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An Assessement of Paddy Production System in Central Kenya with Special Reference to Micronutrients

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Abstract

Soil degradation reduces agricultural productivity and poses a great threat on food security status of households. In Kenya, farmers have for a long time been using only nitrogen and phosphorous based fertilizers oblivious of the soil fertility status. In most cases, there has been lack of plant response to these fertilizers, which could be due to a limitation of nutrients other than nitrogen and phosphorous. Soils are considered as variable natural bodies because of combined intrinsic and extrinsic factors of different intensities at a field or a larger region scale therefore an understanding of such variability is imperative to provide insights needed in their management. This study was thus initiated to assess the availability of soil micronutrients from rice growing Vertisols in the Mwea irrigation scheme. Top (0-15 cm) soil samples were collected across paddy fields in the irrigation scheme and analyzed for iron (Fe), zinc (Zn), copper (Cu) and manganese (Mn) by the 0.1 N HCl extraction method. Soil pH (water and 1 M KCl) was also measured using the glass electrode pH meter. Soil solution pH ranged from 4.56 to 8.05 and 3.33 to 6.63 for water and 1 M KCl respectively. Soil Fe, Zn, Cu and Mn concentration varied greatly and ranged from undetected to 1360.6, 0.12 to 8.00, undetected to 9.29 and 1.50 to 849.2 mg/kg respectively. Coefficient of variations (CVs) for soil micronutrients ranged from 64% to 154% indicating very high variability. Soil pH was least variable with CVs 12% and 15% for water and KCl respectively. These results imply that the paddy soils in Mwea region are highly heterogeneous and soil micronutrients are enriched in some areas and depleted in others due to farm management practices and soil properties. Averagely, soil available Zn was deficient across the scheme and as such Zn fertilization can be effective in increasing soil Zn concentration and availability in the soil-root interface further enhancing soil productivity and yield quality. Attention should also be paid to appropriate farm management practices to avoid accumulation or depletion of nutrients.

Keywords: micronutrients, Mwea irrigation scheme, paddy soil, zinc deficiency, zinc fertilizer

1. Introduction

Soil plays a major role in determining the sustainable productivity of an agro-ecosystem. It is an important source of bioavailable micronutrients and a shortage or surplus of bioavailable micronutrients in the soil limits growth of crops (Liu et al., 2004; Ye et al., 2015). Out of the 16 plants nutrients, zinc (Zn), copper (Cu), iodine (I), manganese (Mn), molybdenum (Mo), boron (B), iron (Fe) are among those referred to as micronutrients. These elements are required in small quantities for plant growth but have agronomic importance as macronutrients playing a vital role in growth and development of plants (Zayed, Salem, & Sharkawy, 2011; Cholarajan & Vijayakumar, 2013). Furthermore, plant growth and development may be retarded if any of these elements is lacking in the soil or is inadequately balanced with other nutrients (Cholarajan & Vijayakumar, 2013; Das, 2014).

Cropping systems and fertilization practices have been shown to influence the availability of soil micronutrients (Wei, Hao, Shao, & Gale, 2006). Studies have shown that soil pH, phosphorus and organic matter contents influence the availability of micronutrients under various soil conditions (Wei et al., 2006; Li et al., 2007). According to Rieuwerts, Ashmore, Farago, and Thomton (2006) and Zhao, Liu, Xua, and Selim (2010), pH is the most important predictor for the estimation of extractable heavy metals from soil because of its strong effects on speciation, solubility and their bioavailability in soil solution. The capacity of a soil to supply microelements directly influences plant structural development and physiological function, regulates plant growth and development and product quality (Ye et al., 2015).

In Kenya, rice is a major cereal food crop ranking third after maize and wheat. In the recent years, its importance has grown as per capita consumption, particularly in urban areas, has increased far more rapidly than for other cereal crops (Ministry of Agriculture [MoA], 2009; European Cooperative for Rural Development [EUCORD], 2012). According to the EUCORD (2012) report, statistics showed that annual rice consumption in Kenya had increased at a rate of 12% compared to wheat at 4% and maize at 1%. Unfortunately, the country is not able to meet the soaring demand and is only able to produce a fifth of its national needs. The deficit is normally covered through imports mainly from Pakistan, Vietnam, Thailand and India (United States Agency International Development [USAID], 2014). Nonetheless, there are enormous possibilities for increasing rice productivity through better crop management, improved timeliness of operations and better market understanding considering the available vast unused productive potential (Rosemary, Bibiana, Njuguna, Dominic, & Daniel, 2010).

Rice production in Kenya is mainly from irrigation schemes covering approximately 13,000 ha and includes irrigation schemes in Nyanza; West Kano and Ahero, Western; Bunyala scheme and Mwea irrigation scheme in Central (MoA, 2009). About 95% of rice consumed in Kenya is produced from government managed irrigation schemes while the remaining 5% is produced under rain-fed conditions (Muhunyu, 2012; USAID, 2014). The largest rice producing area is the Mwea irrigation scheme (MIS); where production is mostly based on the conventional practice of continuously flooding the paddy fields (MoA, 2009; Ndiiri, Mati, Home, & Odongo, 2013). A study by Kondo, Toshinari, and Wanjogu (2001) in the MIS indicated that the soils are medium to high in terms of major essential elements except potassium. Further work by Kihoro, Njoroge, and Hunja (2013) concluded that Mwea soils are suitable for rice cultivation. Despite this great potential, there has been a marked stagnation in the mean crop production which has been attributed to soil chemical and physical degradation due to continuous mono-cropping, use of production techniques that are inefficient among many other factors as reported by Nyamai et al. (2012). Therefore, improving rice yields in existing irrigated areas rather than further expansion is more likely to be the main source of growth for the crop in Kenya only if proper soil and water management is taken into account especially during the vegetative phase of the crop (Nyamai et al., 2012). Sustainable productivity of a soil mainly depends on its ability to supply essential nutrients to growing plants; therefore an understanding of the differences and distribution patterns of soil bioavailable nutrients is vital in its management and fertilizer applications (Liu et al., 2004).

