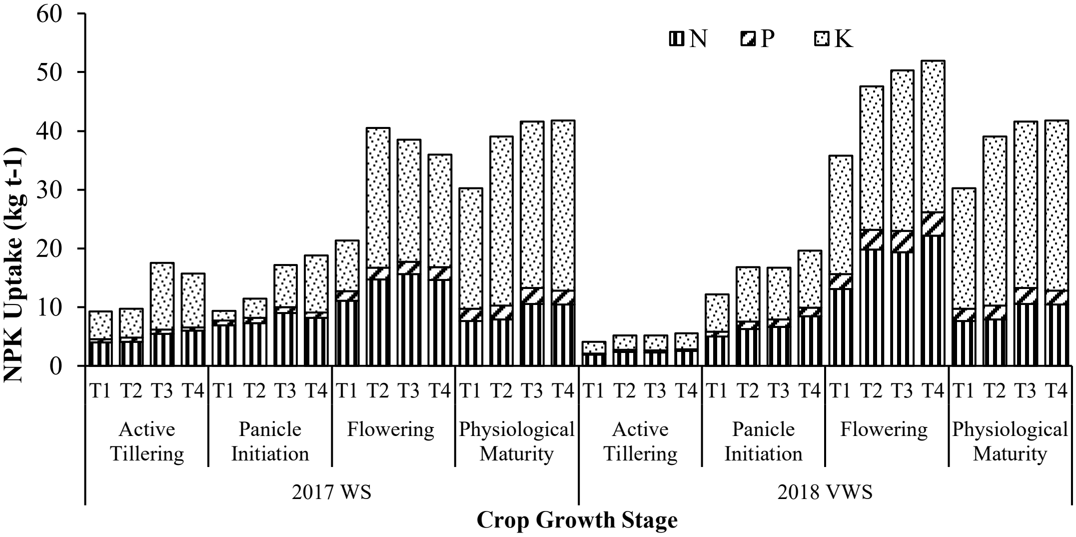

Fig. 1. Total NPK uptake (kg t-1) of rice at various growth stages as influenced by NPK fertilizer application for two cropping seasons.

The N uptake of plants applied with LCC-based N fertilizer (T2 and T3) and based on farmers best practice (T4) showed an increasing trend. In 2017 WS, the application of N ranging from 53 (T4) to 76 kg N ha^{-1} (T2 and T3) resulted in higher N uptake at active tillering stage at 5.44 and 5.99 kg t^{-1} yield compared to controlled plants (T1) with 4.02 kg t^{-1} only. Moreover, at the flowering stage where N requirement is higher, the effect of applied N was statistically higher compared to controlled plants. The uptake significantly increased at 29% in T2, 36 % in T3 and 32% in T4 when additional N fertilizer was applied. In 2018 VWS, the occurrence of episodic flooding was observed to affect the N uptake during tillering stage of rice in controlled plots. Nitrogen uptake obtained at active tillering stage was very low at 1.90 kg t^{-1}. Low N uptake was attributed to the low biomass production during the early to active tillering stage of rice due to flooding episodes. Although, N uptake at panicle initiation, flowering and physiological maturity stage increased at 4.98 kg t^{-1}, 9.56 kg t^{-1} and 13.11 kg t^{-1}, respectively, but it is significantly lower compared to treated plots. This is considered critical since the average N uptake in straw is 7 kg t^{-1} (Dobermann and Fairhurst 2000). Nitrogen is important at early stage since it promotes rapid growth (i.e. increased plant height and number of tillers) and increased leaf size. Moreover, it is also needed at reproductive stage to increase spikelet number per panicle, percentage of filled spikelet in each panicle and grain protein content (Dobermann and Fairhurst 2000).

