CHARACTERIZATION OF PADDY SOILS FOR FERTILITY BASED INTERVENTIONS IN KENYA

（ケニアにおける土壌肥沃度に基づく土壌管理のための水田土壌の特性づけ）

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Approval Sheet

This thesis enclosed herewith, "**CHARACTERIZATION OF PADDY SOILS FOR FERTILITY BASED INTERVENTIONS IN KENYA**" prepared and submitted by KUNDU Caroline Agamala in partial fulfilment of the requirement for the award of Doctor of Philosophy is hereby approved as to style and contents.

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DEDICATION

To my late parents for believing in me! To the memory of my number one fan, my father who passed on during this study, he supported me whatever path I took, a GREAT man he was, and I miss him every day.

To my daughter, for enduring my being away, she makes life fun and worth fighting to live!

To my sisters for supporting me in all my endeavours

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CHAPTER 1

INTRODUCTION

1.1. General Introduction

Achieving food security is a key agenda that many governments in sub-Saharan Africa (SSA) are struggling to accomplish (Shapouri *et al*., 2010). Low productivity of food crops as a result of little or no nutrient application in the region is one of the major contributors to food insecurity (IFDC, 2006; Mueller *et al*., 2012; Shapouri *et al*., 2010). As much as mineral fertilizers are widely used globally in attempts to overcome nutrient deficiencies, their use in SSA remains very low (IFDC, 2006; Morris *et al*., 2007; Liu *et al*., 2010) despite the resolution to increase its use from 8 kg/ha to 50 kg/ha by 2016 in the Africa Fertilizer Summit in 2006 in Nigeria. Furthermore, the fertilizer is often not targeted to specific crop, soil and agro-ecological conditions and application rates are based on 'blanket' recommendations (Giller *et al*., 2011).

Soils are known to be highly variable both spatially and temporally because of land use and management strategies and this variability is expressed in soil physical and chemical properties (Jin and Jiang, 2012) at macro- and micro-scales (Vieira and Gonzalez, 2003). Under such conditions, crop yields are often varied and less than optimum due to nutrient deficiencies as well as excessive fertilizer application that may potentially result in environmental degradation (Mzuku *et al*., 2005).

In a food security review by Godfray *et al.,* (2010), it was noted that the continuing population and consumption growth would mean that the global demand for food would increase. However recently, world food production increased from the expansion of agricultural land and to a lesser extent from increase in yield per unit area, which was accomplished by agricultural developments such as Green Revolution (Bindraban *et al*., 2000). Nonetheless, Alexandratos and Bruinsma, (2012) argued that expansion of arable land is not desirable; and increased food production is likely to be achieved only from increased crop productivity. Crop productivity is an amalgamation of all factors relating to crop growth such as environment, genotype and agricultural management; thus it is essential to understand any limiting factors for crop productivity in target fields. Soil is the medium for plant growth and is one of the important factors influencing crop productivity (Brady and Weil 2014).

In many parts of Kenya, crop yields are low due to declining soil fertility from continuous cropping with minimal or non-application of fertilizers; thus ways of increasing and maintaining crop yields has been a key national problem (Ayuke *et al*., 2004). The importance of rice has significantly increased in SSA (Seck *et al*., 2010) and in Kenya, it forms an important diet for many families; ranking third among cereals after maize and wheat (MoA, 2009). Unfortunately, the country is only able to produce about a fifth of its national needs (MoA, 2009). Rice production is influenced by climate, soil, crop characteristics and management practices such as fertilizer use and water management thus yields are highly variable (Dobermann *et al*., 2003, Kyuma, 2004).

Statistics indicate that rice consumption in the country soared from 294, 000 tons to 548, 000 tons between 2007and 2013 (Figure 1.1), while production increased only from 62,000 ton to 129, 000 ton of paddy rice over the same period (MoALF, 2014). The wide gap between production and consumption has become a burden to the country's economy costing between 2.2B KES to 7.1B KES over the period.

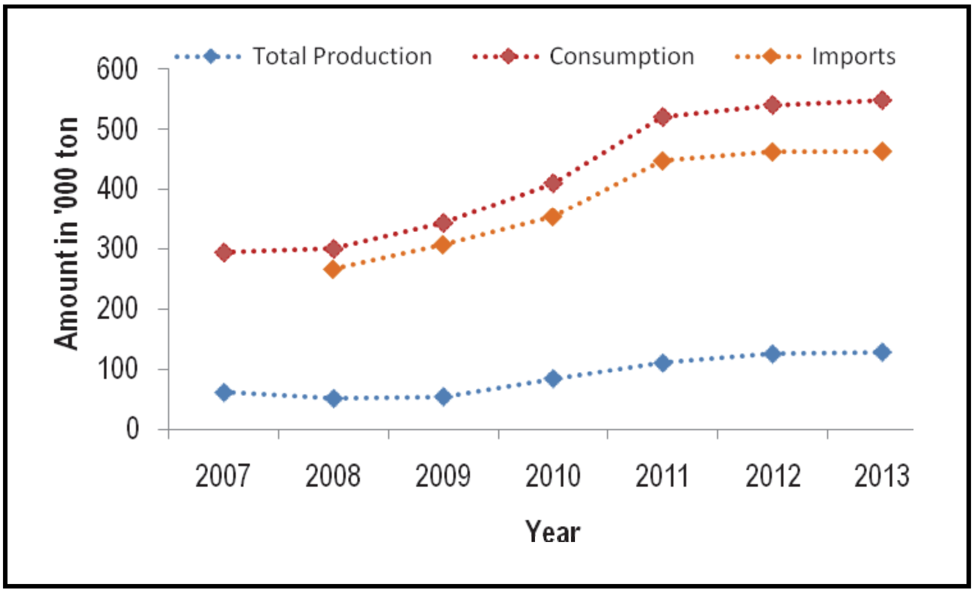

Figure 1. 1: Rice production, consumption and import trends in Kenya

In Kenya, lowland irrigation schemes contribute the most rice produced with about 95% coming from government managed schemes and the remaining 5% from under rain-fed conditions (USAID, 2010). There are currently seven irrigation schemes namely Mwea, Perkerra, Hola, Ahero, West Kano, Bunyala and Bura that are managed by the National Irrigation Board (NIB). Current data indicates that a total of 425, 000 acres (170,000ha) are under irrigation in Kenya (www.nib.or.ke). Of the seven national irrigation schemes, Mwea, Ahero, West Kano and Bunyala are involved in paddy production while the others have diversified in crop production. Rice productivity in the schemes is below optimum (www.nib.or.ke); yet it is known that lowland environment provide water resources and have relatively fertile alluvial soils compared to the upland areas (Buri *et al*., 1999). Moreover, such lowland plains are unlikely to cause competition with other food crops (Tsujimoto *et al*., 2013); thus they should be the focus rather than the upland ecosystem to help meet the increasing demand for rice. A suitability study conducted in the Mwea region indicated that the scheme is appropriate for rice production (Kihoro *et al*., 2013) and an earlier study indicated that it has the ability to sustain continuous and intensive rice cropping because the soil nutrient status was rated as medium to high in terms of essential elements except K (Kondo *et al*., 2001) while no soil information is available on West Kano and Ahero.

Despite this, low rice yields from farmers' fields have been continuously reported and farmers tend to apply fertilizers irrespective of soil nutrient status (Kondo *et al*., 2001). Nonetheless, improved crop yields can be achieved if soil and nutrient variations are established and properly managed through variable fertilizer application rates. Although the schemes could be similar in terms of agricultural activity, the fact that soil basic information including soil fertility status is lacking yet required is a common and imperative issue. Determining soil nutrient concentrations through soil tests provide the means of monitoring the soil so that any deficiencies, extremes and imbalances can be avoided. The objectives of this study were to provide basic soil information and to discuss soil properties and fertility status and assess the effect on rice nutrient status of irrigation schemes in Kenya for enhanced productivity.

In this context, a general introduction is provided in this chapter to help in understanding the importance and the objective of this thesis. Subsequently in Chapter two, paddy soils of Mwea irrigation scheme in central Kenya are assessed to ascertain their fertility status. In Chapter three, rice nutrient status in grain and straw is correlated with the soil nutrient concentration from Mwea fields and in Chapter four, the paddy soils of the lake-zone irrigation schemes of West Kano and Ahero are characterized in terms of nutrient concentration. In the fifth Chapter, all findings obtained in this study are summarized.

1.2. References

Alexandratos N, Bruinsma J, 2012. *World agriculture towards 2030/2050: the 2012 revision.* ESA Working paper No. 12-03. Rome, FAO.

Ayuke FO, Rao MR, Swift MJ, Opondo-Mbai ML, 2004. Effect of organic and inorganic nutrient sources on soil mineral nitrogen and maize yields in western Kenya In *Managing nutrient cycles to sustain soil fertility in sub-Saharan Africa*, pp. 65-76.

Bindraban PS, Stoorvogel JJ, Jasen DM Jansen, Vlaming J, Groot JJR, 2000. Land quality indicators for sustainable land management: proposed method for yield gap and soil nutrient balance *Agriculture Ecosystem and Environment,* 81, 103–112.

Buri MM, Ishida F, Kubota D, Masunaga T, Wakatsuki T, 1999. Soils of flood plains of West Africa: General fertility status *Soil Science and Plant Nutrition*, 45, 37-50.

Brady NC, Weil RR, 2014. *The Nature and Properties of Soils*, 14th Edition, Pearson Education Limited.

Dobermann A, Ping JL, Adamchuk VI, Simbahan GC, Ferguson RB, 2003. Classification of crop yield variability in irrigated production fields *Agronomy Journal*, 95, 1105-1120.

Giller KE, Tittonell P, Rufino MC, ….et al., 2011. Communicating complexity: Integrated assessment of trade-offs concerning soil fertility management within African farming systems to support innovation and development *Agricultural Systems*, 104, 191-203.

Godfray HCJ, Beddington JR, Crute IR, Haddad L, Lawrence D, Muir JF, Pretty J, Robinson S, Thomas SM, Toulmin C, 2010. Food Security: The Challenge of Feeding 9 Billion People *Science*, 327,812-818.

International Fertilizer Development Center (IFDC), 2006. *Africa Fertilizer Summit Proceedings*, Abuja, Nigeria.

Jin J, Jiang C, 2002. Spatial variability of soil nutrients and site-specific nutrient management in the PR China *Computers and Electronics in Agriculture*, 36, 165-172.

Kihoro J, Bosco NJ, Murage H, 2013. Suitability analysis for rice growing sites using a multicriteria evaluation and GIS approach in great Mwea region, Kenya *SpringerPlus*, 2, 265-273.

Kondo M, Toshinari OTA, Wanjogu R, 2001. Physical and chemical properties of Vertisols and soil nutrient management for intensive rice cultivation in the Mwea area in Kenya *Japanese Journal of Tropical Agriculture,* 45, 126-132.

Kyuma K, 2004. *Paddy soil science*, Kyoto University Press.

Liu J, You L, Amini M, Obersteiner M, Herrero M, Zehnder AJ, Yang H, 2010. A high-resolution assessment on global nitrogen flows in cropland *Proceedings of the National Academy of Sciences*, 17, 8035-8040.

Ministry of Agriculture (MoA), 2009, Government of Kenya *National Rice Development Strategy* (2008-2018).

Ministry of Agriculture, Livestock and Fisheries (MoALF), 2014. Government of Kenya, *National Rice Development Strategy* (2008-2018) Revised Edition.

Morris M, Kelly VA, Kopicki RJ, Byerlee D, 2007. *Fertilizer use in African agriculture: Lessons learned and good practice guidelines,* The World Bank. Agriculture and Rural Development.

Mueller ND, Gerber JS, Johnson M, Ray DK, Ramankutty N, Foley JA, 2012. Closing yield gaps through nutrient and water management *Nature*, 7419, 254-257.

Mzuku M, Khosla R, Reich R, Inman D, Smith F, MacDonald L, 2005. Spatial variability of measured soil properties across site-specific management zones *Soil Science Society of American Journal*, 69, 1572-1579.

National Irrigation Board available at http://www.nib.or.ke

Seck PA, Tollens E, Wopereis MC, Diagne A, Bamba I, 2010. Rising trends and variability of rice prices: Threats and opportunities for sub-Saharan Africa *Food Policy*, 35, 403-411.

Shapouri S, Rosen S, Peters M, Baquedano F, Allen S, 2010. *Food security assessment*, 2010-20, DIANE Publishing, 2010.

Tsujimoto Y, Yamamoto Y, Hayashi K, Zakaria AI, Inusah Y, Hatta T, Fosu M, Skagami JI, 2013. Topographic distribution of the soil total carbon content and sulphur deficiency for rice cultivation in a floodplain ecosystem of the Northern region of Ghana *Field Crops Research*, 152, 74-82.

United States Agency International Development (USAID), 2010. *The Competitiveness and Trade Expansion Program, Staple Foods Value Chain Analysis*. Country Report –Kenya, pp: 62-83.

Vieira SR, Gonzalez PA, 2003. Analysis of the spatial variability of crop yield and soil properties in small agricultural plots *Bragantia*, 62, 127-138.

CHAPTER 2

Paddy Soil Characteristics of Mwea Irrigation Scheme in Central Kenya

2.1. Introduction

Agricultural production in most sub-Saharan countries has been under threat due to diminishing soil fertility (Sanchez, 2002) and feeding the bulging population has been a serious challenge. Kenya has not been spared and in the recent years has experienced food shortages arising from declining farm productivity, high input costs and unreliable weather in the face of rising population (Nyang'au *et al*., 2014). A major factor in soil degradation is the soil chemical fertility and in particular its decline as a result of the lack of nutrient inputs (Hartemink, 2010). Smaling (1993) described tropical soils as often having negative soil nutrient balances and in addition to lack of inputs causing soil degradation while Bationo *et al.,* (2006) highlighted the inherently low fertility status, inappropriate land use, poor management, erosion and salinization as other factors. On the other hand, the Global Rice Science Partnership [GRiSP], (2013) noted that the major constraints to production are poor crop management, lack of disease-resistant varieties and unavailability of labour at critical times.

Paddy soils are naturally heterogeneous in their physico-chemical properties which impact on rice productivity. This means that uniform management of fields will often result in over-application of inputs in areas with high nutrient levels and under-application in areas with low nutrient levels (Ferguson *et al*., 2002). However, good agricultural practices can be achieved if soil and nutrient variations within a farm are established and properly managed (Chan *et al*., 2008). Soil chemical properties form the basis for soil fertility evaluation and chemical concentrations in the soil must be regularly tested to develop fertilizer recommendations and site- specific management considerations for optimum crop production (Omonode and Vyn, 2006).

In tackling poverty, food security crises and minimizing environmental degradation among others, rice is one crop that can be effectively used under improved technological innovations in order to improve smallholder livelihoods. Low rice yields from farmers' fields have been continuously reported (MoA, 2009) but the variability in soil fertility and rice growth for formulating soil fertility recommendations has not been investigated in a long time (Kondo *et al*., 2001).

Understanding the link between livelihoods and managing essential services provided by natural ecosystems is critical for achieving sustainable economic growth and poverty reduction. Degradation of natural resources in many developing countries reduces the productivity of the poor households who mostly rely on these resources. In a commentary, Sanchez (2010) stated clearly that too much emphasis has been placed on the development of high yielding crop varieties with little attention given to the ecology on which the plant survives. He further stated that crop yields in Africa can be tripled through proper management of the soil environment, use of fertilizer and appropriate crop varieties.

About 80% of the rice consumed in Kenya is imported from Asian countries mainly Pakistan, Vietnam, Thailand and India (USAID, 2014) yet the country has rice growing irrigation schemes that when well managed can ensure and sustain enough rice production for the country (Kondo *et al*., 2001; Rosemary *et al*., 2010). The Mwea irrigation scheme soils have been earlier rated as having medium to high fertility and are highly suited for rice cultivation (Kondo *et al*., 2001; Kihoro *et al*., 2013). Despite this great potential, there has been a marked fluctuation of the mean crop production which has been attributed to soil chemical and physical degradation due to continuous mono-cropping, production techniques that are inefficient among many other factors (Nyamai *et al*., 2012). Improving the yield of rice 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).