Although rice is an important cereal crop for Kenya's population, no information is available on its soil micronutrient nutritional status yet according to Bell and Dell (2008), micronutrient deficiency is reported as a major constraint to productivity, stability and sustainability of soils in many parts of the world. Micronutrient deficiencies in plants are common in calcareous soils with high pH such as those found in arid and semiarid regions (Alloway, 2008). Due to its special geographical positioning and importance, the MIS represents a critical entry point in ensuring that rice production is enhanced in the country. Therefore this study was initiated to quantify micronutrient (Fe, Mn, Cu and Zn) concentrations and their distribution in the surface soils of MIS. The key challenges and opportunities identified in Mwea could be used as a point of reference for enhancing rice production in other existing or potential rice production areas. In addition, our work aimed at identifying the possible hot spots for micronutrient deficiencies and toxicities and recommend appropriate management strategies to avert the accompanying negative effects. The findings will provide guidelines beneficial for soil management and strategic sustainable agriculture in terms of micronutrients.

2. Materials and Methods

2.1 Description of the Study Site

The MIS is located on the lower slopes of Mt. Kenya in Kirinyaga County in Central Kenya. It lies within latitudes 37°13′E and 37°30′E and longitudes 0°32′S and 0°46′S with a mean annual precipitation of about 950 mm. The area experiences bimodal rainfall with the long rains falling between March and May and short rains between October and December (Kihoro et al., 2013). According to Kenya's agro-climatic zoning the scheme traverses three agro-climatic zones with maximum moisture availability ratios ranging from 0.65 for zone III towards the highland slopes to 0.50 for the vast area covered by zone IV and to 0.4 for the semi-arid zone V (Sombroek, Braun, & van der Pouw, 1982). The area is generally hot and average temperatures range between 23 and 25 °C, with about 10 °C difference between the minimum temperatures in June/July and the maximum temperatures in October/March. The predominant soils of the rice-growing areas of Mwea are Vertisols characterized by imperfectly drained clays, very deep, dark grey to black, firm to very firm and prone to cracking (Sombroek et al., 1982). Kondo et al. (2001) also observed predominant presence of Vertisols in the scheme and surrounded by Alfisols at higher elevation. The most appropriate season for rice cultivation is from August to December, when temperatures are opportune for grain filling and with less risk of disease incidence; but is same period when flow of rivers are at their lowest straining on water availability for irrigation (Mukiama & Mwangi, 1989). Rice crop production is also complicated by the staggered planting calendar implemented in the scheme (Ijumba, Mwangi, & Beier, 1990) since available water is not enough to reach all farmers during the most opportune rice growing season.

Data from MoA (2009) indicate that the entire irrigation scheme covers an area about 12,282 ha of which about 9,000 ha has been developed for paddy production. MIS is the largest and oldest of the seven governments managed irrigation schemes in Kenya developed in 1953. It is divided into five sections/units at different elevations namely Tebere and Mwea covering 1400 and 1300 ha respectively and Thiba, Wamumu and Karaba covering 1200, 1200 and 1100 ha respectively (Njagi, 2012). There is an out-grower section covering about 2300 ha where irrigation infrastructure has not been developed. The farmers in the out-grower section use water drained from the main irrigation scheme (Njagi, 2012). Mwea and Tebere sections are the largest and oldest to be developed while Karaba, the smallest located at the end of the scheme was the last to be developed in 1973 (Kabutha & Mutero, 2002). The irrigation scheme gets its waters from two rivers the Nyamindi and Thiba which have no storage facilities. The Nyamindi mainly serves the Tebere (T) unit, while the Thiba serves Mwea (M), Thiba (H), Wamumu (W) and Karaba (K) units. The water is drawn from the rivers by gravity through dikes and distributed via unlined open channels to and out of the farms. Rice is grown as a mono-crop for one season in a year and uses the flooded-paddy irrigation method. Water resources from the Nyamindi that exceed the sum required for river maintenance flow and for irrigation inTebere section is regarded as surplus water which is transferred to the Thiba river in cases of shortage via a link canal (Kabutha & Mutero, 2002; Abdullahi, Mizutani, Tanaka, Goto, & Matsui, 2003).

2.2 Soil Sampling and Analysis

Soil samples were collected across the five production units of MIS namely Mwea, Wamumu, Karaba, Thiba and Tebere. Surface (0-15 cm) soil samples were collected in August 2013 and 2014 cropping period from Mwea rice fields. Benchmark sampling was applied where benchmark farms were identified and marked on MIS map generated from google. Several benchmark fields were identified across the five units for soil sampling and a total of 166 fields marked. Three to five representative soil samples were collected from fields averaging about 0.4 ha using a soil auger. The samples were mixed thoroughly and a composite sample from each field taken for evaluation. Transparent polythene bags were used to keep the samples and each labelled. The samples were dried, ground and passed through a 2 mm sieve in readiness for chemical analysis. The samples were exported to Japan and analysed in the Soil and Ecological Engineering laboratory, Faculty of Life and Environmental Science at Shimane University. The samples were analysed for pH and micronutrient (Fe, Mn, Cu and Zn) concentration.

Soil pH was measured potentiometrically using a glass electrode pH meter (HORIBA D-51) in 1:2.5 soil-water/1 M KCl ratio suspension as described by the International Institute of Tropical Agriculture [IITA] (1979) and McLean (1982) using 8 g air-dried soil. Soil Cu, Fe, Zn and Mn concentrations were first extracted by mixing 2 g of air dried soil with 20 ml of 0.1 N HCl and shaking for 1 hour at 150 rounds per minute (rpm) as described by Osiname, Schulte, and Corey (1973). The solution was then filtered through ADVANTEC Whatman filter paper No. 6 and the micronutrient concentration in the leachate determined by Inductively Coupled Plasma-Atomic Emission Spectroscopy (ICPE-9000 Shimadzu Co. Ltd., Kyoto, Japan).