Overall, N is an important nutrient that could affect all parameters contributing to yield, thus, N application of 23 kg ha^{-1} at early panicle initiation stage (T4) and early flowering stage (T2 & T3) allowed the plant to take up more N. These applications significantly enhanced the average N uptake of rice at flowering (15.09 kg t^{-1}) and physiological maturity stage (20.43 kg t^{-1}) compared to unfertilized plots (9.56 and 13.11 kg t^{-1}, respectively). Moreover, N uptake of rice was higher during 2017 WS when N rate applied at 76 kg N ha^{-1} compared to 2018 VWS. The difference observed could be attributed to lower LCC-based N fertilizer rate applied at 53 kg N ha^{-1} (T2 & T3) in 2018 VWS. Higher N uptake in plots applied with 53 kg N ha^{-1} (T4) based on farmers' best practice implied that plants were able to optimize the applied N during this growth stage wherein total rainfall decreased and solar radiation slightly increased favoring the physiological activity of the crop. According to Fageria et al. (2006), solar radiation is one of the most important factors of improving crop productivity owing to its direct affects in plant growth through the rate of photosynthesis. At early stage of the crop, photosynthesis products are primarily used in building plant tissues. As the crop matures, these chemical products of photosynthesis are translocated to sites of utilization and are incorporated into plant parts of economic interest i.e., grain in cereal crops. N fertilizer application at 53 kg ha^{-1} (T4) is already sufficient rate that could enhance N uptake for both cropping seasons. The total N taken up by the plants in soil was high at 75 kg N ha^{-1} and 60 kg N ha^{-1} for 2017 WS and 2018 VWS, respectively. Increasing N rate or application based on LCC reading was comparable to farmers' best practice (T4) but it is not economically sound. Thus, lower N rate is more practical and economical particularly in areas where indigenous soil N is high and climatic condition limits the photosynthetic activity in plants.

Phosphorus uptake. The P uptake of rice was significantly affected by episodic flooding and fertilizer management. Like N, P uptake of rice was reduced during flooding due to reduced biomass produced by the plant in soil subjected to flooding or when the soil is highly reduced. In 2017 WS, the effect of applied P was significant during flowering stage only with values ranging from 2.01 to 2.23 kg P t^{-1} yield. In 2018 VWS, effect of P application significantly different from tillering to harvesting. Phosphorus uptake reduced to at least 0.30 kg t^{-1} during 2018 VWS compared during 2017 WS with 0.62 kg t^{-1}.

This could be one of the reasons of reduced tillering when the soil is subjected to episodic flooding. The observed trend is important since P is particularly needed by the plant during early tillering stage to promote root development and tillering. It is also needed by the plant during reproductive stage for early flowering and ripening of rice (Dobermann and Fairhurst 2000). Thus, high P availability for high P uptake is needed during these critical stages of rice. Overall, the P uptake was consistently high in plots applied with 7 kg P_2O_5 ha^{-1} fertilizer rate (T4), which is comparable to those with 30 kg P_2O_5 ha^{-1} (T2 and T3). The results proved that inherent P status in the soil is high.

Potassium uptake. Among the macronutrients, K was the most affected nutrient when the soil was subjected to flooding episodes. It was observed that rice response to different K fertilizer management was significant during 2017 WS from active tiller to physiological maturity stage of the crop. At active tillering stage, highest K uptake was recorded in plants applied with 60 kg K_2O ha^{-1} (T3) and 37 kg K_2O ha^{-1} (T4) with 11.40 and 9.16 kg t^{-1}, respectively. It was also noted that in T2 the amount of K taken up by rice plants during flowering (11.50 kg t^{-1}) and physiological maturity stage (23.76 kg t^{-1}) was comparable. In 2018 VWS, the episodic flooding events affected the K uptake of plants from tillering until flowering stage. Although, the uptake markedly increased at the physiological maturity stage, this might have been too late to improve the yield–promoting parameters. The combined effects of fertilizer management and episodic flooding on rice K uptake was evident in the early stage wherein a lower amount of K uptake was recorded compared with the previous cropping. During this stage also, the crop was exposed to a series of flooding events causing soil K concentration to drop at below the critical level of 0.05 to 0.20 cmol$_c$ kg^{-1} soil. This could be the result of high Ca and Mg carried by the irrigation and floodwaters deposited in the soil, causing imbalanced Ca:Mg:K ratio.

The application of 60 kg K_2O ha^{-1} in two (T2) and three (T3) splits and 37 kg K_2O ha^{-1} applied in two splits (T4) further increased K uptake in both cropping seasons but K uptake recorded in unfertilized plots was also high. In general, K uptake of rice increased as the crop approached to physiological maturity stage. Since K does not have pronounced effect on tillering, K in rice is needed during reproductive to flowering stage to increase the number of spikelet per panicle, percentage of filled grains and 1000-grain weight (Dobermann and Fairhurst 2000). In fact, K uptake of rice during physiological maturity was doubled from the absorbed K at flowering stage for both cropping seasons.

The inherent K supply in the soil is high which is equivalent to 70 kg K per 4.6 t ha^{-1} grain yield in 2017 WS and 90 kg K per 4.6 t ha^{-1} grain yield during 2018 VWS. Thus, application of 53 – 7 – 37 kg N P_2O_5 K_2O ha^{-1} (T4) or even lower was found to be the appropriate and practical fertilizer rate under Agusan del Norte soil and climatic condition. This can increase the availability of soil NPK and enhance NPK uptake which can improve crop growth and productivity. The inherent fertility of Butuan soil is high; applying NPK fertilizer beyond this rate could further enhance grain yield but it is not an economical and sustainable practice. In addition, increasing K fertilizer application in soils high in Ca and Mg content could aggravate nutrient imbalance particularly Mg due to its antagonistic effects.