Within-field variations in soil fertility and rice growth are not desirable for rice production thus accessing within field variation is necessary for identifying and quantifying the limiting factors for rice growth and addressing the spatial variability of rice yield. Spatial variability of rice yield in a paddy field results from differences in management practices and soil properties coupled with their complex interaction (Casanova *et al*., 2002).

Because Kenya needs to raise her rice production levels, increasing rice yields must be achieved with low production costs to ensure that the farmers increase their food and incomes from rice farming. Thus soil fertility and nutrient monitoring in rice production systems needs to be given key consideration. Research has shown that when fertilizer is applied at the proper stage of the crop and in the right amount to match location-specific conditions, the fertilizer is more effective, resulting in more rice yield per unit area, consequently increasing farmer incomes. The purpose of this study was to assess and understand the soil fertility status within the Mwea irrigation scheme for the purpose of management recommendations for enhanced productivity.

2.2. Materials and Methods

2.3.1. Site description

The Mwea Irrigation Scheme is located on the lower slopes of Mt. Kenya in Kirinyaga County in Central Kenya (Figure 2.1).

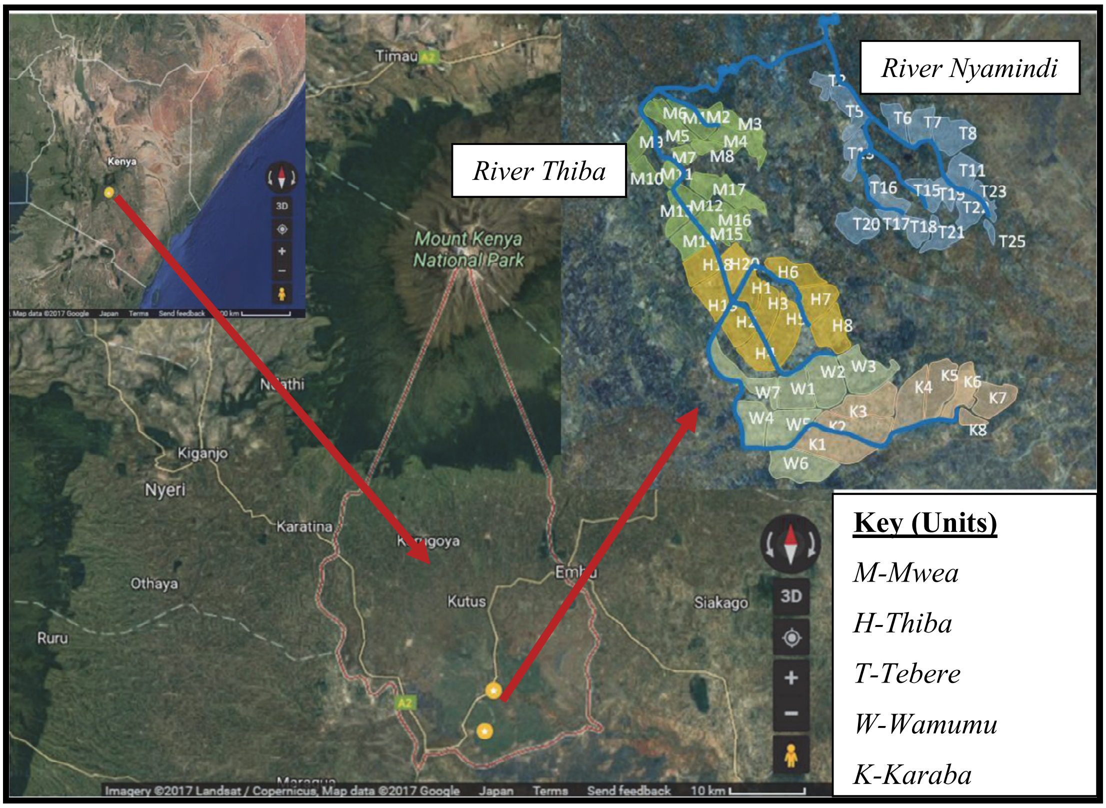

Figure 2. 1: Location and layout of Mwea Irrigation Scheme

It is one of the oldest public irrigation schemes in Kenya (Mati *et al.,* 2011). It lies within latitudes 37^0 13′E and 37^0 30′E and longitudes 0^0 32′S and 0^0 46′S with an annual average precipitation of about 950mm. 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). As per Kenya's agro-climatic zoning by Sombroek *et al.,* (1982), 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. The area is generally hot, with average temperatures ranging 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) with Alfisols occurring at higher elevation (Kondo *et al*., 2001).

Vertisols popularly known as 'black cotton soils' occupy approximately 2.8 million ha which constitutes about 4.9% of Kenya's total land area and are found under different climatic conditions although about 80% are in the semi-arid to arid areas (IBSRAM, 1987). According to Muchena and Gachene (1985), these Vertisols are developed on parent materials ranging from Precambrian Basement System rocks (ferrornagnesian gneisses, etc.), volcanic rocks (basalts, etc.) to alluvial/colluvial deposits derived from various rocks. The Vertisols in the Mwea-Tebere area are reported to have developed on olivine basalt (IBSRAM, 1987). Studies in Mwea irrigation scheme by Mukiama and Mwangi (1989) observed that 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. However, this same period is also when the river flows are at their lowest, coinciding with the dry season thus straining on availability of irrigation water.

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. It is divided into five sections/units located at different topographical elevation namely Mwea (M) and Tebere (T) covering 1300 and 1400 ha respectively and Thiba (H), Wamumu (W) and Karaba (K) covering 1200, 1200 and 1100 ha respectively (Njagi, 2012) (Figure 2.1).

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 and 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 section, while the Thiba serves Mwea, Thiba, Wamumu and Karaba sections (Figure 2.1). Water is drawn from the rivers by gravity through dikes and distributed via unlined open channels into and out of the farms. Rice is grown as a mono-crop for only one season in a year and uses the flooded-paddy irrigation method. A link canal between the rivers transfers surplus water from the Nyamindi to Thiba River mostly in cases of shortage (Kabutha and Mutero, 2002; Abdullahi *et al*., 2003).

2.2.2. Soil Sampling and Analysis

Soil samples were collected from five production units of Mwea irrigation scheme namely Mwea, Wamumu, Karaba, Thiba and Tebere. Benchmark sampling was applied with our benchmark farms marked with a global positioning system (GPS). Several benchmark fields were identified across the five units for soil sampling and surface 0-15cm soil samples collected. Representative samples were collected from each plot, mixed thoroughly and a composite sample per field taken for evaluation. The composite samples collected were air-dried, ground and passed through a 2mm sieve for laboratory analysis. Soil samples were analysed for pH, electrical conductivity (EC), total carbon (TC), total nitrogen (TN), available silica (SiO_2), available sulphur (S), available phosphorus (P_2O_5), available micronutrients (Fe, Mn, Cu and Zn) and exchangeable cations (Ca^{2+}, Mg^{2+}, Na^+ and K^+) using standard procedures for soil analysis.

Soil pH was measured potentiometrically using a glass electrode pH meter (HORIBA D-51) in 1:2.5 soil-water ratio suspensions as described by the International Institute of Tropical Agriculture [IITA], (1979) and McLean (1982). EC was measured with the conductivity meter (HORIBA D-24) after a soil suspension was prepared with a soil-water ratio of 1:5. Exchangeable Ca^{2+}, Mg^{2+}, K^+ and Na^+ in the soil were extracted with 1M neutral ammonium acetate (1M NH_4OAc pH 7.0) according to Thomas (1982) and cation concentration determined by Inductively Coupled Plasma-Atomic Spectroscopy (ICPE-9000, Shimadzu Co. Ltd., Kyoto, Japan). Micronutrients Cu, Fe, Zn and Mn in the soil were extracted by 0.1N HCl as described by Osiname *et al*., (1973) and the concentration determined by Inductively Coupled Plasma-Atomic Emission Spectroscopy (ICPE-9000 Shimadzu Co. Ltd., Kyoto, Japan).

TC and TN contents were determined by the dry combustion method (Nelson and Sommers, 1982) using an Automatic High Sensitive N-C analyzer (SUMIGRAPH NC-22F). Available P_2O_5 and SiO_2 were determined colorimetrically by the molybdenum blue method after extraction by Bray II method (Bray and Kurtz, 1945) and 1M acetate buffer at pH 4 (Imaizumi and Yoshida, 1958) respectively. Available S was extracted by 500ppm KH_2PO_4 solution (Fox *et al*., 1964) and concentration determined by Inductively Coupled Plasma-Atomic Spectroscopy (ICPE-9000, Shimadzu Co. Ltd., Kyoto, Japan).

2.2.3. Data Analysis

All data obtained for the measured soil parameters were subjected to an analysis of variance using R software version 3.4.0 for windows and statistically significant differences between means compared at $p \leq 0.05$. Soil fertility status was evaluated basing on the concentrations of the respective parameters obtained from the laboratory analyses compared with established ratings for rice production.

2.3. Results and Discussions

2.3.1. Soil pH and EC

Soil solution pH in the scheme ranged from 4.5 to 8.1 with unit differences. In the Mwea unit, values varying from 4.6 to 8.1 were observed while in Thiba the values ranged from 4.5 to 7.0. In Tebere unit, soil solution pH ranged between 4.7 and 7.7 and further down in Wamumu and Karaba, values were between 4.9 and 8.0.

EC on the other hand had values ranging from a minimum of 0.08 to 1.52 dS/m in the entire scheme and was 0.46 dS/m on average. At unit level, it varied from 0.08 to 1.12 dS/m in Mwea, 0.11 to 0.60 dS/m in Thiba, 0.10 to 1.52 dS/m in Tebere, 0.10 to 1.34 dS/m in Wamumu and from 0.13 to 1.22 dS/m in Karaba unit. High significant differences ($p \leq 0.05$) were observed in soil pH and EC across the units. Values observed for soil pH and EC across the production units are presented in Table 2.1.

Table 2.1: **S**oil solution pH and EC range (mean±SD) across Mwea irrigation scheme

Unit	pH_{water}	EC (dS/m)
Mwea	4.6-8.1 (6.0±0.8)^{bc}	0.08-1.12 (0.36±0.21)^{bc}
Thiba	4.5-7.0 (5.7±0.8)^{c}	0.11-0.60 (0.30±0.18)^{c}
Wamumu	4.9-7.9 (6.3±0.8)^{abc}	0.10-1.34 (0.55±0.25)^{ab}
Karaba	5.0-8.0 (6.6±0.7)^{a}	0.13-1.22 (0.54±0.28)^{ab}
Tebere	4.7-7.7 (6.3±0.8)^{ab}	0.10-1.52 (0.56±0.38)^{a}
Overall	4.5-8.1 (6.2±0.8)	0.08-1.52 (0.46±0.28)
CV (%)	13	61

Means followed by the same letter within a column are not significantly different at $p \leq 0.05$

As pointed out in soil solution pH results in Table 2.1, soil pH tended to increase from being acidic in Mwea to towards neutral in Karaba while the soil salt concentration was negligible (<4dS/m). High soil pH was observed in Karaba and the lowest was in Thiba unit. In terms of salt concentration, Tebere unit had the highest value while Mwea unit had the lowest.

Soil pH is a major driver of soil fertility because it influences the availability and uptake of many elements both nutrients and toxins by plant roots (Brady and Weil, 2014). As per the ratings for Kenyan soils by the KSS, (1987), the soil pH in the Mwea scheme was found to range from medium acid in Thiba unit to slightly acid in Karaba on average. This medium level condition of soil pH is attributed to the basaltic parent material and the dry climate which favour the formation of Vertisols that largely occupy the scheme (Kondo *et al*., 2001). In crop production, soil pH ranging from 5.5 to 7.0 is said to be appropriate for satisfactory provision of plant nutrients mostly for grain and vegetable crops (Brady and Weil, 2014).

However, given the values of pH observed, there is possibility of insufficient or excessive supply of certain nutrient elements in cases where the pH values were below 5.5 or above 7.0. Our results showed that topographical elevation had an influence on soil pH and averagely, lower values were observed at higher elevation and higher values at lower elevation unit.

The concentration of soluble salts in the Mwea scheme soils is low given the low EC values recorded. The tolerance of rice to salt varies with growth stage and variety. It is said to be very tolerant to salinity during germination but very sensitive at 1-2 leaf stages (seedling stage). Its salt tolerance progressively increases during tillering and elongation and decreases at flowering. At the ripening stage, it appears to be little affected by (Yoshida, 1981; Kyuma, 2004). Soil EC followed similar pattern observed for soil pH increasing down the elevation; although Tebere unit recorded highest EC. Even so, the soils in the Mwea irrigation scheme have negligible salt concentration and are considered non-saline as the values were way below 4 dS/m.

2.3.2. Soil TC, TN and C to N ratio

Surface soil TC content varied from 9.6 to 35.5 g/kg in the scheme and was 19.0 g/kg on average. At unit level, soil TC ranged from 11.5 to 35.5 g/kg in Mwea and from 15.1 to 27.3 g/kg in Thiba. In Tebere unit, TC values varied from 17.4 to 32.0 g/kg while further down in Wamumu and Karaba the values ranged from 11.2 to 24.4 g/kg and from 9.6 to 25.9 g/kg respectively. On the other hand, soil TN ranged from 0.5 to 3.2 g/kg in the scheme with a mean of 1.14 g/kg. Unit-wise, TN varied from 0.6 to 3.2 g/kg in Mwea, 0.7 to 1.8 g/kg in Thiba and from 1.1 to 2.6 g/kg in Tebere. Lower in the scheme, TN values recorded were between 0.6 to 1.6 g/kg in Wamumu and 0.5 to 1.6 g/kg in Karaba. The ratio of soil carbon to nitrogen (C:N) in the scheme ranged from 10.6 to 24.5 with an average of 17.6. Observed ranges for TC, TN and C:N ratio together with the average values in the units and the whole scheme are shown in Table 2.2.

Table 2.2: Soil TC, TN and CN ratio range (mean±SD) across Mwea irrigation scheme units

Unit	**TC (g/kg)**	**TN (g/kg)**	**C:N ratio**
Mwea	11.5-35.3 (19.0±5.2)^{bc}	0.6-3.2 (1.17±0.55)^{b}	10.6-22.4 (17.4±2.53)^{b}
Thiba	15.1-27.3 (20.8±4.0)^{b}	0.7-1.8 (1.21±0.33)^{b}	14.9-21.7 (17.5±1.78)^{b}
Wamumu	11.2-24.4 (17.5±3.8)^{cd}	0.6-1.6 (0.99±0.27)^{bc}	15.6-22.0 (18.0±1.73)^{ab}
Karaba	9.6-25.9 (15.6±4.3)^{d}	0.5-1.6 (0.86±0.33)^{c}	14.6-24.5 (19.0±2.11)^{a}
Tebere	17.4-32.0 (26.1±3.7)^{a}	1.1-2.6 (1.73±0.43)^{a}	11.9-20.2 (15.5±2.14)^{c}
Overall	9.6-35.5 (19.0±5.4)	0.5-3.2 (1.14±0.49)	10.6-24.5 (17.6±2.38)
CV (%)	28	43	14

Means followed by the same letter within a column are not significantly different at p≤0.05

Our results showed a decrease in TC down the elevation being lower in Wamumu and Karaba (17.5 and 15.6 g/kg) and higher in Mwea and Thiba (19.0 and 20.8 g/kg), although Tebere unit recorded the highest soil TC content. Soil TN content followed the trend observed for soil TC and production units low in soil TC were also low in TN. The ratio of carbon to nitrogen however showed a reverse trend increasing with decreasing elevation with higher ratios in Wamumu and Karaba compared to Mwea and Thiba (Table 2.2).

Total carbon is a measure of carbon contained within soil organic matter (SOM) defined as the sum of both organic and carbonate carbon in a soil (Batjes, 1996). Soil carbon levels vary widely with climate, parent material, topographic position, textural class, natural vegetation and land use history (Batjes, 2010). On hill slopes, differences have been attributed to topographic variations in plant inputs, decomposition rates, soil texture, nutrients, water, erosion and deposition (Brejda *et al*., 2001; Burke *et al*., 1999; Garten and Ashwood, 2002; Hook and Burke, 2000).