2.3 Data Analysis

Data were statistically analysed by ANOVA test using a statistical package, SPSS version 22 for windows (IBM SPSS). Descriptive statistics including mean, maximum, minimum and standard deviation were determined. Significant differences in mean soil parameter values were determined using Duncan's multiple range test ($p < 0.05$). The coefficient of variation (CV) which is the ratio of mean and standard deviation and expressed as a percentage for each soil parameter was also calculated. A Pearson correlation analysis was performed to determine the relationship between soil pH and soil micronutrient concentrations. Surface soil micronutrient concentrations in the MIS were evaluated basing on the micronutrient concentrations obtained from the laboratory analyses and were compared with established critical levels for optimum rice production. The CV was used to judge the scale of heterogeneity in surface soil pH and micronutrient status in the scheme.

3. Results and Discussions

3.1 Soil pH

Table 1 shows the mean soil pH for MIS units.

Table 1. Soil pH (mean±SD) across the units

Unit name	pH_{water}	pH_{KCl}
Mwea	5.99 ± 0.75^{b}	4.52 ± 0.71^{c}
Thiba	6.11 ± 0.68^{ab}	4.68 ± 0.60^{bc}
Tebere	6.51 ± 0.81^{ab}	5.24 ± 0.77^{ab}
Wamumu	6.28 ± 0.78^{ab}	4.95 ± 0.77^{abc}
Karaba	6.65 ± 0.57^{a}	5.27 ± 0.55^{a}
Overall mean	6.27±0.76	4.88±0.75
CV (%)	12	15

Note. Means followed by the same superscript letter within a column are not significantly different at $p < 0.05$; SD: standard deviation, CV: coefficient of variation.

Across the irrigation scheme, surface soil solution pH ranged from 4.56 to 8.05 and 3.33 to 6.63 with mean values of 6.27 and 4.88 for pH water and KCl respectively. In our sampling, we observed soil colour variations where higher elevation unit fields especially in the Mwea unit contained reddish/brown characteristics that darkened out progressively in the lower elevation units.

Unit-wise, Mwea unit located at a slightly higher elevation had soil solution pH_{water} ranging from a minimum of 4.56 to a maximum of 8.05. In Thiba unit, the values ranged from 4.90 to 6.96 whereas in Tebere they ranged from 4.90 to 7.74. Further down in Wamumu and Karaba, the values ranged from 4.91 to 7.86 and 5.53 to 7.99 respectively. For pH_{KCl} the values ranged from 3.33 to 6.62 in Mwea unit, 3.53 to 5.48 in Thiba and from 3.85 to 6.56 in Tebere unit. In the lower elevation units of Wamumu and Karaba, the values varied from 3.65 to 6.63 and 4.36 to 6.62 respectively. We noticed that surface soil pH gradually increased from the high elevation areas of Mwea towards the low topographical fields in Karaba. Surface soil solution pH values measured in water were consistently higher relative to pH values in salt solution (KCl), an indication that Mwea irrigation scheme soils have a negative charge. The Kenya Soil Survey [KSS] (1987) rating (Table 2) was used to classify soil solution reaction.

Table 2. Key to soil solution reaction by KSS

Measured pH	Class description	Level of pH
< 4.5	Extremely acid	Very low
4.5-5.0	Very strongly acid	Low
5.1-5.5	Strongly acid	Low
5.6-6.0	Medium acid	Medium
6.1-6.5	Slightly acid	Medium
6.6-7.3	Neutral	Medium
7.4-8.4	Mildly alkaline	High
8.5-9.0	Strongly alkaline	High
> 9.0	Very strongly alkaline	Very high

Generally, the MIS soils can be classified as being slightly acidid with medium level pH. At unit level, Mwea unit soil reaction can be classified as being medium acidic, Thiba, Tebere and Wamumu units as slightly acidic while Karaba unit soils fall in the neutral description according to KSS (1987) key in Table 2. The moderately high soil solution pH had also been recorded by Kondo et al. (2001) who attributed it to the high carbonate concentration in the soils of this semi-arid region. In their study, they noted that the MIS soils which are mainly Vertisols were developed from calcareous-basalt parent material. The occurance of high soil pH has been associated with climate and/or parent material with drier conditions coupled with calcareous parent material favouring high soil pH (Kawaguchi & Kyuma, 1974). In assessing the distribution, characteristics and classification of Vertisols; Murthy, Bhattacharjee, Landey, and Pofali (1982) also related soil pH to the nature of the parent material, climate and topographic situations adding that elements of climate and topography remaining the same, Vertisols are known to develop from parent materials rich in alkaline earths thus higher pH values. The gradual increase in soil solution pH with decreasing elevation can be attributed to increase in water soluble bases in the receiving depression unit of Karaba transported in irrigation water. In assessing the effects of landscape attributes and plant community types on soil chemical properties in a semiarid area in Iran, Rezaei and Gilkes (2004) reported a negative relationship between pH and altitude noting that with increased altitude comes increased leaching that reduces soluble bases and resulting in higher hydrogen ion (H^+) activity that is registered as low pH level.