Synergistic and antagonistic effects of potassium. The effects of K to Ca and Mg obtained at various growth stages of rice and in grains are presented in Figure 2. The synergistic effects of K with Ca and the antagonistic effects of K on Mg were observed in the study.

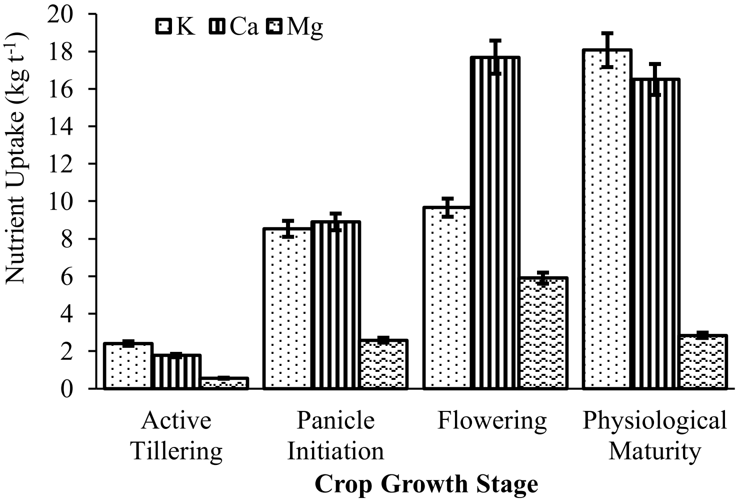

Fig. 2. Potassium, Ca and Mg uptake of rice at various growth stages as affected by different fertilizer management during 2018 VWS.

As K uptake increased, Ca uptake also increased from the active tillering to flowering stage of the crop, but at the maturity stage, K uptake significantly increased. In the 2018 VWS, the application of 53 kg N – 30 kg P_2O_5 and 60 kg K_2O ha^{-1} (K applied in 3 splits or T3) was found to further enhanced the uptake of Ca and is comparable to 53 kg N – 7 kg P_2O_5 and 37 kg K_2O ha^{-1} (T4). The average amount of Ca taken up during panicle initiation was 8.9 kg t^{-1} the straw yield; at the flowering stage, it was highest at 17.69 kg t^{-1} straw yield and during physiological maturity at 16.50 kg t^{-1} straw yield. These values actually exceeded 2 – 3 times higher than the normal range of 3 – 6 kg Ca t^{-1} grain yield as observed by Dobermann and Fairhurst (2000). The results suggest that as long as Ca is available in the soil solution, rice could take it up as this was observed in the amount of Ca taken up by the plants in both fertilized and unfertilized plots.

In contrast, high K and Ca uptake negatively affected Mg uptake of rice. Potassium is known to be an antagonist of Mg absorption in plants which is very evident in the observed Mg concentration in rice plant tissue collected in the study site. Magnesium content both in rice straws and grains ranged at 0.05 to 0.06 % at all growth stages (Table 4), far below the critical limit for deficiency in rice which is of <0.13% and <0.10% during tillering to panicle initiation and maturity stage, respectively (Dobermann and Fairhurst 2000). On the other hand, high Mg concentrations in the soil solution did not inhibit K uptake even at low external concentrations. The soil K solution found in unfertilized plots ranged from 0.30 to 0.46 cmolc kg^{-1}, higher or even double than the critical level set for rice (0.05 to 0.20 cmolc kg^{-1}). In the case of a higher Mg concentration in the soil solution, generally K uptake is not disturbed. Typically, the amount of K in the soil solution is much lower than Mg concentration; therefore, plants have been developed specific K-transport systems in the root cells to ensure sufficient K uptake when its concentration in the soil solution is critically low (Horie et al. 2011).