An analysis of soil TC in our site revealed medium to high contents on average. The moderately high soil TC observed could be as a result of stubble left in the fields as straw is harvested and removed from the field. Soil TC and TN revealed that the concentration tended to decrease with decreasing elevation along the Mwea, Thiba, Wamumu and Karaba while the CN ratio increased. The significant differences observed in soil TC in our site can be attributed to textural differences along the topography as well as the differences in cultivation history that could have resulted in organic matter accumulation. Soil textural analysis showed higher silt content in Wamumu and Karaba at lower elevation (8.3% and 8.2% respectively) compared to Mwea (7.5%) at higher elevation. Clay on the other hand was higher in Mwea at 59.2% whereas Wamumu and Karaba in the lower elevation contained 54.8% and 39.0% clay respectively. Sand particles were higher in Karaba at 55.8% compared to Mwea at 33.4%.

Soil pH and mineralogy are also found to affect soil carbon humification and accumulation (Djukic *et al*., 2010; Rassmussen *et al*., 2006). Soils with higher clay content are known to contain higher organic matter because of slow degradation rates and complexion of clay-humus (Brady and Weil, 2014; Kaiser *et al*., 1996; Aweto and Enaruvbe, 2010). The high silt and low clay content in the lower elevation Wamumu and Karaba could have possibly negated accumulation of organic matter relative to the upslope with low silt and high clay content.

Apart from clay minerals playing a role in the sorption of organic matter, aluminium (Al) or iron (Fe) oxides/hydroxides; particularly hydrous iron oxides have been found to be effective in sorbing and stabilizing organic matter in soils (Kaiser *et al*., 1996; Kaiser and

Guggenberger, 2000; 2003). Surface properties of colloidal clays and mostly Fe oxide particles play a major role in the formation, arrangement and strength of aggregates in soils and it has been shown that iron oxides specifically haematite and magnetite adsorb more humic acids than clay minerals (Tombacz *et al*., 2004).

Carbon sorption by Fe oxide or clay minerals is further influenced by pH being highly favoured under acid conditions (Meier *et al*., 1999) and the capacity drops as pH increases above 6 (Gu *et al*., 1994). In our results, higher elevation areas of Mwea and Thiba had soil pH values <6 which could have possibly led to higher sorption of organic matter thus higher TC as observed. Furthermore, the units contained higher soil available Fe (see soil micronutrients results) compared to lower elevation units. The soil TC trend observed in our results can therefore be attributed to elevation differences in soil texture, pH and soil Fe concentration.

In rice production, N has been regarded as the most limiting nutrient because of the various biochemical processes in paddy soils (Fageria *et al*., 2003; Ishii *et al*., 2011). In our site, despite the widespread use of N fertilizers and some organic manure (Kihoro *et al*., 2013), soil TN contents were generally low. This could be probably due to low and improper application methods that often lead to N losses because surface application of ammoniacal fertilizers enhances their losses through nitrification and denitrification (Ishii *et al*., 2011). In addition, high pH of Vertisols has been shown to favour gaseous loss and leaching of ammonia especially when urea or ammonium fertilizers are applied to the surface (Sahrawat, 1980; Fillery *et al*., 1986). In our study site, the calcareous nature of the soil thus moderately high pH especially at lower elevation and improper fertilizer application are likely to exacerbate N losses thus low soil TN as recorded. While assessing the suitability of effluents from Mwea irrigation scheme, Onderi, (2016) observed that the waste water was high in nitrate (>5 mg/l), an indication that much of the ammonium nitrate applied is lost through irrigation water. Removal of plant material also contributes to N removal (Brady and Weil, 2014) and this common practice in the Mwea scheme for ease in land preparation (Kondo *et al*., 2001) further contributes to N mining.

Rice yield and N uptake efficiency was shown to increased when green manure was incorporated in soil or applied on the surface (Asagi and Ueno, 2009). According to Olk *et al*., (2007), anaerobic decomposition inhibits N mineralization in continuous rice cropping systems; therefore soil aeration and aerobic residue decomposition or crop rotation practices can be adopted to improve N supply in lowland soils. In this regard, alternating between aerobic and anaerobic soil conditions could help enhance stubble decomposition and thus N supply.

Soil carbon to nitrogen ratio gives information about the degree of organic matter decomposition as a result of microbial activity and the quality held in the soil (Kaiser and Guggenberger, 2003). In our results, average C:N ratios varied from 15.5 to 18.4 which is considered to be moderately high; an indication that decomposition rates are lower. In addition, the low soil TN as observed compared to TC could result in the moderately high ratios. There is thus need to enhance soil N concentration probably through combined organic and inorganic fertilization in addition to sustainable management practices like plant residue return for better N efficiencies and thus lower the C:N ratio to acceptable ranges of 10 to 15.

2.3.3. Soil Available P_2O_5

Values from 6.3 to 549 mg/kg were recorded for soil available phosphorus and varied statistically across the units ($p<0.05$). In the upper elevation units of Mwea and Thiba, available P_2O_5 ranged from 10.7 to 417.4 mg/kg and from 22.8 to 178.6 mg/kg respectively. In Tebere unit, values from 20.3 to 549.0 mg/kg were recorded and further down in Wamumu and Karaba, values from 6.3 to 292.2 mg/kg and 19.3 to 272.9 mg/kg respectively were recorded. On average, no clear trend was observed along the elevation and from the coefficient of variation (CV) statistic of 101%, there is an extremely high variation in soil available P_2O_5 in the scheme as some fields seem severely deficient while others are highly enriched. Such high variability in soil phosphorus was also observed by Kondo *et al.*, (2001). Observed values for soil available phosphorus in the Mwea irrigation scheme ranged within values shown in Table 2.3.

Table 2.3: Range of available P_2O_5 (mean±SD) across Mwea irrigation scheme units

Unit	Available P_2O_5 (mg/kg)
Mwea	10.7-417.4 (52.2±61.8)^{bc}
Thiba	22.8-178.6 (98.2±47.1)^{ab}
Wamumu	6.3-292.2 (41.6±46.5)^{c}
Karaba	19.3-272.9 (107.0±71.4)^{a}
Tebere	20.3-549.0 (96.4±104.7)^{ab}
Overall	6.3-549 (71.1±71.6)
CV (%)	101

Means followed by the same letter within a column are not significantly different at p≤0.05

In rice production soil P_2O_5 less than 12-20 mg/kg is regarded as being deficient (Dobermann and Fairhurst, 2000). Values observed in our sites seem sufficiently high except for some parts in Mwea and Wamumu units where values below 12 mg/kg were observed. Nonetheless, averagely at unit level, Bray II extractable P_2O_5 revealed high concentrations of available phosphorus in the soil (Table 2.3).

In many alkaline and neutral soils, phosphate anions are immobilized through sorption and/or precipitation with cations such as Ca^{2+} and Fe or Al in acid soils exhibiting very slow dissolution and thus very little are available for plant use and as a result, there is low response to added P (Gough, 1961; Syers *et al*., 2001; Garg and Bahl, 2008). Although diammonium phosphate (DAP) fertilizers are widely used during planting in the area (Kihoro *et al*., 2013), it is likely that much of it is easily transformed to insoluble Ca and Fe-phosphates as we observed Ca^{2+} dominated the exchangeable cations and soil Fe was also reasonably high. Such probable soil P transformations to insoluble Ca-phosphates have been reported in Ethiopia where Ca was the dominant cation on Vertisol exchange complex (Beyene, 1988).

Bray II extractant (ammonium fluoride and hydrochloric acid) has been shown to dissolve Ca-P that are abundant in Ca-rich soils such as Vertisols (Mamo *et al*., 1988), thus the reasonably high Bray II P_2O_5 observed in our surface soils could be because of the dissolution of Ca-P and Fe-P. In this regard, there is need to increase phosphate fertilizer use efficiency in these soils. Application of organic manures/crop residues has been shown to result in direct P addition and acceleration of native P solubilization through mineralization or solubilization (Garg and Bahl, 2008; Parham *et al*., 2002). Therefore addition of organic manure/crop residues could likely assist in P availability apart from C and N in the soil, thus should be encouraged.

2.3.4. Soil Available Sulphur

Highly significant difference ($p<0.05$) was observed in surface soil 500ppm KH_2PO_4-extractable sulphur in the scheme with values ranging from 8.1 to 168.5 mg/kg. Within the units, soil S levels varied from 8.1 to 156.2 mg/kg in Mwea and from 28.1 to 85.1 mg/kg in Thiba. In Tebere, soil S ranged from 28.8 to 129.0 mg/kg while further down in Wamumu and Karaba the levels ranged from 33.0 to 143.4 mg/kg and from 39.3 to 168.5 mg/kg respectively. A CV statistic of 43% indicates that the scheme is moderately heterogeneous in terms of soil S concentration. It was observed that soil S was higher in lower elevation units compared to upper elevation units. Table 2.4 shows the range of values recorded for soil available S in the Mwea irrigation scheme.

Table 2.4: Soil available S (mean±SD) across Mwea irrigation scheme units

Unit	Avail. S (mg/kg)
Mwea	8.1-156.2 (49.0±23.1)[b]
Thiba	28.1-85.1 (49.1±14.3)[b]
Wamumu	33.0-143.4 (75.2±26.5)[a]
Karaba	39.3-168.5 (69.8±27.5)[a]
Tebere	28.8-129.0 (77.6±25.5)[a]
Overall mean	8.1-168.5 (63.4±27.4)
CV (%)	43

Means followed by the same letter within a column are not significantly different at p≤0.05

Soil S concentration in our site exceeded the <9mg kg^{-1} deficiency criteria for rice production (Dobermann and Fairhurst, 2000) on average. According to Brady and Weil, (2014), atmospheric dry and wet deposition, fertilizer application and soil organic matter comprise the major additions in soil available S. On the other hand, leaching and plant removal form major part of soil S losses. Although plant removal at harvest is a common practice in Mwea (Kondo *et al*., 2001), the reasonably high S concentration observed is attributable to the widespread use of sulphate of ammonium (SA) fertilizers (Kihoro *et al*., 2013). This fertilizer is recommended as a convenient source of S in rice production (Yamaguchi, 1999) and S deficiency is less frequent in rice since most of production occurs in lowland alluvial soils where the availability of many plant nutrients is higher than in free-draining upland soils (Dobermann and Fairhurst, 2000). Deficiencies have been observed on highly weathered soils in many West African lowlands (Abe *et al*., 2010; Yamaguchi, 1999).

In the Mwea irrigation scheme, additional S could be originating from atmospheric deposition given the proximity to the volcanic Mt Kenya through wet and dry deposition. Incorporation of straw rather than removal is said to return considerable amounts of S into the soil (Dobermann and Fairhurst, 2000) and can reduce the need of chemical fertilizer application. Although our site contain sufficient amounts of soil S with unlikelihood of its deficiency, the aspect of straw management should be encouraged to sustainably maintain high levels of S together with other essential elements like N and C.

2.3.5. Soil Available SiO_2

The concentration of soil SiO_2 in the scheme ranged from 108 to 812 mg/kg with an average of 413 mg/kg and showed significant differences between units ($p<0.05$). Unit-wise in the Mwea unit, soil SiO_2 levels ranged from 108 to 729 mg/kg and from 252 to 812 mg/kg in Thiba unit. In Tebere, the values varied from 260 to 765 mg/kg while further down in Wamumu and Karaba the values ranged from 187 to 783 mg/kg and from 241 to 761 mg/kg respectively. The concentration of SiO_2 in the scheme varied slightly (CV= 36%) and increased from 321 mg/kg in Mwea at higher elevation to 501 mg/kg in Karaba at lower elevation on average. Ranges observed for available SiO_2 are shown in Table 2.5.

Table 2.5: Observed ranges for available SiO_2 (mean±SD) across Mwea irrigation scheme

Unit	**Avail. SiO_2 (mg/kg)**
Mwea	108-729 (321±127)^b
Thiba	252-812 (419±131)^a
Wamumu	187-783 (425±143)^a
Karaba	241-761 (501±108)^a
Tebere	260-765 (478±150)^a
Overall mean	108-812 (413±148)
CV (%)	36

Means followed by the same letter within a column are not significantly different at p≤0.05

The high silica contents observed in our site is attributed to Si-rich parent material. As a component element of almost all parent material, rice plants take up silica from soils at levels several-fold greater than N, P and K (Tsujimoto *et al*., 2014). Soil silica content in our site exceeded the 86 mg/kg deficiency level for rice (Dobermann and Fairhurst, 2000). Studies on clays from the MIS have also indicted that the clays contain 42-50% silica (Muriithi *et al*., 2012). Apart from the Si-rich parent material, irrigation water is also known to supply additional silica into the soil (Desplaques *et al*., 2006).

In rice production, straw is said to contain about 86% of silica taken up from the soil, thus return of rice straw is a crucial factor in rice soil SiO_2 (Klotzbücher *et al*., 2015; Marxen *et al*., 2016). Even though the Mwea irrigation scheme soils contain high silica and therefore unlikely risks of its deficiency, the practice of straw removal after harvest reduces silica concentration (Klotzbücher *et al*., 2015); thus the aspect of crop residue management in soil silica balance as well as other soil nutrient components remains critical.

2.3.6. Soil Exchangeable Cations

Variations were observed in the concentration of soil exchangeable cations except for soil exchangeable Mg^{2+} that did not show significant difference between units (p>0.05). Among the exchangeable cations, exchangeable Ca^{2+} occurred in higher concentration closely followed by Mg^{2+} as exchangeable Na^+ and K^+ were in lower concentration. In scheme, soil exchangeable Ca^{2+} ranged from 8.7 to 69.6 $cmol_c$/kg, exchangeable Mg^{2+} from 5.0 to 40.3 $cmol_c$/kg, exchangeable Na^+ from 0.3 to 5.0 $cmol_c$/kg and exchangeable K^+ ranged from 0.1 to 1.5 $cmol_c$/kg.

At unit level, exchangeable Ca^{2+} ranged from 8.7 to 51.7 $cmol_c/kg$ while exchangeable Mg^{2+}, K^+ and Na^+ ranged from 5.0 to 40.3 $cmol_c/kg$, 0.1 to 1.3 $cmol_c/kg$ and 0.3 to 5.0 $cmol_c/kg$ respectively in Mwea unit. In Thiba unit, Ca^{2+} ranged from 29.9 to 51.8 $cmol_c/kg$, Mg^{2+} from 15.2 to 38.3 $cmol_c/kg$, Na^+ from 0.3 to 1.7 $cmol_c/kg$ while K^+ varied from 0.1 to 0.6 $cmol_c/kg$. In Tebere unit, exchangeable Ca^{2+} and Mg^{2+} dominated the exchangeable sites and ranged from 12.0 to 65.6 $cmol_c/kg$ and from 7.9 to 39.2 $cmol_c/kg$ of soil respectively. In the same unit, the exchangeable Na^+ ranged from 0.4 to 3.3 $cmol_c/kg$ and exchangeable K^+ from 0.2 to 1.5 $cmol_c/kg$. In Wamumu unit, exchangeable cation concentrations ranged from 17.2 to 66.4 $cmol_c/kg$ for Ca^{2+}, from 8.3 to 32.9 $cmol_c/kg$ for Mg^{2+}, from 0.5 to 2.6 $cmol_c/kg$ for Na^+ and from 0.1 to 1.0 $cmol_c/kg$ for K^+. In Karaba unit, cation concentration ranged from 32.5 to 69.6 $cmol_c/kg$, 16.7 to 37.8 $cmol_c/kg$, 0.6 to 1.7 $cmol_c/kg$ and 0.1 to 1.2 $cmol_c/kg$ for exchangeable Ca^{2+}, Mg^{2+}, Na^+ and K^+ respectively.

As the soil exchange site was dominated by divalent cations compared to monovalent cations, there seems to be disproportionate exchangeable cation distribution. The high concentration of Ca and Mg in relation to K brings about an antagonistic effect making K least available for plant uptake. Average values recorded for soil exchangeable cations in the scheme are shown in Table 2.6.