Descriptive statistics for soil solution pH gave CVs values of 12% and 15% for water and KCl respectively an indication that very low variability exists in soil pH. Similar low variance in soil solution pH has been reported elsewhere for instance Aimrun, Amin, Ahmad, Hanafi, and Chan (2007) in Malaysia (2.6%); Abu and Malgwi (2011) in Nigeria (10.3%) and Addis, Klik, and Strohmeier (2015) in Ethiopia (6.5%). This is because pH values are indicated on log scale of proton concentration in soil solution; otherwise there would be a much higher variability if soil acidity is expressed in terms of proton concentration directly (Sun, Zhou, & Zhao, 2003). Given the results from the low CV statistics, we can construe that the soils in the study site are relatively homogenous in view of their pH status and this could be attributed to the homogeneous calcareous parent material and the drier climate in the area.

3.2 Soil Micronutrient Concentration

Mean soil concentrations for 0.1N HCl-extractable Cu, Fe, Mn and Zn across the units is shown in Table 3.

Table 3. Soil micronutrient concentration (mean±SD) across the units

	Soil micronutrient concentration (mg/kg)			
	Fe	Mn	Cu	Zn
Mwea	205.0±286.7^{a}	191.0±167.6^{ab}	1.69±1.06^{b}	1.47±1.22^{a}
Thiba	172.5±236.8^{a}	242.6±125.2^{a}	2.33±099^{b}	0.88±0.96^{a}
Tebere	102.7±91.5^{a}	114.9±83.3^{b}	2.21±1.37^{b}	1.09±0.67^{a}
Wamumu	94.9±96.1^{a}	139.0±109.6^{ab}	4.23±1.98^{a}	1.62±0.64^{a}
Karaba	49.6±42.3^{a}	130.0±69.6^{b}	2.70±1.52^{b}	1.53±0.69^{a}
Overall mean	130.1±199.8	159.6±130.0	2.66±1.77	1.44±0.94
CV (%)	154	81	67	64

Note. Means followed by the same superscript letter within a column are not significantly different at $p < 0.05$; SD: standard deviation, CV: coefficient of variation, Fe: iron, Mn: manganese, Cu: copper, Zn: zinc.

In our results, very wide variations in surface paddy soil micronutrient concentration were found. Surface soil Mn concentration ranged from 1.5 mg/kg to 849.2 mg/kg, soil Fe concentration ranged from undetected to 1360.6 mg/kg, soil Cu concentration from undetected to 9.3 mg/kg and soil Zn from 0.1 mg/kg to 8.0 mg/kg. The ranking order of micronutrient concentration in the MIS paddy soils was Fe > Mn >> Cu > Zn indicating that soil Fe concentration followed by Mn were in higher concentrations compared to soil Cu and Zn concentrations.

Within the production units, surface soil Fe concentration varied from undetected to 1360.6 mg/kg in Mwea unit, soil Mn from 1.5 to 849.2 mg/kg, soil Cu from undetected to 5.5 mg/kg and soil Zn from 0.1 to 8.0 mg/kg. In Thiba unit, values varying between 22.1 and 795.4 mg/kg were recorded for soil Fe, soil Mn from 63.6 to 504.3 mg/kg, soil Cu from 0.68 to 4.22 mg/kg while soil Zn ranged from 0.13 to 2.68 mg/kg. In Tebere unit, soil Fe varied from 13.9 to 398.8 mg/kg, soil Mn from 28.5 to 380.0 mg/kg, soil Cu from 0.18 to 4.5 mg/kg and soil Zn from 0.3 to 2.57 mg/kg. Further lower the irrigation scheme in Wamumu, surface soil Fe ranged from 16.3 to 433.0 mg/kg, soil Mn from 41.4 to 433.2 mg/kg, soil Cu from 0.96 to 9.29 mg/kg and Zn from 0.38 to 2.77 mg/kg. In Karaba at the end of the scheme, soil Fe ranged from 0.5 to 226.8 mg/kg, soil Mn from 35.7 to 292.9 mg/kg and 0.23 to 6.78 mg/kg for soil Cu whereas soil Zn ranged from 0.35 to 3.69 mg/kg. In general, except for soil Fe and Mn, soil Cu and Zn concentration showed an increasing trend from the higher elevation Mwea unit to the lower elevation units of Wamumu and Karaba. This can be attributed to the irrigation water flow that carries dissolved Zn and Cu depositing them in the receiving depression areas as the slope gradient decreases. Although statistical analysis indicted lack of significant differences in soil Fe concentration, CV values depicted a highly heterogeneous irrigation scheme with 154%, 81%, 67% and 64% for Fe, Mn, Cu and Zn respectively. The variability observed in the micronutrient concentration could be attributed to the differences in land management practices and other anthropogenic activities.

Micronutrients are involved in the entire metabolic enzyme system of plants. The range between toxic and deficient levels is often very small; thus a proper supply of micronutrients is essential for good plant growth. The electrochemical and biochemical changes caused by submergence are known to directly and indirectly influence the solubility and availability of micronutrients in the soil (Neue & Mamaril, 1985) and therefore care must be taken in maintaining the right soil condition to avoid the adverse effects of micronutrient stresses in the soil.

3.2.1 Soil Fe Concentration

In soils, Fe occurs mainly in oxides and hydroxides forms as small particles or associated in amorphous form with the surfaces of other minerals. In horizons rich in organic matter, it appears to be in chelated forms (Kabata-Pendias, 2011). In paddy soils, Fe is one of the most notable elements because it is abundant and undergoes redox transformation (Kyuma, 2004). It is required for electron transport in photosynthesis and its solubility is known to increase after flooding when it is reduced to a more soluble form during organic matter decomposition (Dobermann & Fairhurst, 2000). In rice production, Fe deficiency occurs when the soil concentration is below 4-5 mg/kg while toxicity occurs when the soil Fe concentration is above 300 mg/kg (Dobermann & Fairhurst, 2000). In our site, it is likely that stresses related to Fe toxicities and deficiencies can be experienced given the minimum and maximum values recorded.