Despite high Mg concentration in the soil, plants were not able to utilize Mg possibly due to wide exchangeable Mg:K and Ca:Mg ratios. Mg uptake will be reduced if the exchangeable Mg:K ratio is greater than 1:1 while Ca:Mg ratio would be greater than 3 – 4:1 (Dobermann and Fairhurst 2000). The recorded Mg:K ratio ranged from 50:1 up to 77:1 while Ca:Mg ratio ranged from 1.1:1 up to 1.8:1 (Table 3). It is, in fact, possible that wide exchangeable Mg:K and very low exchangeable Ca:Mg ratios found in Butuan soils inhibits Mg uptake despite the very high soil Mg content recorded. The total Mg uptake of rice showed a very interesting trend since the amount of Mg taken up by the plants at the early tillering to panicle intiation stage across fertilizer management treatments was very low at 0.20 and 2.62 kg Mg t^{-1} grain yield. This is far below the average crop removal of 3.5 kg Mg t^{-1} grain yield (Dobermann and Fairhurst 2000) indicating that Mg is the major problem in the plant system. Although the application of NPK fertilizers increased significantly Mg uptake by the plants during flowering to physiological maturity stage, this was very low compared to Ca. Ca was preferred by the plant over Mg, making the Ca:Mg ratio in the plant higher at 3-4:1 than the normal level of 2:1. The enhanced Mg uptake of the plant with the application of NPK fertilizers at different rates and stages was an indicator that Mg was deficient in the soil system despite the observed high concentrations. Under Agusan soil conditions, the competition between Ca and K to Mg in the exchange site prevails, particularly when it is present in high concentrations.

Table 4. Potassium, Ca and Mg content and ratio in rice plant tissue at various growth stages as affected by different fertilizer management during 2018 VWS.

Fertilizer Management	Potassium (%)	Calcium (%)	Magnesium (%)	Ca:Mg Ratio	Mg:K Ratio
Active tillering	2.68 (ns)	0.19 (ns)	0.06 (ns)	3.1:1	45:1
Panicle initiation	1.82 *	0.19 (ns)	0.06 (ns)	3.4:1	30:1
Flowering	2.41 (ns)	0.18 **	0.06 (ns)	3.0:1	40:1
Physiological maturity					
Straws	1.82 (ns)	0.32 (ns)	0.05 *	5.8:1	36:1
Grains	0.30 (ns)	0.08 *	0.04 (ns)	2.0:1	8:1

Mg deficiency is the major cause of the yellowing and chlorosis of the older leaves, and shorter or undeveloped root system rice as observed after the soil was subjected to flooding episodes (Fig. 3). Mg deficiency results in shorter roots, smaller shoots, and necrotic spots on leaves owing mainly to abnormal physiological processes reflected in impaired carbon metabolism and decline in chlorophyll and carbon fixation (Hermans et al. 2010). As a rule, amounts of assimilate transported to roots significantly decreased, thus the first symptoms to appear is the root system reduction that would negatively affects the water and nutrient uptake. Under Mg deficiencies root growth decreased markedly, leading to an increase in shoot to root dry weight ratios in plants (Bose et al. 2013). Next visible symptom is the reduction of growth of the aerial parts of plants resulting in pale-colored interveinal chlorosis on older leaves and later on in younger leaves. In severe cases, chlorosis progresses to yellowing and finally necrosis in older leaves which could lead to reduced number of spikelet and reduced 1,000-grain weight (Dobermann and Fairhurst 2000).

Magnesium deficiency mimics K deficiency symptoms. The same type has been observed for K but not P (Cakmak 2008 and Hermans 2005), this could be due to the high mobility of Mg under Mg starvation; thus, Mg deficiency symptoms typically appear on older leaves of the plant just like K (Dobermann and Fairhurst 2000). The diagnosis of the previous nutrient deficiency symptoms observed in the area was associated mainly with K because Mg deficiency rarely occurs in irrigated lowland soils.

Fig. 3. Comparison of healthy plant (center) and Mg deficient plants (left and right side) showing yellow orange interveinal chlorosis appeared in older leaves of stunted plants observed after flooding episodes in the irrigated lowland rice of PhilRice Agusan experimental fields.

CONCLUSION

Among the macro nutrients, K was the most dynamic in the irrigated lowland rice and when soils were subjected to episodic flooding. The high levels of indigenous K supply in the soil plus the high K fertilizer application and the synergistic effects of K and Ca are the major cause of Mg deficiency despite high Mg concentration in the soil. Discovering K-induced Mg deficiency in irrigated lowland rice soil of Agusan del Norte is the breakthrough of this study, thus further in-depth research work on soil nutrient dynamics and interactions of K, Ca and Mg as well as the management of these major cations particularly when the soil is subjected to this kind of flooding and exposed to this kind of climatic condition is needed since this problem is expected to worsen as more intense rainfall and frequent flooding are being experienced due to climate change.