Table 2.6: Mean soil exchangeable cations (mean±SD) across Mwea irrigation scheme units

	Exchangeable cations ($cmol_c/kg$)				
Unit	**Ca^{2+}**	**Mg^{2+}**	**Na^+**	**K^+**	**$(Ca^{2+}+Mg^{2+})/K^+$ ratio**
Mwea	31.3±8.1^{c}	25.0±6.8^{a}	1.48±1.15^{ab}	0.22±0.16^{c}	322±179^{ab}
Thiba	39.5±7.1^{b}	23.8±7.5^{a}	0.68±0.35^{c}	0.22±0.15^{c}	390±235^{a}
Wamumu	37.2±9.4^{bc}	21.1±6.8^{a}	1.06±0.33^{abc}	0.30±0.16^{bc}	223±101^{bc}
Karaba	46.9±7.3^{a}	23.9±6.3^{a}	0.95±0.23^{bc}	0.40±0.24^{b}	231±134^{b}
Tebere	38.7±12.0^{b}	23.7±7.2^{a}	1.49±0.72^{a}	0.71±0.42^{a}	121±79^{c}
Overall mean	37.7±10.4	23.6±6.7	1.20±0.79	0.34±0.28	259±167
CV (%)	28	28	66	82	64

Means followed by the same letter within a column are not significantly different at $p \leq 0.05$

In our site, the concentration of Ca^{2+} and Mg^{2+} exceeded the critical deficiency level and hence sufficient for rice production besides, Ca and Mg deficiency is uncommon in lowland soils because it is usually sufficient enough in the soil; is supplied from mineral fertilizers and also from irrigation water (Dobermann and Fairhurst, 2000; Fairhurst *et al.*, 2007). Moreover, changes in their concentration in flooded soils negligible (Fageria *et al.*, 2011).

The soil exchange complex exhibits differential attraction and divalent cations are shown to be have a higher selectivity coefficient being retained in higher concentrations and for longer periods by the soil colloidal particles than the monovalent cations thus their higher concentration (Giday *et al*., 2015).

Compared to Tropical Asian and Japanese paddy soils (Kawaguchi and Kyuma, 1974; Kyuma, 2004), Mwea soils contain higher exchangeable Ca and Mg which could be attributed to differences in parent material composition and climate. This high calcium and magnesium levels contribute to the relatively high soil pH as observed. On average, soil Ca and Mg content in our study site was very high according to KSS, (1987) criteria.

In terms of soil exchangeable K^+, the contents in our site varied from low to very low (KSS, 1987) on average and therefore insufficient; but according to Dobermann and Fairhurst, (2000), the concentration exceeded the 0.2 $cmol_c/kg$ deficiency criteria for rice production. Potassium has been acknowledged as an important crop production constraint including rice in Kenya (Kondo *et al*., 2001; Smaling, 1993). This is because in many farming systems, emphasis has been on N and P fertilizers only. Earlier in western Kenya, an annual depletion of 112 kg ha^{-1}, 3 kg ha^{-1} and 70 kg ha^{-1} for N, P and K respectively was observed majorly through harvested products (Smaling, 1993).

Straw together with stubble retains 80-85% of K and other nutrients taken up at maturity (Fairhurst *et al*., 2007). However, the common practice of straw removal after harvest for livestock feed and to ease land preparation in our site (Kondo *et al*., 2001) contributes to mining of K as well as other nutrients. In addition, negative K balance is also attributed to the lack of fertilizer K use in line with the increasing N fertilizer use (Dobermann *et al*., 1998).

In rice production, it is shown that where exchangeable (Ca+Mg):K ratio exceeds 100, K availability for rice uptake becomes limiting (Dobermann and Fairhurst, 2000). Although soil exchangeable K^+ exceeded the deficiency criteria for rice, the disproportionate distribution of soil exchangeable cations in the soil brings about antagonistic effect causing K to be unavailable for rice uptake. In Asia, studies under irrigated rice systems have shown that excessive soil Ca and Mg compared to K reduces K uptake by rice (Dobermann *et al*., 1996a, b). In our results as shown in Table 2.6, in all the production units, the ratio of divalent cations to K^+ was rather high an indication that the divalent cations induce K deficiency. The cation imbalance was notably higher in the upper elevation units of Mwea and Thiba at 322 and 390 respectively and tended to show a decreasing trend in the lower elevation units of Wamumu and Karaba (Table 2.6).

In our results, 86% of the sampled fields showed disproportionate cation distribution with ratios exceeding 100; an indication of widespread soil K deficiencies induced by high Ca^{2+} and Mg^{2+}. With the additions of Ca and Mg into the system through irrigation water and fertilizers, their concentration increases and further aggravates K deficiency. Elsewhere in Ethiopia, similar disproportionate distribution of soil exchangeable cations was reported on wheat growing Vertisols where high Mg induced K deficiency (Hailu *et al*., 2015).

Since much of K taken up in retained in straw, returning rice straw to the soil returns about 90% of K to the soil which considerably reduces the need for K fertilizer application (Sahrawat, 2000); therefore the practice of straw return should also be advocated for. Research has shown that long-term cropping declined soil K over time but with return of crop residue or manure application, K depletion slowed down (Kapkiyai *et al*., 1999). The practice of incorporating straw together with mineral fertilizer use helps in maintaining or increasing soil K as well as P, N and Si reserves (Fairhurst *et al*., 2007). Given the predisposing K deficiency factors in Mwea, efforts should be made to enhance soil K availability and to correct the disproportionate concentration of exchangeable cations in the soil through sufficient application of K fertilizers. Given the extreme cation imbalances in the scheme, efforts should be made to enhance soil K availability through sufficient K fertilizer application and appropriate soil management practices like straw return.

2.3.7. Soil Available Micronutrients

Soil micronutrients varied significantly ($p<0.05$) between units with Fe and Mn occurring in very high concentrations compared to Cu and Zn. Soil Fe ranged from undetected to 2074 mg/kg, soil Mn from 1.5 to 859 mg/kg, Cu from undetected to 9.3 mg/kg and soil Zn from 0.1 to 8.0 mg/kg. At unit level, the concentrations varied from undetected to 1361 mg/kg, 1.5 to 849 mg/kg, undetected to 5.5 mg/kg and from 0.1 to 8.0 mg/kg for soil Fe, Mn, Cu and Zn respectively in Mwea unit. In Thiba unit, soil Fe ranged from 22.1 to 795 mg/kg, Mn from 63.6 to 859 mg/kg while soil Cu and Zn ranged from 0.7 to 4.2 mg/kg and 0.1 to 4.1 mg/kg respectively. In Tebere, soil Fe was high and ranged from 13.9 to 2074 mg/kg while Mn ranged from 28.5 mg/kg to 465 mg/kg. On the other hand, Cu ranged from 0.2 to 7.1 mg/kg while Zn ranged from 0.3 to 5.9 mg/kg. In Wamumu unit, Fe varied from 16.3 to 433 mg/kg, Mn from 41.4 to 433 mg/kg, Cu from 1.0 to 9.3 mg/kg and Zn from 0.4 to 3.0 mg/kg. In Karaba unit, Fe concentration ranged from 0.5 to 395 mg/kg, Mn from 1.5 to 859 mg/kg while Cu and Zn ranged from 0.2 to 6.8 mg/kg and from 0.4 to 3.7 mg/kg respectively.

Mean values for soil micronutrient concentration at unit level is shown in Table 2.7.

Table 2.7: Mean soil available micronutrients across (mean±SD) Mwea irrigation scheme

	Soil available micronutrients (mg/kg)			
Unit	**Fe**	**Mn**	**Cu**	**Zn**
Mwea	205±284^{ab}	193±167^{b}	1.7±1.1^{c}	1.5±1.3^{a}
Thiba	313±285^{a}	349±228^{a}	2.5±0.8^{bc}	1.9±1.6^{a}
Wamumu	100±97.0^{bc}	141±108^{b}	4.2±2.0^{a}	1.7±0.7^{a}
Karaba	59.7±69.0^{c}	131±68.3^{b}	2.8±1.5^{b}	1.6±0.7^{a}
Tebere	252±430^{ab}	146±104^{b}	2.5±1.6^{bc}	1.9±1.6^{a}
Overall mean	165±258	175±148	2.7±1.7	1.7±1.1
CV (%)	156	85	63	65

Means followed by the same letter within a column are not significantly different at p≤0.05

2.3.7.1. Soil Available Fe

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 and Fairhurst, 2000). In rice production systems, Fe deficiency is likely to occur when the soil concentration is below 4-5 mg/kg and toxicities when the concentration is above 300 mg/kg (Dobermann and Fairhurst, 2000).

In Mwea scheme, stresses related to Fe deficiencies are likely to be experienced in the Mwea and Karaba units where minimum values of below 4-5 mg/kg were recorded in about 3% of samples from each unit. Apart from the low soil Fe concentration, high pH of calcareous soils after submergence decreases solubility and uptake of Fe because of high bicarbonate concentrations (Fairhurst *et al*., 2007). Soil Fe deficiency is said to occur on neutral, calcareous and alkaline soils especially those with low organic matter. In lowland soils, irrigation with alkaline water further exacerbates Fe deficiency (Fairhurst *et al*., 2007). Furthermore, high soil P levels, excessive irrigation, poor drainage causing prolonged wet soil conditions and low soil temperature are also associated with Fe deficiency (Zekri and Obreza, 2015). In the United States, Fe deficiency was commonly observed on Florida's calcareous soils with high soil pH (Zekri and Obreza, 2015). In Mwea, apart from the low soil Fe concentration and calcareous nature of the soils, poor drainage where in most cases farmers tend to 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. While there have been no observations on Fe toxicity occurrence in Mwea paddy fields, the conditions and soils present indicate likelihood of Fe toxicity occurring where about 17% of

the sampled fields recorded over 300 mg/kg soil Fe. 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 and Asch, 2005; Abah *et al*., 2012). Toxicity occurs as a result of excessive Fe uptake by rice plants 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 although it is generally high in lowland rice soils with permanent flooding during crop growth (Yoshida, 1981; Fairhurst *et al.,* 2007). Fe toxicity is associated with poor water control, resulting in reducing soil conditions that promote the accumulation of soluble ferrous iron in the soil solution. Under these specific water conditions, soluble Fe in the soil solution (Fe^{2+}) is absorbed by roots and accumulates in leaves (Audebert and Fofana, 2009).
Unit-wise Fe toxicity stress could occur in a number of fields in Mwea unit (25%), Thiba unit (44%), Tebere unit (25%) and to a lesser extent in Wamumu (5%) and Karaba unit (3%) where soil Fe values exceeded the 300 mg/kg limit. Previous work by Muriithi *et al*., (2012) in Mwea indicated Fe as the major contaminant in the clays occurring at between 12-16%.
It is acknowledged that Fe toxicity is likely to be a serious problem in many parts of the world such as Africa, South America and Asia where rice is grown on acid soils that have great potential for rice production (Fageria *et al*., 1990). Yield losses in rice associated with Fe toxicity commonly ranges from 15% to 30%; but crop failure has been reported to occur under severe toxicity (Auderbert and Sahrawat, 2000). In West Africa, a yield reduction of 40-45% was reported in rice though the extent depended on cultivar, intensity of toxicity and crop management strategies in terms of water control and mineral fertilization (Auderbert and Fofana, 2009).
Fe toxicity can be alleviated by application of potassium sulphate, introduction of tolerant genotypes, adoption of ridge culture, improvement in soil drainage and water and nutrient management practices (Auderbert and Fofana, 2009; Yamauchi, 1989; Sahrawat, 2005). Elevated soil Fe has been shown to decrease the absorption of other plant nutrients especially P and K by the rice (Yoshida, 1981; Olaleye *et al*., 2001) and as such, application of plant nutrients that could be limiting such as P, K, Ca, Mg and Zn may possibly alleviate iron toxicity effects by enhancing plant tolerance (Tanaka *et al*., 1966). 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. However, under high iron toxicity stress an integrated use of tolerant cultivars and improved soil and nutrient management may give the best results (Sahrawat *et al*., 1996).

Micronutrient cations are most stable and available under low pH conditions and as the pH increases, their ionic forms are changed into insoluble and unavailable forms (Brady and Weil, 2014). In this study, the soils of Thiba unit recorded the lowest pH (5.7) and this could be the reason for higher soil Fe concentration. The decrease in surface soil Fe concentration down the elevation as observed is because in paddy fields as water percolates through soil, Fe as well as Mn is known to accumulate below the plough layer in the subsoil. Leaching of nutrients from the plough layer by water percolation and their accumulation in the subsoil has been observed in paddy fields in Japan (Katoh *et al*., 2004a). The accumulation of leached Fe occurs in the uppermost part of the subsoil (Katoh *et al*., 2004b) therefore the decrease in top soil Fe concentration in the depression areas is attributable to its percolation to the subsoil through irrigation water and increase in surface soil pH.

2.3.7.2. Soil Available Mn

Mn as a micronutrient is important in mitigating Fe toxicity and its availability just like Fe increases with flooding (Dobermann and Fairhurst, 2000). Deficiencies of Mn, together with Cu and B are rare in rice but a concentration of 3-30 mg/kg is used as the optimum soil Mn concentration and its application is said to be unnecessary in soils with above 40 mg/kg 0.1M HCl extractable Mn (Dobermann and Fairhurst, 2000). Mn deficiency stress occurs because of small quantities of soil available Mn and large concentrations of Ca^{2+}, Mg^{2+}, Zn^{2+} etc as well as large Fe in the soil (Dobermann and Fairhurst, 2000; Fairhurst *et al*., 2007). Mn deficiency stress is uncommon in lowland rice as its solubility is said to increase in submerged conditions when the redox potential is low and Mn is reduced to plant-available forms (Dobermann and Fairhurst, 2000; Fairhurst *et al*., 2007; Tao *et al*., 2007).

Mn deficiency is however said to occur on both acidic and alkaline soils probably due to leaching in acid soils and insolubility in alkaline soils. In addition, it is said to be associated with deficiencies of Zn, Fe and Cu on both acid and alkaline soils and with Mg deficiency on sandy acidic soils (Zekri and 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). 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 and Fairhurst, 2000; Fairhurst *et al*., 2007). In scheme, results indicated that Mn deficiency is unlikely to be critical issue because less than the optimum soil Mn concentration was recorded in only 2% of the sampled fields.

On the other hand, Mn toxicity has been reported in soil with readily reducible Mn of more than 300mg/kg and such soils are said to occur in lowlands that have ground-water containing elevated amounts of Mn (Kyuma, 2004). In a separate scenario, Mn toxicity has been reported to affect plants where soil Mn contents exceeded 500 mg/kg (Kabata-Pendias, 2011). Mn toxicity however is said to be rare in lowland rice even with large Mn concentrations because rice is said to be comparatively tolerant to large Mn concentrations (Dobermann and Fairhurst, 2000; Fairhurst *et al*., 2007). Mn toxicity is however expected to occur in field crops grown on acid soils of pH around 5.5 or lower and with high Mn levels (Kabata-Pendias, 2011). 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/drained (Kabata-Pendias, 2011). In rice production, Mn toxicity is likely to occur on acid upland soils with pH values below 5.5 in combination with Al toxicity; lowland soils with large amounts of easily reducible Mn, acid-sulphate soils and on areas affected by Mn mining as found in Japan (Dobermann and Fairhurst, 2000; Fairhurst *et al*., 2007).

Although rice is said to be tolerant to Mn toxicity (Dobermann and Fairhurst, 2000; Fairhurst *et al*., 2007), toxicity stress is likely to be experienced in 16% of Mwea and 44% of Thiba unit sampled fields. In these cases, the soil solution pH recorded was below 5.5 and soil Mn concentration was above the critical 300 mg/kg level for rice. To mitigate the negative Mn toxicity stress effects, proper fertilizer management should be taken into account and application of lime on acid soils to reduce the concentration of active Mn together with proper straw management is recommended (Dobermann and Fairhurst, 2000; Fairhurst *et al*., 2007).

Similar to soil Fe, soil Mn decreased 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. This is because Mn and Fe together with other nutrient elements in paddy fields tend to percolate through irrigation water and accumulate in the subsoil (Katoh *et al.,* 2004a). Furthermore, micronutrients in soil are known to be most soluble and readily available under acid conditions and as the pH increases, they change into insoluble hydroxides or oxides thus unavailable (Brady and Weil, 2014). The decrease in Mn concentration down the elevation in our study site is thus attributed to its percolation through irrigation water and the increase in surface soil pH as the exchangeable bases particularly Ca increased down the slope.