Fe deficiency is likely to occur in the Mwea and Karaba unit fields where minimum values of below 4-5 mg/kg were recorded in about 3% of fields from each unit. In rice production, Fe deficiency is known to occur in soils with low concentration of soluble Fe and high pH as well as lowland soils irrigated with alkaline irrigation water (Fairhurst, Witt, Buresh, & Dobermann, 2007). In the United States, Zekri and Obreza (2015) noted that Fe deficiency was common on Florida's calcareous soils with high soil pH. Calcareous soils could be containing appreciable amounts of Fe but the fact that the soils are high in calcium carbonate concentration, Fe in such soils exists in forms unavailable for plants uptake. Apart from high alkalinity and low soil Fe concentration, high P levels, poor drainage causing prolonged wet soil conditions and low soil temperature are also associated with Fe deficiency (Zekri & Obreza, 2015). In the possible Fe deficiency fields from the MIS, both low soil Fe and alkalinity are factors likely to lead to Fe deficiency stress because high pH values were also recorded. Generally in the MIS, high Ca concentrations in the soil were observed (Kundu et al., 2016) which contribute to the high soil pH values. Poor drainage where in most cases farmers leave the fields flooded for longer periods of time (1-3 months) before transplanting as observed by Kondo et al. (2001) could also aggravate Fe deficiency stresses.

On the other hand, toxicity is mainly caused by the toxic effects of excessive Fe uptake by the rice plant because of a large concentration of Fe in the soil solution and is known to occur on a wide range of soils with pH values 4-7; but is generally high in lowland rice soils with permanent flooding during crop growth (Yoshida, 1981; van Mensvoort, Lantin, Brinman, & Breemen, 1985; Neue, Quijano, Senadhira, & Setter, 1998; Fairhurst et al., 2007). Generally, high levels of soil Fe concentration and low pH has been associated with toxicity (Fageria et al., 1990). In the MIS, Fe toxicity stress is likely to occur in a number of fields in the Mwea unit (22%), Thiba unit (20%) and to a lesser extent in Tebere unit (6%) and Wamumu unit (5%) where maximum soil Fe values exceeded the 300 mg/kg limit for rice growth. The reasonable likelihood of Fe toxicity stress as observed for Mwea unit (22%) concur with earlier findings by Kondo et al. (2001) who noted moderately high presence of free Fe oxides in the unit. In our results, the soils of Mwea unit generally had moderately low pH and this could further exacerbate Fe toxicities in the unit. Moreover, a study on the physical and chemical analysis of Mwea region clays showed Fe as a major contaminant occurring at 12-16% (Muriithi, Karoki, & Gachanja, 2012).

Fe toxicity is said to be a likely serious problem in many parts of the world such as Africa, South America and Asia especially where rice is grown on acid soils that have great potential for rice production (Fageria, Baligar, & Wright, 1990). Yield losses associated with Fe toxicity in rice commonly range from 15% to 30%; but complete crop failure has been reported to occur under severe toxicity (Audebert & Sahrawat, 2000). In West Africa, Fe toxicity caused a yield reduction of about 40-45% although the extent of yield loss depended on rice cultivar, iron toxicity intensity and crop management strategies in terms of water control and mineral fertilization (Audebert & Fofana, 2009). Soil and water conditions that prevail in inland valley swamps and other wetlands such as irrigated lowlands and rain fed lowlands are known to lead to the development of iron toxicity in rice (Becker & Asch, 2005). It has been observed that in Africa, soils with high levels of Fe toxicities in rice occur in many inland valleys and irrigated fields (Narteh & Sahrawat, 1999; Abah et al., 2012) and yield losses of 12-100% have been reported in West Africa (Sahrawat et al., 1996; Sahrawat, 2004).

Elevated Fe concentration in the soil solution has been shown to decrease the absorption of other plant nutrients especially P and K by the rice plant (Yoshida, 1981; Olaleye, Tabi, Ogunkunle, Singh, & Sahrawat, 2001) and as such, application of plant nutrients that could be limiting such as P, K, Ca, Mg and Zn may alleviate iron toxicity effects by enhancing plant tolerance (Tanaka, Loe, & Navasero, 1966). Toxicity stress can also be countered by using Fe-tolerant rice genotypes as well as through proper soil, water and nutrient management practices (Sahrawat, 2004) although under high iron toxicity stress, an integrated use of tolerant cultivars and improved soil and nutrient management give the best results (Sahrawat et al., 1996). Audebert and Fofana (2009) reiterated that the application of P, K and Zn in conjunction with N is an effective way of reducing Fe toxicity effects on rice growth and yield.

In soil, micronutrient cations are known to be most stable and available under acid (low pH) conditions and as the pH increases, their ionic forms are changed into insoluble and unavailable forms (Brady & Weil, 2014). The decrease in surface soil Fe concentration at lower elevation as observed in our study is because in paddy fields, Fe as well as Mn tends to accumulate below the plough layer in the subsoil as water percolates. Leaching of nutrients from the plough layer by water percolation and their accumulation in the subsoil has been observed in a Japanese paddy field by Katoh, Murase, Hayashi, Matsuya, and Kimura (2004a). In a separate study, Katoh, Murase, and Kimura (2004b) also demonstrated the accumulation of Fe in the uppermost part of the subsoil. The decrease in top soil Fe concentration in the depression areas with decreased gradient of our study site is attributable to percolation to the subsoil through irrigation water and increase in surface soil pH.

In the MIS, fields to be monitored for possible Fe toxicity or deficiency stresses are listed in Table 4.