ACKNOWLEDGMENT

I am sincerely extending my deep gratitude to the following who helped me accomplish this project: the Philippine Rice Research Institute (PhilRice) management; the Department of Science and Technology – Science Education Institute (DOST – SEI) through the Accelerated Science and Technology Human Resource Development Program (ASTHRDP) for my scholarship grant and thesis support; my advisory committee and co-authors - Dr. Pearl B. Sanchez, Dr. Rodrigo B. Badayos, Dr. Erlinda S. Paterno, and Dr. Pompe C. Sta Cruz; PhilRice Agusan, Agricultural Systems Institute, Soil Science and PhilRice Agusan families.

REFERENCES CITED

Bear, F.E and A.L. Prince. 1945. Cation – equivalent constancy in alfalfa. Journal of the American Society of Agronomy. 37:217 – 222.

Bergmann W. 1992. Colour Atlas: Nutritional disorders of plants – development, visual and analytical diagnosis. Jena, Germany: Fischer Verlag.

Bose, J., O. Babourina, S. Shaabala and Z. Rengel. 2013. Low pH and aluminum resistance in Arabidopsis correlates with high cytosolic magnesium and increased magnesium uptake by roots. Plant Cell Physiol. 54:1093 – 1104.

Cakmak, I. and A.K. Kirkby 2008. Role of magnesium in carbon partitioning and alleviating photo-oxidative damage. Physiol. Plant., 133: 692-704.

Collado, W.B. and M.R. Obico. 2007. Result of the soil analysis on the physical and chemical characteristics of Butuan series. PhilRice AES, Basilisa, R.T. Romualdez, Agusan del Norte. 2 pp.

Dobermann, A. and T. Fairhurst. 2000. Rice Nutrient Disorders and Nutrient Management. p. 84 – 86. Singapore: Phosphorus and Potash Institute and International Rice Research Institute.

Fageria, N.K., V.C. Baligar, and R.B. Clark. 2006. Physiology of crop production. Food Products Press. The Haworth Press, Inc. New York. 345 pp.

Fernandez, N.C. and J.I. Clar De Jesus. 1980. Philippine Soils. General Land Use and Parent Materials. College, Laguna. 229 pp. NFAC – UPLB Country side Action Program.

Gomez, K.A and A.A. Gomez. 1984. Statistical procedures for agricultural research. John Wiley & Sons, Inc. 680p.

Grauer, U.E. and W.J. Horst. 1992. Modelling cation amelioration of aluminum phytotoxicity. Soil Science Society of America Journal 56:166-172.

Hermans, I. 2005. Magnesium deficiency in sugar beets alters sugar partitioning and phloem loading in young mature leaves. Planta, 220: 541-549.

Hermans, C., Vuylsteke, M., Coppens, F., Cristescu, S.M., Harren, F.J., Inze, D. and N. Verbruggen. 2010. Systems analysis of the response to long-term magnesium deficiency and restoration in *Arabidopsis thaliana*. New Phytol. 187. 132 – 144.

Horie, T., Brodsky, D.E., Costa, A., Kaneko, T., Lo Schiavo, F., Katsuhara, M., and J.I. Schroeder. 2011. K^+ transport by the OsHKT2;4 transporter from rice with atypical Na^+ transport properties and competition in permeation of K^+ over Mg^{2+} and Ca^{2+} ions. Plant Physiol 156:1493–1507.

Ishizuka Y. and A. Tanaka. 1952. Biochemical studies on the life history of rice plants. Journal of the Science of Soil and Manure, Japan 23: 23–28.

Mabayag, C. A. and R. G. Sobrevilla. 2012. Identification of Micronutrient Deficiency/Toxicity Indicators and Development of Quick Remediation Techniques. PhilRice Agusan 2012 Semi-Annual Report. 83 pp.

Marschner, H. 1995. Mineral nutrition of higher plants. Academic press. London. Britain. 647pp.

Mohanty, S.K. and S. Patnaik. 1974. Uptake of nutrients in relation to growth of rice as influenced by varying nutrient environments in different soil types. Riso 23:351–363.

Nemeno, G.A and S. M. Paculba. 2012. Correction of micronutrient disorders in soils planted to rice in Mindanao. PhilRice Agusan 2012 Semi-Annual Report. 83 pp.

Perkin – Elmer. 1996. Analytical Methods for Atomic Absorption Spectroscopy. The Perkin-Elmer Corporation. United States of America. 310 pp.

Philippine Rice Research Institute, and Food and Agriculture Organization. 2007. PalayCheck® System for Irrigated Lowland Rice. Philippine Rice Research Institute. 90 pp.

Ponnamperuma, F.N. 1972. The chemistry of submerged soils. Adv. Agron. 24:29–96.