2.3.7.3. Soil Available Cu

Generally, Cu is accumulated in the upper few centimetres of soils; however, due to its tendency to be adsorbed to 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, Cu 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 and 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 and Fairhurst, 2000; Fairhurst *et al*., 2007; Kabata-Pendias, 2011). In our study, Cu soil concentrations in the study area are sufficient as they are above critical deficiency level of 0.1mg/kg (Dobermann and Fairhurst, 2000; Fairhurst *et al*., 2007). Cu availability decreases with flooding as a result of the formation of copper sulphides and ferrite and further complexion with organic matter. As a result, its availability for plant uptake decreases with increase in pH (Dobermann and 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.

2.3.7.4. Soil Available Zn

Zn is an essential micronutrient required by both plants and animals including humans (Alloway, 2009). 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 and Weil, 2014). It has been reported to be generally of low mobility in soils and has a tendency of being adsorbed on clay size particles (Kabata-Pendias, 2011; Alloway, 2008). As an essential plant micronutrient, Zn has been shown to be the most critical yield limiting micronutrient to rice growth after N (Neue and Mamaril, 1985; Alloway, 2008; Buri *et al*., 2000). Zn is accessible to plant as exchangeable Zn^{2+} ion most of which 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 and Weil, 2014). With flooding, Zn availability generally decreases compared to well-aerated soils and when prolonged, the potential for Zn deficiencies increase due to the formation of sulphates and carbonates (Neue and Mamaril, 1985).

In rice production, 2.0 mg/kg 0.1N HCl-extractable is set as the critical level for deficiency to occur (Dobermann and Fairhurst, 2000; Fairhurst *et al*., 2007). Under severe Zn deficiency, tillering of rice is affected or may stop completely and spikelet sterility is also known to increase (Dobermann and Fairhurst, 2000) which has a negative effect on grain yield (Mei *et al*., 2009). Zn deficiency has been shown to decrease rice yields by as much as 50 % in Burkina Faso (van Asten *et al*., 2004). In Japan, Zn deficiency stress causes a disorder known as '*Akarage Type II*' that damages rice throughout its growth cycle (Dobermann and Fairhurst, 2000). Zn deficiency stress is said to occur on a wide range of soils with several contributing factors. Soils with low Zn, 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 (Kyuma, 2004; Dobermann and Fairhurst, 2000; Fairhurst *et al*., 2007; Alloway, 2008; 2009).

Results showed high variability in soil Zn concentration across the unit blocks and the concentration was below the 2.0 mg/kg critical level on average. Overall in the larger scheme, 72% of our sampled fields had soil Zn concentration below the 2.0 mg/kg critical limit. Such high incidences of Zn deficiency stress have also been reported on Ethiopian Vertisols (Kebede and Yamoah, 2009; Hailu *et al*., 2015). In soil, small amounts of available Zn, 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 cause Zn deficiencies (Dobermann and Fairhurst, 2000; Fairhurst *et al*., 2007). In addition, large P fertilizer application is also known to cause Zn immobilization in the soil thus making it unavailable for plant uptake (Dobermann and Fairhurst, 2000; Fairhurst *et al*., 2007).

In Mwea apart from the low soil available Zn, the calcareous nature of soils, high soil Fe and high P in the region exacerbate Zn deficiency. Famers in the scheme rarely use micronutrient fertilizer and in most cases they apply only 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 to help in leaching out cations and to reduce on carbonate accumulation. The recommended Zn fertilizer dose for lowland rice is generally between 5-10 kg Zn/ha (Dobermann and Fairhurst, 2000; Fairhurst *et al*., 2007) and therefore studies to determine the optimum Zn dose for Mwea is necessary. In addition, selection of Zn-efficient varieties and application of organic manure or Zn fertilizers before seeding or transplanting (Fairhurst *et al*., 2007) are helpful management strategies to explore. Organic matter input as well as crop residue management are seen as keys to replenishing Zn as well as S in the soil (Abe *et al*., 2010) and should be advocated for in the scheme.

2.4. Relationship between Soil Parameters

In order to detect the relationship between the studied parameters, Pearson's correlation coefficients (*$p \leq 0.001$, $p \leq 0.01$ and $p \leq 0.05$*) were calculated and are shown in Table 2.8. From the Pearson correlation analysis, results show that pH affected most of the parameters negatively and positively. A highly significant negative correlation was found between pH and TC ($r=-0.54$, $p \leq 0.001$), TN ($r=-0.51$, $p \leq 0.001$) and micronutrients Fe, Mn and Zn ($p \leq 0.001$) except Cu ($p>0.05$). On the other hand, the correlation was positive with C/N ratio ($r=0.44$, $p \leq 0.001$), exchangeable Na^+ (($r=0.42$, $p \leq 0.001$), exchangeable Ca^{2+} ($r=0.58$, $p \leq 0.001$), Ca+Mg/K ratio ($r=0.17$, $p \leq 0.05$) and soil available SiO_2 ($r=0.68$, $p \leq 0.001$).

Table 2.8: Pearson Correlation matrix of analyzed soil elements

	pH	EC	TC	TN	C/N	P_2O_5	Ex.K	Ex.Na	Ex.Mg	Ex.Ca	Ca+Mg/K	Zn	Cu	Fe	Mn	SiO_2	S
pH																	
EC	0.11ns																
TC	-0.54***	0.03ns															
TN	-0.51***	0.07ns	0.96***														
C/N	0.44***	-0.14ns	-0.76***	-0.86***													
P_2O_5	0.13ns	0.04ns	0.16*	0.20**	-0.09ns												
Ex.K	0.10ns	0.34***	0.31***	0.26***	-0.16*	0.24***											
Ex.Na	0.42***	0.22**	-0.13ns	-0.13ns	0.05ns	-0.03ns	0.11ns										
Ex.Mg	0.11ns	-0.15*	-0.08ns	-0.21**	0.34***	-0.23**	0.18*	0.22**									
Ex.Ca	0.58***	0.13ns	-0.28***	-0.36***	0.39***	0.27***	0.27**	0.19**	0.36***								
Ca+Mg/K	0.17*	-0.40***	-0.33***	-0.35***	0.33***	-0.16*	-0.59***	0.06ns	0.21**	0.15*							
Zn	-0.51***	0.32***	0.48***	0.55***	-0.44***	0.24***	0.03ns	-0.22**	-0.34***	-0.37***	-0.42***						
Cu	-0.10ns	-0.06ns	0.09ns	0.11ns	-0.19**	-0.07ns	0.01ns	-0.13ns	-0.26***	-0.14ns	-0.23**	0.16*					
Fe	-0.58***	-0.03ns	0.58***	0.66***	-0.54***	0.17*	-0.05ns	-0.27***	-0.32***	-0.52***	-0.23**	0.66***	0.21**				
Mn	-0.41***	-0.09ns	0.25***	0.21**	-0.10ns	0.02ns	-0.08ns	-0.31***	-0.05ns	-0.23**	-0.06ns	0.34***	-0.07ns	0.43***			
SiO_2	0.68***	0.31***	-0.30***	-0.30***	0.27***	0.15*	0.32***	0.15*	0.05ns	0.55***	-0.03ns	-0.27***	-0.06ns	-0.33***	-0.22**		
S	-0.01ns	0.55***	0.13ns	0.11ns	-0.11ns	0.03ns	0.27***	0.06ns	-0.15*	0.09ns	-0.26***	0.09ns	0.29***	0.01ns	-0.12ns	0.15*	

*Significance levels are noted by ***: $p \leq 0.001$; **: $p \leq 0.01$; *: $p \leq 0.05$; ns (not significant): $p > 0.05$*

The association observed in the correlation was clearly manifested in soil Mn, Fe, TC, TN and CN ratio as our sites that had high soil pH recorded low TC and TN but with high CN ratio. Similarly, where the soil pH was low, soil Mn and Fe was relatively high. Generally, micronutrients Zn, Cu, Fe and Mn are said to be greatly available under acidic to neutral pH soils but are much less available at pH above 7 (Fageria *et al*., 2003; 2011; Aref 2012; Brady and Weil, 2014). Zn had very strong and highly significant positive correlation with Fe ($r=0.66$, $p<0.001$) and Mn ($r=0.34$, $p<0.001$) but with Cu, it was relatively weak ($r=0.16$, $p<0.05$). In addition, micronutrients showed negative correlation with soil exchangeable bases; the strongest being between Fe and Ca^{2+} ($p=-0.52$, $r<0.001$). The negative correlation was also seen with SiO_2 and C/N ratio. On the contrary, soil exchangeable cations, SiO_2 and C/N ratio showed positive correlation with soil pH (Table 2.8).

Soil exchangeable cations correlated positively with each other while (Ca+Mg)/K ratio showed the highest negative correlation with exchangeable K^+ ($r=-0.59$, $p<0.001$) with TC ($r=-0.33$, $p<0.001$) and TN ($r=-0.35$, $p<0.001$). What's more, exchangeable Ca^{2+}, Mg^{2+} and Na^+ correlated negatively with soil TC and TN being significantly higher with Ca^{2+} ($r=-0.28$ and $r=-0.36$ at $p<0.001$) an indication that high soil exchangeable Ca^{2+} negates accumulation of carbon in soil as revealed from our site where units with high exchangeable Ca^{2+} in the lower elevation had low TC and TN. Conversely, soil exchangeable K^+ correlated positively with TC and TN ($r=0.31$ and $r=0.26$ at $p<0.001$). Soil exchangeable cations correlated negatively with soil micronutrients and positively with pH such that as micronutrients are increased at low pH, exchangeable cations are decreased.

2.5. Extraction of Factors Characterizing Soil Properties

Factor analysis by Principal Component Analysis (PCA) was used to reduce multidimensional datasets to interpretable sizes by identifying factors that contain most of the variance of the associated variables (Barona and Romero, 1996). Factors that contained Eigen values greater than 1 were retained. In the scheme, five principal components (PC1 to PC5) with Eigen values exceeding 1.0 were derived which accounted for about 72 % of total variance (Table 2.9).

The first component, PC1, showed high positive loadings for TN, Fe, Zn and TC while C/N ratio, pH and Ca loaded negatively on the same component. Since N is related to soil and fertilizer management, this first component can be referred to as "soil management factor". The factors that loaded positively on PC1 showed positive correlation between them but correlated negatively with the negatively loading factors. The negative loading for C/N ratio is as a result of high carbon and low nitrogen together with slow decomposition rates under prolonged anaerobic conditions that probably accelerate gaseous and hydrologic N losses and hinder N mineralization. Furthermore, inappropriate N application methods that lead to leaching losses are contributing factors to the low soil N accumulation. The negative Ca loading effect, which is positively associated with high pH, showed a negative association with TC and TN and the units that had higher soil exchangeable Ca^{2+} and higher soil pH in the lower elevation position of the scheme recorded lower soil TC and TN. Furthermore, the high concentration of Ca^{2+} in the soil seemed to negatively affect straw yield and compromised grain quality by hindering accumulation of a number of nutrients in the grain (Chapter 3).

PC2 showed high positive loading for K and EC which correlated well positively, thus can be termed as the “K factor”. PC3 loaded negatively for S, an indication that probably limited S utilization for rice growth. On the other hand, PC4 and PC5 loaded positively for P_2O_5 and Mn respectively.

Table 2.9: Factor loadings, eigen-values and cumulative contribution ratio

Variables	PC1	PC2	PC3	PC4	PC5
pH	-0.741	0.383	0.190	0.154	-0.326
EC	0.227	0.634	-0.373	0.036	0.385
TC	0.782	0.314	0.280	-0.293	-0.076
TN	0.842	0.283	0.270	-0.228	-0.199
C/N	-0.779	-0.241	-0.129	0.245	0.285
Avail. P_2O_5	0.147	0.371	0.450	0.604	-0.182
Ex. K	0.095	0.817	0.094	-0.105	0.144
Ex. Na	-0.332	0.439	0.001	-0.297	-0.237
Ex. Mg	-0.478	0.132	0.173	-0.506	0.345
Ex. Ca	-0.665	0.470	0.212	0.182	0.138
Ex. Ca+Mg/K ratio	-0.491	-0.544	0.209	-0.081	-0.116
Avail. Zn	0.802	0.038	-0.052	0.257	0.196
Avail. Cu	0.123	-0.002	-0.556	0.249	-0.433
Avail. Fe	0.814	-0.135	0.106	0.168	-0.087
Avail. Mn	0.422	-0.269	0.214	0.286	0.550
Avail. SiO_2	-0.456	0.570	0.186	0.253	0.032
Avail. S	0.084	0.518	-0.612	0.017	0.038
Eigen-value	5.30	3.00	1.45	1.29	1.18
Cumulative contribution (%)	31.1	48.8	57.4	64.9	71.9

A pictorial representation of results from factor analysis is presented in Figure 2.2. As the figure shows, the variables S and P_2O_5 that loaded highly on PC3 and PC4 respectively have close association and show positive correlation with PC2 variables though with a lesser contribution on component 2. They can probably be summed as ‘fertilizer management’ factors as they form the essential nutrients required for high yields to be realized. Therefore supplying them in adequate rates and application times are important factors that influence their use efficiency for enhanced productivity and sustainability of rice.

Mn loaded highly and positively on PC5 and is closely associated with PC1 factors of TN, Fe, Zn and TC. Since PC1 is N factor related to its management and the relative efficiency of rice utilization of N fertilizer is directly related to water management, thus rice growth stage at N application, N source and the chemical transformations that occur to N after it is applied to the soil need to be considered. Continuously flooded rice does not absorb NO_3 because of rapid losses via denitrification (Fageria *et al.*, 2003) making it of little or no benefit to rice. For N use efficiency, application on dry rather than wet soil is recommended to avoid losses. Proper flood water management is critical for efficient N uptake which also aids in reducing Fe and Mn accumulation to toxic ranges in the soil.

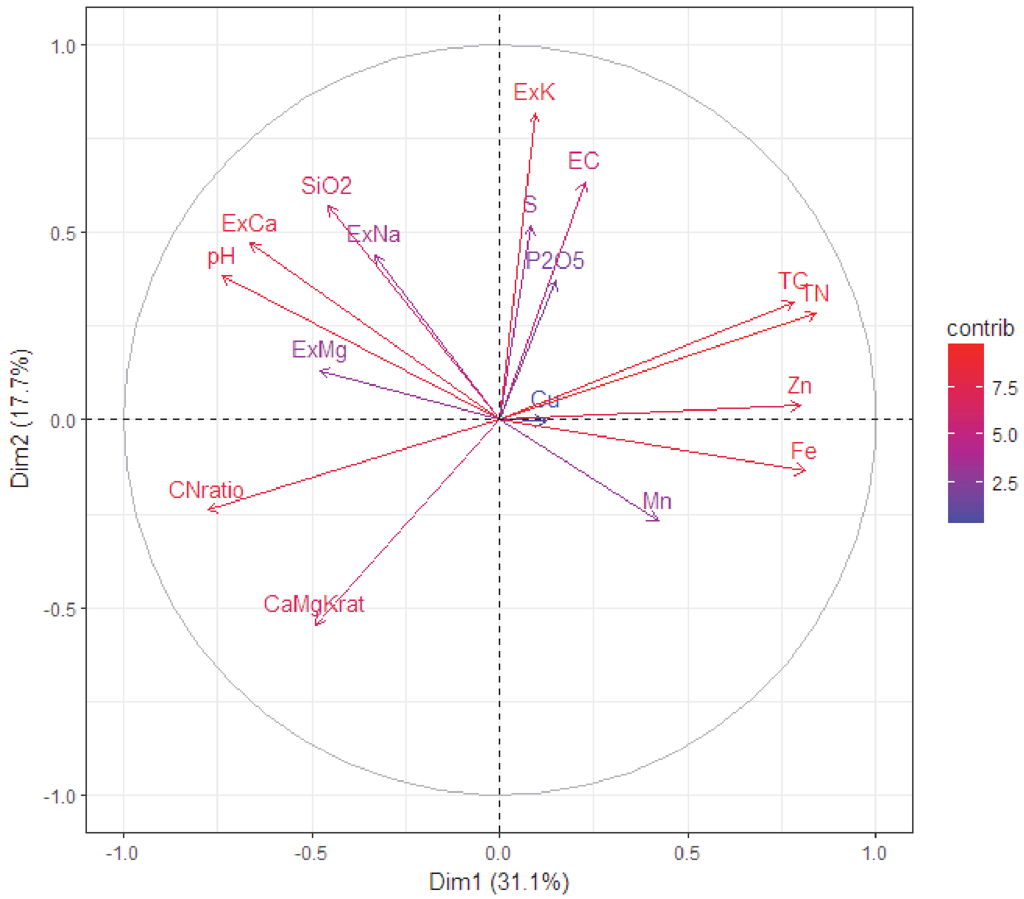

Figure 2. 2: Variable loading on PC 1 and PC 2.