Table 4. Unit fields likely to suffer Fe stress (toxicities or deficiencies)

Fe toxicity (> 300 mg/kg soil concentration)			Fe deficiency (< 4-5 mg/kg soil concentration)		
Unit/field	pH_{water}	Fe (mg/kg)	Unit/field	pH_{water}	Fe (mg/kg)
M1	5.12	1360.6	M4	6.53	nd
M1	5.02	935.7	M4	8.05	3.8
M4	5.31	1047.3	K6	7.99	0.5
M4	5.40	313.4			
M4	5.40	363.2			
M4	5.02	556.6			
M9	4.87	808.9			
M11	4.95	535.6			
M11	4.95	376.2			
M11	4.56	707.4			
M11	5.07	326.9			
M11	5.36	416.6			
M11	4.85	339.0			
W1	5.64	346.0			
W7	4.91	433.0			
T8	4.90	398.8			
H1	4.90	795.4			
H3	5.11	347.7			

Note. M-Mwea unit, H-Thiba unit, K-Karaba unit, T-Tebere unit, nd-not detected.

3.2.2 Soil Mn Concentration

Mn is one of the most abundant trace elements in the lithosphere ranging from 350 to 2000 mg/kg where higher concentrations are associated with mafic rocks (Kabata-Pendias, 2011). According to her, the highest levels occur in loamy and calcareous soils. Mn as a micronutrient is involved in oxidation-reduction reactions in the electron transport system and oxygen evolution in photosynthesis. It is essential in activation of certain enzymes, protein synthesis and in formation and stability of chloroplasts. It is also important in mitigating Fe toxicity and its availability just like Fe increases with flooding (Dobermann & Fairhurst, 2000). Deficiencies of Mn, Cu and B are rare in rice and hence less research has been done on fixing their critical limits (Savithri, Perumal, & Ngarajan, 1999), but a concentration of 3-30 mg/kg is used as the optimum soil Mn concentration and its application in unnecessary in soils with above 40 mg/kg 0.1M HCl extractable Mn (Dobermann & Fairhurst, 2000).

Mn deficiency stress occurs because of small quantities of soil available Mn coupled with large concentrations of Ca^{2+}, Mg^{2+}, Zn^{2+} etc as well as large Fe in the soil solution (Dobermann & Fairhurst, 2000; Fairhurst et al., 2007). In lowland rice, Mn deficiency stress is uncommon because its solubility is said to increase in submerged conditions when it is reduced to plant-available forms (Dobermann & Fairhurst, 2000; Fairhurst et al., 2007; Tao et al., 2007). In Florida, Mn deficiency has been observed on both acidic and alkaline soils and was attributed to leaching in acid soils and to insolubility in the alkaline soils (Zekri & Obreza, 2015). In addition, it has been associated with deficiencies of Zn, Fe and Cu on both acid and alkaline soils and with Mg deficiency on acidic sandy soils (Zekri & Obreza, 2015). In Iran, Mn deficiency is recognized as an important nutritional problem in cereal production where it is known to occur on sandy soils with neutral to slightly alkaline pH, soils from marine sediments and rich in carbonates as well as soils rich in clay and organic matter (Aref, 2010, 2012). In our site, Mn deficiency is unlikely to be a critical issue even though less than the optimum soil concentrations were recorded in some fields. This is because stresses related to Mn deficiency are said to be typically rare under flooded conditions because of the low soil redox potentials under such conditions (Tao et al., 2007). Nonetheless, preventive strategies to prevent Mn deficiencies include application of farm yard manure or returning crop residues which reduces Mn losses in the soil. The use of acid forming fertilizers such as ammonia sulphate as a fertilizer management strategy is also recommended (Dobermann & Fairhurst, 2000; Fairhurst et al., 2007).

In rice production, Mn toxicity has been reported in lowlands with ground-water containing elevated amounts of Mn and soils with readily reducible Mn of more than 300 mg/kg (Kyuma, 2004). In a separate scenario, Kabata-Pendias (2011) observed that most plants are affected when soil Mn contents are around 500 mg/kg and pH of around 5.5 or lower. Nonetheless, the critical Mn content and unfavourable soil pH ranges depend upon several other environmental factors and toxicity is also known to occur at higher pH levels where soils are poorly aerated and poorly drained (Kabata-Pendias, 2011). Dobermann and Fairhurst (2000), and Fairhurst et al. (2007) however noted that Mn toxicity rarely occurs in lowland rice even with large Mn concentrations in soil solution because rice is said to be comparatively tolerant to large Mn concentrations. Mn toxicity stress is likely to occur on acid upland soils with pH values below 5.5 where Al toxicity also occurs; lowland soils with large amounts of easily reducible Mn, acid-sulphate soils and on areas affected by Mn mining as found in Japan (Dobermann & Fairhurst, 2000; Fairhurst et al., 2007). From our findings, Mn toxicity stress is likely to be experienced in just about 1% of the sampled fields with all of them occurring in the higher elevation units of Mwea and Thiba. In these cases, the soil solution pH recorded was below 5.5 and soil Mn concentration was above 500 mg/kg.

To mitigate against the negative Mn toxicity stress effects, proper fertilizer management should be taken into account. Application of lime on acid soils to reduce the concentration of active Mn and proper straw management should be embraced (Dobermann & Fairhurst, 2000; Fairhurst et al., 2007). Similar to soil Fe, soil Mn tended to decrease in the surface soil down the elevation with Mwea and Thiba units at higher elevation recording higher surface soil Mn compared to the lower elevation Wamumu and Karaba units. Like Fe, Mn together with other nutrient elements in paddy fields percolates through irrigation water and accumulates in the subsoil (Katoh et al., 2004a). Additionally, Brady and Weil (2014) noted that micronutrients are most soluble and readily available under acid conditions and as the pH increases, they are changed into insoluble hydroxides or oxides therefore the decrease in Mn concentration down the elevation in our study site is attributed to its percolation through irrigation water and the increase in surface soil pH.