2.6. Conclusions and Recommendations

This results show clearly that the soils of Mwea irrigation scheme are highly variegated in terms of nutrient concentration and therefore blanket fertility recommendation is not suitable.

The variation could be linked to topographical differences, differences in cultivation/establishment history as well as field management. With regard to topography, there is a lot of surface downward movement of nutrients through irrigation water and deposition in the lower elevation. Although fertilizer recommendations exist, they do not capture differences in topography and are rather ‘blanket’. The variations in soil properties require specific and adapted management practices for improved yields and sustainable use of the irrigation scheme. Some of the deficiencies (Zn and K availability) identified are due to the inherently low availability of nutrients in the soil as a consequence of non-application of fertilizers or manures containing them coupled with inappropriate farm management practices that lead to losses. Improvements in rice productivity in the scheme should be knowledge-based arising from interactions and integrated management of agronomic inputs such as nutrients and water management. With some improvement in the soil drainage situation, correcting the deficiencies of K and Zn could increase rice productivity well above the present level. Furthermore, efficient fertilizer application modes for instance nitrogen fertilizer incorporation into the soil rather than wet surface application should be avoided to reduce losses. Incorporation of straw into the soil as opposed to removal after harvest could also help return some of the nutrients taken up by the crop and help conserve soil nutrient reserves in the long term.

2.7. References

Abah J, Umar A, Bashir M, Dramé KN, Manneh B, Abo ME, Sie M, 2012. Soil characteristics of three iron toxic sites in Nigeria *Journal of Science Multidisciplinary Research*, 4, 68-72.

Abdullahi M, Mizutani M, Tanaka S, Goto A, Matsui H, 2003. Changes in Water Management Practices in the Mwea Irrigation Scheme Kenya from 1994 to 1998, *Rural and Environmental Engineering* 44, 60-67.

Abe SS, Buri MM, Issaka RN, Kiepe P, Wakatsuki T, 2010. Soil fertility potential for rice production in West African lowlands *Japanese Agricultural Research Quarterly*, 44, 343-355.

Alloway BJ, 2008. *Zinc in Soils and Crop Nutrition*, (2nd Ed.) IFA and IFIA, Brussels, Belgium and Paris, France.

Alloway BJ, 2009. Soil factors associated with zinc deficiency in crops and humans *Environmental Geochemistry and Health*, 31, 537-548.

Aref F, 2010. Influence of zinc and boron interaction on residual available iron and manganese in the soil after corn harvest *American- Eurasian Journal of Agriculture and Environmental Science*, 8, 767-772.

Aref F, 2012. Manganese, iron and copper contents in leaves of maize plants (*Zea mays* L.) grown with different boron and zinc micronutrients *African Journal of Biotechnology*, 11, 896-903.

Asagi N, Ueno H, 2009. Nitrogen dynamics in paddy soil applied with various 15N-labelled green manures *Plant and Soil*, 322, 251-262.

Audebert A, Fofana M, 2009. Rice yield gap due to iron toxicity in West Africa, *Journal of Agronomy and Crop Science*, 195, 66-76.

Audebert A, Sahrawat KL, 2000. Mechanisms for iron toxicity tolerance in lowland rice *Journal of Plant Nutrition*, 23, 1877-1885.

Aweto AO, Enaruvbe GO, 2010. Catenary variation of soil properties under oil palm plantation in south western Nigeria *Ethiopian Journal of Environmental Studies and Management*, 3, 1-7.

Barona A, Romero F, 1996. Distribution of metals in soils and relationships among fractions by Principal Component Analysis. *Soil Technology*. 8, 303-319.

Bationo A, Hartemink A, Lungu O, Naimi M, Okoth P, Smaling E, Thiombiano L, 2006. African Soils: Their productivity and profitability of fertilizer use. Background paper prepared for the African Fertilizer Summit June 2006, Abuja Nigeria.

Batjes NH, 1996. Total carbon and nitrogen in the soils of the world *European Journal of Soil Science*, 47, 151-163.

Batjes NH, 2010. A Global Framework of Soil Organic Carbon Stocks under Native Vegetation for Use with Simple Assessment Option of the Carbon Benefits Project System, Carbon Benefits project (CBP) and ISRIC- World Soil Information, Wageningen, Report.

Becker M, Asch F, 2005. Iron toxicity in rice- conditions and management concepts *Journal of Plant Nutrition and Soil Science*, vol. 168, 558-573.

Beyene D, 1988. Soil fertility research on some Ethiopian Vertisols, In *Proceedings of a Conference on the Management of Vertisols in Sub-Saharan Africa* held at ILCA, Addis Ababa, Ethiopia pp. 223-231.

Brady NC, Weil RR, 2014. The Nature and Properties of Soils, 14th Edition, Pearson Education Limited.

Bray RH, Kurtz LT, 1945. Determination of Total, Organic and Available forms of Phosphorus in Soils *Soil Science*, 59, 39-46.

Brejda JJ, Mausbach MJ, Goebel JJ, Allan DL, Dao TH, Karlen DL, Moorman TB, Smith JL, 2001. Estimating surface soil organic carbon content at a regional scale using the National Resource Inventory *Soil Science Society of American Journal*, 65, 842-849.

Buri MM, Masunaga T, Wakatsuki T, 2000. Sulphur and zinc levels as limiting factors to rice production in West Africa lowlands *Geoderma*, 94, 23-42.

Burke IC, Lauenroth WK, Riggle R, Brannen P, Madigan B, Beard S, 1999. Spatial variability of soil properties in the shortgrass steppe: the relative importance of topography, grazing, microsite and plant species in controlling spatial patterns *Ecosystems,* 2, 422-438.

Casanova D, Goudriaan J, Catala FMM, Withagen JCM, 2002. Rice yield prediction from yield components and limiting factors *European Journal of Agronomy,* 17, 41–61.

Chan CS, Amin MSM, Lee TS, Mohammud CH, 2008. Apparent Soil Electrical Conductivity as Indicator of Paddy Soil Productivity Journal *of Tropical Agriculture and Food Science,* 36*,*145–153.

Desplanques V, Cary L, Mouret JC, Trolard F, Bourrié G, Grauby O, Meunier JD, 2006. Silicon transfers in a rice field in Camargue (France). *Journal of Geochemical Exploration*, 88, 190-193.

Djukic I, Zehetner F, Tatzber M, Gerzabek MH, 2010. Soil organic matter stocks and characteristics along an Alpine elevation gradient *Journal of Plant Nutrition and Soil Science,* 173, 30-38.

Dobermann A, Cruz PS, Cassman KG, 1996. Fertilizer inputs, nutrient balance and soil nutrient-supplying power in intensive, irrigated rice systems, I: Potassium uptake and K balance *Nutrient Cycling in Agroecosystems*, 46, 1-10.

Dobermann A, Cassman KG, Cruz PS, Adviento MA, Pampolino MF, 1996. Fertilizer inputs, nutrient balance and soil nutrient-supplying power in intensive, irrigated rice systems, II: Effective soil K-supplying capacity *Nutrient Cycling in Agroecosystems*, 46, 11-21.

Dobermann A, Cassman KG, Mamaril CP, Sheehy JE, 1998. Management of Phosphorus, Potassium and Sulphur in intensive irrigated lowland rice *Field Crops Research*, 56, 113-138.

Dobermann A, Fairhurst T, 2000. *Rice Nutrient Disorders and Nutrient Management*, International Rice Research Institute.

Fageria NK, Baligar VC, Wright RJ, 1990. Iron nutrition of plants: An overview on the chemistry and physiology of its deficiency and toxicity *Pesquisa Agropecuaria Brasileira*, 25, 553-570.

Fageria NK, Slaton NA, Baligar VC, (2003) Nutrient Management for improving lowland rice productivity and sustainability *Advances in Agronomy,* 88, 63-152.

Fageria NK, Carvalho GD, Santos AB, Ferreira EP, Knupp AM, 2011. Chemistry of lowland rice soils and nutrient availability *Communications in Soil Science and Plant Analysis*, 42, 1913-1933.

Fairhurst T, Witt C, Buresh R, Dobermann A, 2007. *Rice: A practical guide to nutrient management*, 2nd ed. International Rice Research Institute.

Ferguson RB, Hergert GW, Schepers JS, Gotway CA, Cahoon JE, Peterson TA, 2002. Site-specific nitrogen management of irrigated maize: yield and soil residual nitrate effects *Soil Science Society of American Journal, 66*, 544–553.

Fillery IRP, Vlek PLG, 1986. Reappraisal of the significance of ammonia volatilization as an N loss mechanism in flooded rice fields *Fertilizer Research,* 9, 79-98.

Fox RL, Olson RA, Rhoades HF, 1964. Evaluating the Sulphur Status of Soils by Plant and Soil tests *Soil Science Society of American Journal*, 28, 243-246.

Garg S, Bahl GS, 2008. Phosphorus availability to maize as influenced by organic manures and fertilizer P associated phosphatase activity in soils *Bioresource Technology* 99, 5773-5777.

Garten CT, Ashwood TL, 2002. Landscape level differences in soil carbon and nitrogen: implications for soil carbon sequestration *Global Biogeochemical Cycles,* 16, 6101-6114.

Giday O, Gibrekidan H, Berhe T, 2015. Soil Fertility Characterization in Vertisols of Southern Tigray, Ethiopia *Advances in Plants and Agriculture Research*, 2(1), 00034.

Global Rice Science Partnership (GRiSP), 2013. *Rice almanac*, 4th edition. Los Baños (Philippines): International Rice Research Institute.

Gough NA, 1961. *Phosphorus availability in two calcareous soils,* Doctoral dissertation, University of British Columbia.

Gu B, Schmitt J, Chen Z, Liang L, McCarthy JF, 1994. Adsorption and desorption of natural organic matter on iron oxide: Mechanisms and Models *Environmental Science and Technology,* 28, 38-46.

Hailu H, Mamo T, Keskinen R, Karltun E, Gebrekidan H, Bekele T, 2015. Soil fertility status and wheat nutrient content in Vertisol cropping systems of central highlands of Ethiopia *Agriculture and Food Security*, 4, 19-28.

Hartemink AE, 2010. *Land use change in the tropics and its effects on soil fertility*, 19th World Congress of Soil Science, Soil Solutions for a Changing World 1- 6 August 2010 Brisbane, Australia.

Hook PB, Burke IC, 2000. Biogeochemistry in a shortgrass landscape: control by topography, soil texture and microclimate *Ecology*, 81, 2686-2703.

Imaizumi K, Yoshida S, 1958. Edaphological studies on Silicon supplying power of paddy soils *Bulletin of the National Institute of Agricultural Sciences,* 8, 261-304.

International Board for Soil Research and Management Inc. (lBSRAM), 1987. Management of Vertisols under Semi-Arid Conditions *Proceedings of the First Regional Seminar on Management of Vertisols under Semi-Arid Conditions*, Nairobi, Kenya.

International Institute of Tropical Agriculture (IITA), 1979. *Selected Methods for Soil and Plant Analysis. Manual Series No. 1* International Institute of Tropical Agriculture, Ibadan, Nigeria.

Ishii S, Ikeda S, Minamisawa KK, Senoo K, 2011. Nitrogen cycling in rice paddy environments: past achievements and future challenges *Microbes and Environments*, 26, 282-292.

Kabata-Pendias A, 2011. *Trace elements in Soils and Plants*, CRC Press, Taylor and Francis Group, LLC.

Kabutha C, Mutero C, 2002. From government to farmer-managed smallholder rice schemes: The unresolved case of the Mwea Irrigation Scheme In Blank HG, *et al.,* (eds.) *The changing face of irrigation in Kenya: Opportunities for anticipating changes in Eastern and Southern Africa* (pp 191-210). Colombo, Sri Lanka, IWMI.

Kaiser K, Guggenberger G, Zech W, 1996. Sorption of DOM and DOM fractions to forest soils *Geoderma*, 74, 281-303.

Kaiser K, Guggenberger G, 2000. The role of DOM sorption to mineral surfaces in the preservation of organic matter in soils *Organic Geochemistry,* 31, 711-725.

Kaiser K, Guggenberger G, 2003. Mineral surfaces and soil organic matter *European Journal of Soil Science,* 54, 219-236.

Kapkiyai JJ, Karanja NK, Qureshi JN, Smithson PC, Woomer PL, 1999. Soil organic matter and nutrient dynamics in a Kenyan Nitisol under long-term fertilizer and organic input management *Soil Biology and Biochemistry,* 31, 1773-1782.

Katoh M, Murase J, Hayashi M, Matsuya K, Kimura M, 2004. Nutrient leaching from the plow layer by water percolation and accumulation in the subsoil in an irrigated paddy field *Soil Science and Plant Nutrition*, 50, 721-729.

Katoh M, Murase J, Kimura M, 2004. Sites and processes of nutrient accumulation in the subsoil through water percolation from the plow layer in a submerged paddy soil microcosm *Soil Science and Plant Nutrition*, 50, 731-738.

Kawaguchi K, Kyuma K. 1974. Paddy Soils in Tropical Asia, Part 1: Description of Fertility Characteristics. *Southeast Asian Studies,* 12(1), 3-24.

Kebede F, Yamoah C, 2009. Soil fertility status and Numass Fertilizer Recommendation of Typic Hapluusterts in the Northern Highlands of Ethiopia *World Applied Sciences Journal*, 6, 1473-1480.

Kenya Soil Survey (KSS), 1987. Manual for Soil Survey and Land Evaluation, vol. 1 *Soil Survey, Miscellaneous Soil Paper No: M24, Kenya Soil Survey*.

Kihoro J, Njoroge JB, Murage H, Ateka E, Makihara D, 2013. Investigating the impact of rice blast disease on the livelihood of the local farmers in greater Mwea region of Kenya *SpringerPlus*, 2, 308-320.

Kihoro J, Njoroge JB, Murage H, 2013. Suitability analysis for rice growing sites using a multicriteria evaluation and GIS approach in great Mwea region, Kenya *SpringerPlus* 2, 265.

Klotzbücher T, Marxen A, Vetterlein D, Schneiker J, Türke M, Sihn NV, Manh NH, Chien HV, Marquez L, Villareal S, Bustamante JV, Jahn R, 2015. Plant-available silicon in paddy soils as a key factor for sustainable rice production in Southeast Asia *Basic and Applied Ecology*, 16, 665-673.

Kondo M, Toshinari OTA, Wanjogu R, 2001. Physical and chemical properties of Vertisols and soil nutrient management for intensive rice cultivation in the Mwea area in Kenya *Japanese Journal of Tropical Agriculture,* 45: 126-132.

Kyuma K, 2004. *Paddy soil science*, Kyoto University Press.

Mamo T, Haque I, Kamara CS, 1988. Phosphorus status of some Ethiopian highland Vertisols, In *Management of vertisols in Sub-Saharan Africa, Proceedings of a conference held at ILCA*, Addis Ababa, Ethiopia pp: 232-252.

Marxen A, Klotzbücher T, Jahn R, Kaiser K, Nguyen VS, Schmidt A, Schädler M, Vetterlein D, 2016. Interaction between silicon cycling and straw decomposition in a silicon deficient rice production system *Plant and Soil*, 398, 153-163.

Mati BM, Wanjogu R, Odongo B, Home PG, 2011. Introduction of the System of Rice Intensification in Kenya: Experiences from Mwea Irrigation Scheme *Paddy Water Environment,* 9, 145–154.

McLean EO, 1982. Soil pH and lime requirement In Page AL, *et al*., (eds) *Methods of soil analysis Part 2 - Chemical and microbiological properties*. (2nd Ed.) *Agronomy* 9, 199-223.

Meier M, Namjesnik-Dejanovic K, Maurice PA, Chin YP, Aiken GR, 1999. Fractionation of aquatic natural organic matter upon sorption to Goethite and Kaolinite *Chemical Geology*, 157, 275-284.

Mei Y, Lei S, Fang-Sen X, Jian-Wei L, Yun-Hua W, 2009. Effects of B, Mo, Zn and their interactions on seed yield of Rapeseed (*Brassica napus* L.) *Pedosphere*, 19, 53-59.