3.2.3 Soil Cu Concentration

Generally, Cu is accumulated in the upper few centimetres of soils; however, due to its tendency to be adsorbed by soil organic matter, carbonates, clay minerals and oxyhydroxides of Mn and Fe; it may be also accumulated in deeper soil layers (Kabata-Pendias, 2011). In soils, it is present as oxides, carbonates, silicates and sulphides and its chemistry in submerged soils is similar to that of Zn, forming sparingly soluble sulphides (Neue & Mamaril, 1985). Cu is required for lignin synthesis and is a constituent of ascorbic acid and as well as some enzymes. It is a regulatory factor in enzyme reactions and a catalyst in oxidation reactions. As a micronutrient, it plays a key role in nitrogen, protein and hormone metabolism, pollen formation and fertilization as well as photosynthesis and respiration (Dobermann & Fairhurst, 2000; Fairhurst et al., 2007; Kabata-Pendias, 2011). It is observed that sandy, calcareous, lateritic soils and high organic matter induce Cu deficiencies (Das, 2014). In our study, Cu soil concentrations are sufficient as they are above critical deficiency levels of 0.1 mg/kg for rice production

(Dobermann & Fairhurst, 2000; Fairhurst et al., 2007). Cu availability decreases at flooding as a result of the formation of copper sulfides and ferrite and further complexes with organic matter. As a result, its availability for plant uptake decreases with increase in pH (Dobermann & Fairhurst, 2000; Fairhurst et al., 2007). In Mwea irrigation scheme therefore there is neither risk of Cu deficiency nor toxicity given that its solubility and availability decreases with flooding.

3.2.4 Soil Zn Cconcentration

Zn is essential for several biochemical processes in rice plant for instance enzyme activation and chlorophyll production. It promotes seed and grain formation, plant maturity and is essential for protein synthesis (Brady & Weil, 2014). It is accessible to plants as exchangeable Zn^{2+} ions but most of the ions are bound to clay particles or inorganic constituents like iron and aluminium oxides and thus unavailable for plant uptake. It is also known to chelate and bind to organic matter which can be decomposed and release ions for plant uptake (Brady & Weil, 2014). In soil solution, Zn is reported to be generally of low mobility because of the tendency to be adsorbed on clay size particles (Alloway, 2008; Kabata-Pendias, 2011). In rice production, 2.0 mg/kg 0.1N HCl-extractable is set as the critical level for deficiency to occur (Dobermann & Fairhurst, 2000; Fairhurst et al., 2007). In our results although there was an increasing trend in soil Zn down the slope, high variations existed with about 80% of the sampled fields recording below the 2.0 mg/kg critical soil limit. On average all the units in the MIS showed deficiency in soil Zn concentration (< 2.0 mg/kg). Such high incidences of Zn deficiency stress have also been reported on Ethiopian Vertisols (Kebede & Yamoah, 2009; Hailu et al., 2015) and in West African lowlands (Abe, Buri, Issaka, Kiepe, & Wakatsuki, 2010).

As an essential plant micronutrient, Zn has been shown to be the most critical yield limiting micronutrient to rice growth after N (Neue & Mamaril, 1985; Alloway, 2008; Buri, Masunaga, & Wakatsuki, 2000). Zn deficiency has been shown to decrease cereal yields by as much as 50% according to work done by van Asten, Barro, Wopereis, and Defoer (2004). Under severe Zn deficiency, tillering of rice is affected and may stop completely; spikelet sterility is also known to increase (Dobermann & Fairhurst, 2000) which has a negative effect on grain yield (Yang, Shi, Xu, Lu, & Wang, 2009). In Japan, Zn deficiency stress causes a disorder known as '*Akarage Type II*' that damages rice crop throughout its growth cycle (Dobermann & Fairhurst, 2000). Zn deficiency stress is said to occur on a wide range of soils in combination with several other contributing factors. Soils low in Zn concentration, high in available P and Si as well as leached, aged acid-sulphate, sodic soils, saline-neutral soils, calcareous, peat, sandy, highly weathered acid and course textured soils are said to be prone to Zn deficiency (Dobermann & Fairhurst, 2000; Kyuma, 2004; Fairhurst et al., 2007; Alloway, 2008, 2009). Under flooded soil condition, Zn availability decreases compared to well-aerated soils and when prolonged, the deficiency is exacerbated by the formation of sulpahtes and carbonates (Neue & Mamaril, 1985; Neue & Bloom, 1989). Furthermore, the high carbonate concentration especially in calcareous soils, high pH under anaerobic conditions as well as increased availability of Ca, Mg, Fe, Mn, Cu and P after flooding bring about Zn deficiencies (Dobermann & Fairhurst, 2000; Fairhurst et al., 2007). Excessive P fertilizer application causes Zn immobilization in the soil thus making it unavailable for plant uptake (Dobermann & Fairhurst, 2000; Fairhurst et al., 2007).

In the MIS, the low soil available Zn and the calcareous nature of the soils are factors contributing majorly to the widespread Zn deficiency stress. Famers in the scheme rarely use micronutrient fertilizer and in most cases they apply N and P fertilizers (Kihoro et al., 2013). In this regard, management practices to help alleviate Zn deficiency stress would be to introduce Zn-based fertilizers and using fresh water for irrigation especially in the receiving depression units to reduce on the carbonate accumulation. Where possible, selection of Zn-efficient varieties and application of organic manure or Zn fertilizers before seeding or transplanting are other helpful management strategies to explore as suggested by Fairhurst et al. (2007).

3.3 Relationship between Soil pH and Micronutrient Concentration

To examine the relationship between soil micronutrient concentration and soil pH, a Pearson correlation analysis was performed. Correlation analysis result for Mwea irrigation scheme soil pH and micronutrient concentration is shown in Table 5.