Ministry of Agriculture (MoA), 2009. Government of Kenya *National Rice Development Strategy* (2008-2018).

Muchena FN, Gachene CKK, 1985. Properties, Management and Classification of Vertisols in Kenya. In *Fifth Meeting of the Eastern African Sub-committee for Soil Correlation and Land Evaluation*, Wad Medani, Sudan. *World Soils Resources Reports no.* 56. Rome: FAO.

Mukiama TK, Mwangi RW, 1989. Field Studies of larval *Anopheles arabiensis* Patton of Mwea Irrigation Scheme, Kenya *International Journal of Tropical Insect Science* 10, 55-62.

Muriithi NT, Karoki KB, Gachanja AN, 2012. Chemical and Mineral Analyses of Mwea clays *International Journal of Physical Sciences*, 7, 5865-5869.

Nelson DW, Sommers LE, 1982. Total Carbon, Organic Carbon and Organic Matter. In Page AL, *et al*., (eds.) *Methods of Soil Analysis, Part 2, Chemical and Microbiological Properties*. *Agronomy*, 9, 539-594.

Neue HE, Mamaril CP, 1985. Zinc, sulphur and other micronutrients in wetland soils, In *Wetland soils: Characterization, Classification and Utilization*, (ed. IRRI), Los Banõs, Philippines, pp. 307-319.

Njagi TN, 2012. *An Investigation into the Possibility of a Rice Green Revolution in Sub-Saharan Africa: Lessons from the Mwea Irrigation Scheme in Kenya*. (Unpublished Doctoral dissertation), National Graduate Institute for Policy Studies (GRIPS), Tokyo Japan.

Nyamai M, Mati BM, Home PG, Odongo B, Wanjogu R, Thuranira EG, 2012. Improving land and water productivity in basin rice cultivation in Kenya through System of Rice Intensification (SRI) *AgricEngInt: CIGR Journal 14,* 1-9.

Nyang'au WO, Mati BM, Kalamwa K, Wanjogu RK, Kiplagat LK, 2014. Estimating Rice Yield under Changing Weather Conditions in Kenya Using CERES Rice Model *International Journal of Agronomy* Volume 2014*, Hindawi Publishing Corporation*

Olaleye AO, Tabi FO, Ogunkunle AO, Singh BN, Sahrawat KL, 2001. Effect of toxic iron concentrations on the growth of lowlands rice, *Journal of Plant Nutrition*, 24, 441-457.

Olk DC, Samson MI, Gapas P, 2007. Inhibition of nitrogen mineralization in young humic fractions by anaerobic decomposition of rice crop residues *European Journal of Soil Science,* 58, 270-281.

Omonode RA, Vyn TJ, 2006. Spatial Dependence and Relationships of Electrical Conductivity to Soil Organic Matter, Phosphorus and Potassium *Soil Science* 171, 223-238.

Onderi JN, 2016. Suitability Assessment of Effluents from Mwea Irrigation Scheme for reuse in Irrigation for Rice Production, Kirinyaga County, Kenya. Unpublished MSc Thesis, Kenyatta University.

Osiname OA, Schulte EE, Corey RB, 1973. Soil tests for available copper and zinc in soils of Western Nigeria *Journal of the Science of Food and Agriculture*, 24, 1341-1349.

Parham JA, Deng S, Raun W, Johnson G, 2002. Long-term cattle manure application in soil *Biology and Fertility of Soils*, 35, 328-237.

Rasmussen C, Southard RJ, Horwath WR, 2006. Mineral control of organic carbon mineralization in a range of temperate conifer forest soil *Global Change Biology,* 12, 834-847.

Rosemary AE, Bibiana MW, Njuguna N, Dominic MK, Daniel A, 2010 Rice Value Chain Study Report for Kenya, Ministry of Agriculture (MoA) and Kenya Agricultural Research Institute (KARI).

Sahrawat KL, Mulbah CK, Diatta S, Delaune RD, Patrick WH, Singh BN, Jones MP, 1996. The role of tolerant genotypes and plant nutrients in the management of iron toxicity in lowland rice *The Journal of Agricultural Science*, 126, 143-149.

Sahrawat KL, 1980. Control of urea hydrolysis and nitrification in soil by chemicals - Prospects and problems *Plant and Soil,* 57, 335-352.

Sahrawat KL, 2000. Macro-and micronutrients removed by upland and lowland rice cultivars in West Africa *Communications in Soil Science and Plant Analysis,* 31, 717-723.

Sahrawat KL, 2005. Iron toxicity in wetland rice and the role of other nutrients *Journal of Plant Nutrition*, 27, 1471-1504.

Sanchez PA, 2002. Soil Fertility and Hunger in Africa *Science* 295*,* 2019-2020.

Sanchez PA, 2010. Tripling crop yields in Tropical Africa *Nature Geoscience*, 3, 299-300.

Smaling EMA, 1993. *An Agro-Ecological Framework of Integrated Nutrient Management with Special Reference to Kenya* (Unpublished Doctoral thesis) Agricultural University, Wageningen, The Netherlands.

Smaling EMA, 1993. Soil nutrient depletion in Sub-Saharan Africa, In: The Role of Plant Nutrients for Sustainable Food Crop Production in Sub-Saharan Africa, van Reuler, H. and W. H. Prins (eds), Leidschendam, The Netherlands: VKP (Dutch Association of Fertilizer Producers), pp: 53-67.

Sombroek WG, Braun HMH, van der Pouw BJA, 1982. The exploratory soil map of Kenya and Agro- Climatic Zone Map of Kenya scale 1:1million. Exploratory Soil Survey Report No.E1. Kenya Soil Survey, Nairobi.

Syers JK, de Vries FP, Nyamudeza P, (Editors), 2001. *The Sustainable Management of Vertisols*, CABI.

Tanaka A, Loe R, Navasero SA, 1966. Some mechanisms involved in the development of iron toxicity symptoms in the rice plant *Soil Science and Plant Nutrition*, 12, 32-38.

Tao H, Dittert K, Zhang L, Lin S, Römheld V, Sattelmacher B, 2007. Effects of soil water content on growth, tillering and manganese uptake of lowland rice grown in the water-saving ground-cover rice-production system (GCRPS) *Journal of Plant Nutrition and Soil Science*, 170, 7-13.

Thomas GW, 1982. Exchangeable cations In Page AL *et al.,* (eds.) *Methods of Soil Analysis, Part 2, 2nd ed. Agronony Monograph,* 9. ASA and SSSA, Madison, WI.

Tombacz E, Libor Z, Illes E, Majzik A, Klumpp E, 2004. The role of reactive surface sites and complexation by humic acids in the interaction of clay mineral and iron oxide particles *Organic Geochemistry*, 35, 257-267.

Tsujimoto Y, Muranaka S, Saito K, Asai H, 2014. Limited Si-nutrient status of rice plants in relation to plant-available Si of soils, nitrogen fertilizer application and rice-growing environments across Sub-Saharan Africa. *Field Crops Research*, 155, 1-9.

United States Agency International Development (USAID), 2014. *The Competitiveness and Trade Expansion Program, Staple Foods Value Chain Analysis*, Country Report –Kenya.

van Asten PJ, Barro SE, Wopereis MC, Defoer T, 2004. Using farmer knowledge to combat low productive spots in rice fields of a Sahelian irrigation scheme *Land Degradation and Development*, 15, 383-396.

Yamaguchi J, 1999. Sulphur deficiency of rice plants in the lower Volta area, Ghana *Soil Science and Plant Nutrition*, 45: 367-383.

Yamauchi M, 1989. Rice bronzing in Nigeria caused by nutrient imbalances and its control by potassium sulphate application *Plant and Soil*, 117, 275-286.

Yoshida S, 1981. *Fundamentals of Rice Crop Science* International Rice Research Institute.

Zekri M, Obreza TA, 2015. Micronutrient deficiencies in citrus: Iron, Zinc and Manganese, University of Florida Co-operative Extension Service, Institute of Food and Agricultural Sciences, EDIS; pp. 1-3.

CHAPTER 3

Relationship between Soil and Rice Nutrient Content

3.1. Introduction

The demand for rice in Kenya continues to increase owing to continued growth of population. As such, yield increases in rice are likely to occur through fine-tuning of crop management options. Plant growth and development is highly reliant on the uptake of nutrients from the soil. According to the amount required by plants, nutrients can be divided into macronutrients (N, P, Ca, P, Mg and S) and micronutrients (Fe, Cl, Mn, Zn, B, Cu, Mo and Ni) (Marschner, 2012). The amount of nutrients present in plant tissues is mainly dependent on the plant demand and soil availability for each particular nutrient. Similar to plants, humans also require most of the same nutrients, which are obtained from the daily diet. Unfortunately, not all plant-derived food contains the necessary amounts of nutrients to meet the dietary requirements of humans. This becomes even more critical when the diet is based on a poor variety of plant derived food, and the majority of the plant derived food contains low amounts of bioavailable nutrients. For instance, a diet based only on staple cereals like maize, rice, wheat, etc is not able to cover the demand of many nutrients, since cereals are low known to be in protein and micronutrients, such as Fe and Zn (White and Broadley, 2005; Cakmak, 2008; Newell-McGloughlin, 2008). Presently grown high yielding rice varieties even though are a major staple food and energy source for a large world's population are poor in essential micronutrients such as Zn especially the white rice (Kennedy *et al*., 2002, Sharma *et al*., 2013).

Understanding soil test results and plant tissue analysis is vital in developing nutrient management. Soil and straw nutrient concentrations were positively correlated for most nutrients since the concentration of a particular nutrient in the plant is generally greater when the concentration in the soil is high. Studies have shown that there exists variability in soil properties and yield in rice production systems, which may potentially lead to site-specific management of paddy fields (Moritsuka *et al*., 2004; Shoji *et al*., 2005).

Grain quality after yield is the most important factor for rice production and rice nutritional quality has been considered as one of the main objectives for rice improvement (Ning *et al*., 2009). Nitrogen supply commonly limits grain yield in irrigated rice systems. Rice plant demand for other macronutrients mainly depends on N supply (Dobermann *et al*., 1998). Environmental pollution by nutrient leaching or runoff from rice fields has become another concern. Application of other macronutrients such as potassium has lagged behind, leading to imbalanced plant nutrition and negative potassium input-output balances (Dobermann *et al*., 1998). As a result of negative nutrient balances, significant depletion of soil nutrients such as K and P seem to occur in irrigated rice (Dobermann *et al*., 1996). There are considerable reservations about crop N, P and K requirements because the internal efficiencies vary greatly depending on variety, nutrient supply, crop management and climatic conditions. Several investigators suggested that genetic variation in internal efficiency of P and K may exist in rice (Fageria *et al*., 1988).

At the end of growing seasons, mass senescence typically occurs in leaves and other tissues. These remobilized nutrients are most likely moved to developing seeds in annual crop species, provided that the senescence and seed import are synchronized to provide source-sink relationships (Waters and Sankaran, 2011). During this stage of plant development, remobilization i.e. net export of stored or recycled nutrients of some nutrients occurs from vegetative tissues, such as leaves and stems or there is continuous uptake by the plant roots, therefore understanding soil test results and plant tissue analysis is vital in developing nutrient management.

In rice production systems in Kenya, mineral fertilisation is mainly restricted to N and P applications (Kihoro *et al*., 2013) and the relationship between soil minerals and grain quality has not received any attention. This research thus focused attention on crop nutrient contents while assessing soil nutrient supplying capacity. Furthermore, the relationships between the plant nutrient content and chemical properties of the soil such as available P_2O_5, K, S, total N, exchangeable cations and micronutrient contents were investigated. The investigation aimed at analyzing the effects of soil nutrient supplying power on rice nutrient accumulation and considering implications for efficient and sustainable management of paddy soil fertility.

3.2. Materials and Methods

3.2.1. Site description, sample collection and analysis

Details about site characteristics, soil sampling procedures and analysis are provided in Chapter 1. At harvesting time, grain and straw samples were collected from selected fields across the scheme, dried, ground and analysed for total straw and grain elements.

3.2.2. Plant Nutrient Analysis

Plant digests were prepared using concentrated HNO_3 and analyzed for total Ca, Mg, K, Cu, Fe, Mn, P_2O_5, S and Zn according to Koyama and Sutoh, (1987). The concentrations were thereafter determined by Inductively Coupled Plasma-Atomic Spectroscopy (ICPE-9000, Shimadzu).

3.2.3. Statistical Analysis

All data were subjected to an analysis of variance using R software version 3.4.0 for windows and statistically significant differences between means compared at $p \leq 0.05$. Plant nutrient concentration was evaluated basing on the concentrations of the respective parameters obtained from the laboratory analyses compared with set standards for rice straw and grain quality. Correlation between soil and plant nutrient concentration was also done.

3.3. Results and Discussions

3.3.1. Soil Parameters

Statistically significant differences ($p < 0.05$) were observed across the units in selected soil parameters. Results revealed that the selected fields were generally low in total nitrogen on average and soil Zn was below the deficiency limit for rice production. Soil exchangeable Ca^{2+} and Mg^{2+} exceeded the deficiency criteria for rice according to Dobermann and Fairhurst, (2000) while exchangeable K^+ was below the deficiency level in Mwea and Thiba units. Soil available P_2O_5, S, Fe, Mn and Cu were also sufficiently high enough as they all were above the deficiency level for rice as stated by Dobermann and Fairhurst, (2000). Mean values for the selected soil parameters across the units is shown in Table 3.1.

Table 3. 1 : Selected soil chemical properties of plant sampled fields in the Mwea scheme

	TN (g/kg)	Available (mg/kg)		Exchangeable cations (cmol$_c$/kg)			(Ca+Mg)/ K ratio	Available micronutrients (mg/kg)			
		S	P_2O_5	Ca^{2+}	Mg^{2+}	K^+		Fe	Mn	Cu	Zn
Mwea	1.30	48.2	87.0	33.0	20.6	0.08	625	134	72.9	2.10	0.22
Thiba	1.20	51.5	123	41.7	21.7	0.12	533	94.8	198	1.14	0.26
Wamumu	0.90	60.0	50.0	47.2	24.4	0.36	240	69.4	136	4.77	0.55
Karaba	0.87	90.1	36.4	51.7	35.4	0.40	226	68.5	112	5.64	0.62
Tebere	1.43	78.7	152	36.9	21.2	0.56	150	90.9	94.7	2.90	0.63
Deficiency level		9	12-20	1	1	0.2	100	4-5	3-30	0.1	2

As pointed out in soil results in Table 3.1, soil TN decreased down the elevation from Mwea to Karaba and the contents are somewhat low. Soil exchangeable Ca^{2+}, Mg^{2+} and K^+

increased in Karaba from Mwea due to accumulation in the lower depression area. However, soil K^+ is very low when compared to Ca^{2+} and Mg^{2+} concentration thus severe cation imbalances especially at the higher elevation units of Mwea and Thiba. Soil available phosphorus did not show a clear trend but lower elevation units had lower concentration compared to upper elevation units. The differences in soil phosphorus content could in part be attributed to the differences in farmer capacities to apply phosphate fertilizers and differences in cultivation history where higher elevation units with longer cultivation history could have more accumulation than lower Wamumu and Karaba. Soil available S tended to increase down the elevation and so did Cu and Zn. However, Zn content was way below the deficiency level and thus need to introduce Zn fertilization as farmers only apply N and P fertilizers (Kihoro *et al*., 2013). Soil Fe and Mn were found to be in sufficient ranges and soil Fe tended to decrease down the elevation as Mn trend was not clear.

3.3.2. Straw and Grain yield

Rice grain yield significantly ($p<0.01$) varied with the different unit positions. Overall, grain yield ranged from 3.3 to 8.2 t/ha with some fields in Mwea, Tebere, Wamumu and Karaba recording yields less than 5 t/ha.

Straw yield on the other hand did not vary significantly ($p>0.05$) between the units and values ranging from 2.4 to 8.7 t/ha were observed. Fields that had low grain yield also recorded low straw yield. Generally, straw and grain yields decreased down the elevation. Values observed in straw and grain yield across the units with mean are shown in Table 3.2.