Table 5. Pearson correlation between soil micronutrient concentration and pH

	pH_{water}	pH_{KCl}	Cu	Fe	Mn	Zn
pH_{water}						
pH_{KCl}	$.975^{**}$					
Cu	-.078	-.053				
Fe	$-.594^{**}$	$-.585^{**}$	$.143^{*}$			
Mn	$-.382^{**}$	$-.361^{**}$	-.064	$.455^{**}$		
Zn	$-.422^{**}$	$-.392^{**}$	$.143^{*}$	$.565^{**}$	$.238^{**}$	

Note. ** and * Correlation is significant at the 0.01 and 0.05 level.

There was a significant negative correlation between soil solution pH and Fe, Mn and Zn except with Cu that showed a negative insignificant correlation. Soil solution pH_{water} showed a very good correlation with pH_{KCl} ($r = 0.975$, $p < 0.01$). All micronutrients showed significant positive correlation with each other except for Mn and Cu that showed an insignificant and negative correlation.

Plant uptake of micronutrients is mainly dependent on their mobility and availability in soils (Zeng et al., 2011). According to Kashem and Singh (2001) and Antoniadis, Robinson, and Alloway (2008), the adsorption and desorption of heavy metals has been associated with soil properties including pH, organic matter content, cation exchange capacity (CEC), oxidation-reduction status (Eh), calcium carbonate and Fe and Mn oxides among others. Of these soil properties, soil pH was found to play the most important role in determining metal speciation, solubility, movement and eventual bioavailability due to its strong effects on solubility and speciation of the metals in the soil solution (Zhao, Liu, Xua, & Selim, 2010). Soil pH is an important chemical property governing the availability of nutrients in the soil nutrient pool. It plays an important role in soil microbial activity and decomposition of mineral substances and organic matter; thus influences the release, fixation and migration of soil nutrients (Fageria & Baligar, 1999).

During rice cultivation when an aerobic soil is initially submerged, the entire soil layer is reduced, redox potential is lowered and there is an increase in ferrous iron and ammoniacal nitrogen coupled with a decrease in pH (Ponnamperuma, 1985; Kyuma, 2004). With time, the formation of ammoniacal nitrogen subsides, the amount of ferrous iron decreases, the redox potential increases and the pH increases asymptotically. The substances liberated during the reduction process become adsorbed onto soil surface or are dissolved in soil solution as anions and thus increasing soil pH towards alkaline (Kyuma, 2004). As the soil pH increases, so does ionic strength which depresses activity coefficients and alters the concentrations of ecologically important ions in the soil solution (Ponnamperuma, 1985). The antagonistic relationship between soil pH and heavy metal as reported in our study is similar to what has been documented in studies elsewhere for instance Speir, Schaik, Percival, Close, and Pang (2003), Wang, Angle, Chaney, Delome, and Reeves (2006), and Aref (2012).

Generally, micronutrients Zn, Cu, Fe and Mn are said to be greatly available in slightly acidic to neutral pH soils but are much less available at pH above 7 (Fageria, Slaton, & Baligar, 2003; Fageria, Caryalho, Santos, Ferraira, & Knupp, 2011; Aref, 2012; Brady & Weil, 2014). As the pH is increased, the ionic forms of the micronutrients are changed to hydroxyl ions and then to unavailable insoluble hydroxides or oxides. However, the exact pH at which precipitation occurs varies from element to element (Brady & Weil, 2014). Studies by Wang et al. (2006) and Du Laing, Rinklebe, Vandecasteele, Meers, and Tack (2009) have also demonstrated that the mobility and bioavailability of heavy metals increase with decreased soil pH. In acidic soil, Mn and Fe solubility has been shown to increase with flooding due to reductive dissolution of their hydroxides/oxides and decreased during drainage because of re-oxidation (Pan et al., 2014; Brady & Weil, 2014).

Taking into account the negative correlation between soil pH and micronutrients, it can be deduced that soil pH has a depressing effect on availability of micronutrients and therefore it is imperative to have the proper soil solution pH maintained. While reviewing the soil fertility potential for rice production in West Africa, Abe et al. (2010) urged that appropriate soil pH should be maintained as micronutrient availability is greatly affected by soil pH. Furthermore, there should be sufficient nutrient supply in the soil and in particular sufficient supply of Zn in the MIS through Zn fertilizers to avert the negative Zn deficiency stresses. Other strategies for Zn deficiency management should focus on proper irrigation water and manure/fertilizer management. In improving the drainage situation, periodic draining of the waterlogged rice fields should be practiced to avoid excessive accumulation of metal elements especially Fe in the soil. Delayed planting on flooded fields for atleast over 20 days after flooding has also been shown to reduce Fe accumulation in the soils.

4. Conclusions and Recommendations

Rice yields in MIS do not exceed 5 ton/ha; which is far below the optimum of about 10 ton/ha (MoA, 2009). Statistical analysis showed that soil Fe, Mn, Zn and Cu had high CVs indicating high variability but low for pH indicating low variability hence a serious challenge to homogenous nutrient management recommendations. The micronutrients are obviously enriched in some parts of the studied soils and slightly or least enriched in some areas thus likely to cause toxicity and deficiency stresses. From the present study, the MIS Vertisols of Kenya showed both excess and insufficiencies in the levels of Fe and Mn, deficiencies in Zn levels and adequacy in the levels of Cu. The micronutrient deficiencies observed are due to their inherently low concentration in the soils as a consequence of continuous cropping without applying fertilizer or manure containing them. There is need for further studies to determine rice response to proper and balanced fertilization in this area. Farmers should be provided for and made aware of the benefits of inorganic fertilizers other than the N and P fertilizers in improving soil fertility, soil nutrient status and crop production. Application of appropriate field management approaches could help avert the negative toxicity and deficiency effects. Mid-season drainage to help aerate the soil and remove accumulated Fe and Mn could help avert toxicity stress. To correct Zn deficiencies, Zn fertilizers should be applied in combination with other macronutrient fertilizers. Straw return should also be encouraged as most of the farmers tend to remove all the straw after harvest which exacerbates nutrient mining from the farms.

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