Table 3. 2 : Straw and grain yield ranges (mean±SD) in Mwea irrigation scheme units

	Straw yield (t/ha)	Grain yield (t/ha)
Mwea	4.6-7.2 (5.0±1.41)^{ab}	4.6-7.3 (5.8±0.87)^{ab}
Thiba	5.5-7.3 (6.2±0.77)^{a}	6.1-8.2 (6.8±0.96)^{a}
Wamumu	3.5-6.6 (5.1±0.82)^{ab}	3.6-7.4 (5.6±0.94)^{ab}
Karaba	2.4-8.7 (4.4±1.67)^{b}	3.7-8.1 (5.0±1.16)^{b}
Tebere	3.5-7.4 (5.4±1.08)^{ab}	3.3-7.5 (5.6±1.02)^{ab}
Overall mean	2.4-8.7 (5.1±1.25)	3.3-8.2 (5.6±1.05)
CV (%)	25	19

Significantly higher yields for both straw and grain were observed in Thiba unit and the lowest were recorded in Karaba (Table 3.2) which is located in the depression area.

3.3.3. Rice nutrient content and transfer from straw to grain

Data on average total straw and grain nutrient contents across the units is shown in Tables 3.3 and 3.4 respectively with deficiency criteria according to Dobermann and Fairhurst, (2000).

Table 3. 3 : Straw total nutrient concentration across units

Unit/ Nutrient	Total Nutrient content (%)								
	Zn	Cu	Fe	Mn	P_2O_5	S	K	Mg	Ca
Mwea	0.0059	0.0024	0.1045	0.0590	0.3303	0.0696	0.6619	0.2687	0.2793
Thiba	0.0042	0.0022	0.0581	0.0926	0.2448	0.0864	0.6858	0.2280	0.2511
Wamumu	0.0052	0.0026	0.1509	0.0869	0.3092	0.0857	1.4574	0.2729	0.3266
Karaba	0.0044	0.0019	0.0967	0.0802	0.2139	0.0840	1.5985	0.2850	0.3828
Tebere	0.0045	0.0012	0.1303	0.0822	0.2416	0.0896	1.6725	0.3028	0.3244
Deficiency level*	0.003	0.0003	0.035	0.045	0.1	0.075	1.4	0.2	0.3

**Dobermann and Fairhurst (2000)*

Highly significant differences ($p \leq 0.05$) were observed in straw total Ca, Cu, K, P_2O_5 and Zn whereas straw total Fe, Mg, Mn and S did not show significant differences ($p > 0.05$) across the five units. As pointed out in Table 3.3, straw total Zn, Cu, Fe, Mn, P_2O_5 and Mg content exceeded the deficiency level in all units. Although soil Zn was below the deficiency level (Table 3.1), total content in straw was somewhat high exceeding the deficiency level.

For nutrients to accumulate in straw they must be taken up from the soil through the xylem transport in the transpiration stream (Sperotto, 2013). In our results, positive associations between soil and straw nutrient accumulations were noted in Ca, K, Mg, Mn and S. On the other hand, Fe and Zn showed a negative association between soil contents and straw accumulation. As soil Cu, Fe, Mn, P_2O_5 and Mg were above the deficiency limit, so was their total contents in the straw. However, Mwea and Thiba unit showed deficiency in straw total Ca and K as mean values were below the deficiency criteria. The two units also showed lower soil concentration of Ca and K compared with the rest of the units. In addition, Mwea unit indicated deficiency in straw total S (<0.075%) and it somewhat correlated with the lower S concentration in the soil as indicated in Table 3.1.

The distribution of nutrients in plant edible parts occurs through redistribution of initially accumulated nutrients or they are continuously taken up from the soil as the crop cycle ends with the onset of senescence. This is normally accomplished through phloem transport from old to new leaves and the process is somewhat selective largely dependent on how mobile the nutrient element is in the phloem (Sperotto, 2013).

Grain nutrient analysis revealed significant differences ($p \leq 0.05$) in total Ca, Cu, K, Mg, S, P_2O_5 and Zn while grain total Fe and Mn were not significantly different ($p > 0.05$) across the five units. As pointed out in Table 3.4, grain total Cu, Mn, P_2O_5 and Zn exceeded the deficiency level for rice while total Ca, Fe, K, Mg and S were deficient in all units.

Table 3. 4 : Grain total nutrient concentration across the units

	Total Nutrient content (%)								
Unit/Nutrient	Zn	Cu	Fe	Mn	P_2O_5	S	K	Mg	Ca
Mwea	0.0050	0.0017	0.0085	0.0083	0.6915	0.0751	0.1844	0.1285	0.0393
Thiba	0.0044	0.0016	0.0086	0.0112	0.6133	0.0731	0.1705	0.1182	0.0385
Wamumu	0.0045	0.0019	0.0097	0.0092	0.6475	0.0734	0.1901	0.1219	0.0395
Karaba	0.0046	0.0013	0.0134	0.0080	0.6347	0.0729	0.1755	0.1192	0.0369
Tebere	0.0044	0.0018	0.0119	0.0086	0.6454	0.0790	0.1977	0.1220	0.0342
Deficiency level*	0.002	0.001	0.025	0.005	0.2	0.1	0.29	0.15	0.05

**Dobermann and Fairhurst (2000)*

The first step of nutrient accumulation in rice is the nutrient uptake by roots; a process that depends on the soil availability of each nutrient which is affected by the soil condition. Transfer coefficients (TCs) of nutrients from straw to the grain were calculated and average values are shown in Table 3.5.

Table 3. 5 : Grain nutrient transfer coefficient* from straw to grain

	Ca	Cu	Fe	K	Mg	Mn	P_2O_5	S	Zn
Mwea	0.147	0.757	0.094	0.359	0.487	0.149	2.210	1.093	0.862
Thiba	0.158	0.798	0.150	0.419	0.530	0.119	2.543	0.885	1.066
Wamumu	0.131	0.791	0.090	0.178	0.477	0.111	2.559	0.892	0.889
Karaba	0.102	0.672	0.173	0.115	0.433	0.105	3.590	0.908	1.098
Tebere	0.114	2.000	0.123	0.122	0.415	0.121	3.058	0.917	1.225
Overall	0.124	1.191	0.121	0.193	0.452	0.120	2.854	0.939	1.050

**Transfer coefficient=Nutrient concentration in grain/Nutrient concentration in straw*

As pointed out in Table 3.5 in overall, phosphorus had generally the highest TC while manganese had the lowest. The trends observed revealed inconsistence trends and in some cases, where straw nutrient content was low, the transfer rates to the grain were high for instance Mg, K and Zn. In a separate case, Fe and S showed positive association between straw content and transfer rate.

Nutrient mobility in rice is said to be in the sequence P>N>S>Mg>K>Ca which is in close agreement with the trend observed in our straw-grain transfer (P>Cu>Zn>S>Mg>K>Ca>Fe>Mn). The mobility however is further controlled by soil and plant conditions.

3.3.4. Nutrient Uptake, Distribution and Accumulation in Rice

3.3.4.1. Phosphorus and Sulphur

Phosphorus is vital in plant metabolism, playing a role in the transfer and storage of energy from photosynthesis and carbohydrate metabolism (Fairhurst *et al*., 2007; Bi *et al*., 2013). Phosphorus in most soils and particularly in the tropics is limited for plant uptake because of its immobilization (Maranguit *et al*., 2017) but with flooding, it can be mobilized under anaerobic conditions (Ponnamperuma, 1972; Rakotoson *et al*., 2015; 2016). Additionally, flooding releases available phosphorus contents much higher when compared with aerobic soil conditions (Fairhurst *et al*., 2007; Rakotoson *et al*., 2014).

Application of phosphorus is recommended as a major agronomical practice for increasing crop yield and phosphorus nutrition is particularly important in early growth stages (Fairhurst *et al*., 2007). Phosphorus is mobile within the plant and a large fraction of it accumulated in aboveground tissue in rice is located in the grain, a phenomenon that results in high phosphorus removal from fields (Rose *et al*., 2010; Bi *et al*., 2013; Wang *et al*., 2016). As a consequence, seed phosphorus has a value as a target in phosphorus management in rice. In cereal grains, inorganic phosphorus consists of about 10% of total phosphorus whereas the majority of grain phosphorus accounting for 50-80% occurs in the form of phytic acid (Raboy, 2007). However, phytic acid is an anti-nutrient that cannot be digested by humans and other monogastric animals resulting in high loads of P in waste that eventually becomes an environmental hazard (Raboy 2007; 2009).

Phosphorus uptake by lowland rice during growing season increases with plant development and on phosphorus deficient soils, the uptake increases as phosphorus fertilizer rate increases (Fageria *et al*., 2003). In the straw, phosphorus accumulation increases with age until flowering after which the content in straw drops from translocation to the developing seed. Under some cases, root uptake may continue between flowering and maturity to meet the grain P demands (Fageria *et al*., 2003).

Phosphorus loads rapidly into the grains between 6 and 15 days after flowering (Ogawa *et al*., 1979; Wang *et al*., 2016) although a field study in Philippines by Julia *et al*., (2016) observed continuous partitioning of phosphorus to the grains after 14 days after flowering and up to maturity. Thus phosphorus in the grains at maturity is possibly from 2 sources; post-flowering root uptake from the soil i.e. exogenous or remobilization from vegetative plant parts i.e. endogenous sources (Julia *et al*., 2016). With the reduction in leaf and stem phosphorus concentrations between flowering and maturity one can clearly deduce that endogenous source is an important process in rice phosphorus grain loading (Rose *et al*., 2010). They however added that post anthesis uptake of phosphorus by rice may be due to its perennial growth habit, which results in the continuous production of new tillers during grain filling with only partial senescence of leaves and stems at maturity (Rose *et al*., 2010). In another experiment in the Philippines, Julia *et al*., (2016) observed that post-flowering phosphorus uptake represented 40-70% of aerial plant phosphorus accumulation at maturity; with the panicle as the main sink remobilization from vegetative tissues to the panicle during grain filling accounting for only 20%. In their view, post-flowering phosphorus uptake does not move directly to the grains but grain filling involved indirect phosphorus fluxes originating from phosphorus previously taken up and located in the vegetative tissues.

As much of phosphorus accumulating in the grain is removed through harvest, efforts should focus on reducing the amount of grain phosphorus accumulation with the aim of minimizing unnecessary export from fields at harvest which consequently would help improve phosphorus use efficiency in smallholder cropping systems (Richardson *et al*., 2011; Rose *et al*., 2013b; Vandamme *et al*., 2016).

In Mwea case, given the sufficiently high enough soil available phosphorus status, there was probably continuous uptake such that as remobilization from vegetative tissues to the grain occurred, influx from the soil at post-flowering could have also occurred resulting in high concentrations. This means that straw and grain have a luxury concentration of P which caused a dilution effect to other mineral nutrients in the grain.

Sulphur is a secondary element required by plants in relatively large amounts for normal growth (Fageria *et al*., 2003). Sulphur in soils occurs in four major forms, namely C-bonded S, ester sulphate, adsorbed SO_4^{2-} and SO^{2-} in soil solution. Plants acquire S in the form of SO_4^{2-} from the soil solution. (Dobermann *et al*., 1998) and is transported in the xylem.

Sulphur, less mobile in plants is required for protein synthesis, plant function and structure and is also involved in carbohydrate metabolism (Fairhurst *et al*., 2007). Reduction of sulphur can take place in the roots, but largely takes place in chloroplasts after which it is incorporated into cystine, cysteine, and methionine and it is important for the formation of chlorophyll. Reduced forms of S move to the panicle during grain filling in the phloem (Dobermann *et al*., 1998). Deficiency in sulphur reduces grain yield and grain quality through a reduction in cystein and methionine contents in rice which further affects human nutrition (Khurana *et al.,* 1999; Dobermann and Fairhurst, 2000). Interestingly, the reduction in yield can be as high as between 10-40% without any visible symptoms of its stress (Khurana *et al.,* 1999).

Sulphur occurs in diverse valence states, from $^{+}6$ as sulphate to $^{-}2$ as sulphide with numerous inorganic and organic S compounds. Extreme S in paddy field ecosystem negates its uptake by rice because its behaviour is closely linked to redox potential with transformation of inorganic species from $^{-}2$ to $^{+}6$ and oxidation of organic S compounds (Hu *et al*., 2007).
Pot experiments at IRRI have revealed that S deficiency as indicated by N:S ratios of 16 and 25 may also significantly affect grain quality due to reduced cysteine and methionine contents (Juliano *et al*., 1987; Randall *et al*., 2003). Grain data from Mwea revealed low S contents probably because of high soil N:S ratio that varied between 6 and 48 (data not shown). Therefore N nutrition should be enhanced to improve on S accumulation in the grain and thus grain quality.
Elsewhere, Randall *et al*., (2003) in a green house experiment observed highest grain S concentration in treatments where S supply was inadequate during early growth and S added after anthesis. Under S deficient conditions, plants have shown increased capacity to take up S compared with S adequate plants (Clarkson *et al*., 1983) because of high up-regulation of sulphate transporters (SULTR) in S deficiency conditions (Forieri *et al*., 2013).

3.3.4.2. Exchangeable Cations (Ca, Mg and K)

The three cationic elements calcium (Ca), magnesium (Mg) and potassium (K) are required in large amounts by both plants and animals. In plants, these elements must be acquired by roots from the soil solution and thereafter redistributed to edible tissues to support the terrestrial food chain (Karley and White, 2009). K is present in relatively high concentrations in most plant tissues; particularly concentrated in the growing tissues and reproductive organs a reflection of its natural abundance, biochemical and biophysical functions and its ease of transport within the plant (Karley and White, 2009; Maathius, 2009; Gierth and Maser, 2007).
Just like K, Mg is also translocated readily within the plant but Ca tends to be in low concentrations especially in phloem-fed tissues such as fruits, seeds and tubers as significant amounts are retained in mature and senescing organs (White and Broadley, 2003; Karley and White, 2009).
Much of leaf Mg is associated with protein synthesis while part of it is associated with chlorophyll (Maathius, 2009; White and Broadley, 2009). Calcium on the other hand is required for various structural roles in the cell wall and membranes, as a counter-cation for anions in the vacuole and for co-ordinating responses to developmental signs and environmental challenges through changes in its cytosolic concentration (Maathius, 2009; White and Broadley, 2003; McAinsh and Pittman, 2009). Nonetheless, mechanisms for

uptake, translocation, accumulation and remobilisation of these three essential elements differ and the transport processes are highly discriminatory between their cations (Karley and White, 2009).

Magnesium is said to enter root cells through Mg^{2+} permeable cation channels (White, 2000; White and Broadley, 2003). Mg is associated with proteins and the vacuole is the main storage compartment for Mg in plants (White *et al*., 1990). It is released from the vacuole through Mg^{2+}-permeable cation channels and ATPases possibly catalyze its efflux from root cells into the xylem where it is transported as either Mg^{2+} or as a complex with organic acids (White, 2000; Welch, 1995). Since Mg is mobile in the phloem, it is readily translocated to fruit, seed and tubers (Wilkinson *et al.,* 1990); however, results of our grain analysis indicated that Mg contents were below the deficiency level (<0.15%). This could be attributed to binding by phytic acid that is known to be a strong chelator of metal cations forming a phytate salt (Raboy, 2009).

Pronounced declines of Mg concentration in cereal grains have been reported over the past several decades, which have been linked to yield dilution coupled with the Green Revolution (Rosanoff, 2013). Additionally, it is observed that the declines in seed Mg may also have some correlation with long-term unbalanced crop fertilization with nitrogen, phosphorus and potassium (NPK) over the last decades which lower Mg accumulation in seeds (Guo *et al.,* 2016). In the Mwea irrigation scheme, there has been emphasis on N and P fertilizers only and this unbalanced fertilization could also be a contributing factor to low grain Mg accumulation.

Potassium is delivered to the root surface principally by diffusion and mass flow of the soil solution (Ahmad and Maathius, 2014) from where it is taken up by the plant root through the epidermal and cortical cells. It is then transported symplastically through the endodermal cells to the stele from where it is loaded into the xylem for transport to the shoot (Karley and White, 2009). Once in the shoot, it flows to the parenchyma cells in the xylem sap and distributed symplastically to the mesophyll cells flowing to the phloem companion cells that load the phloem for transport into the fruit/seed and tubers (Karley and White, 2009). Figure 3.1 illustrates movement of K from the root surface through the plant cells.

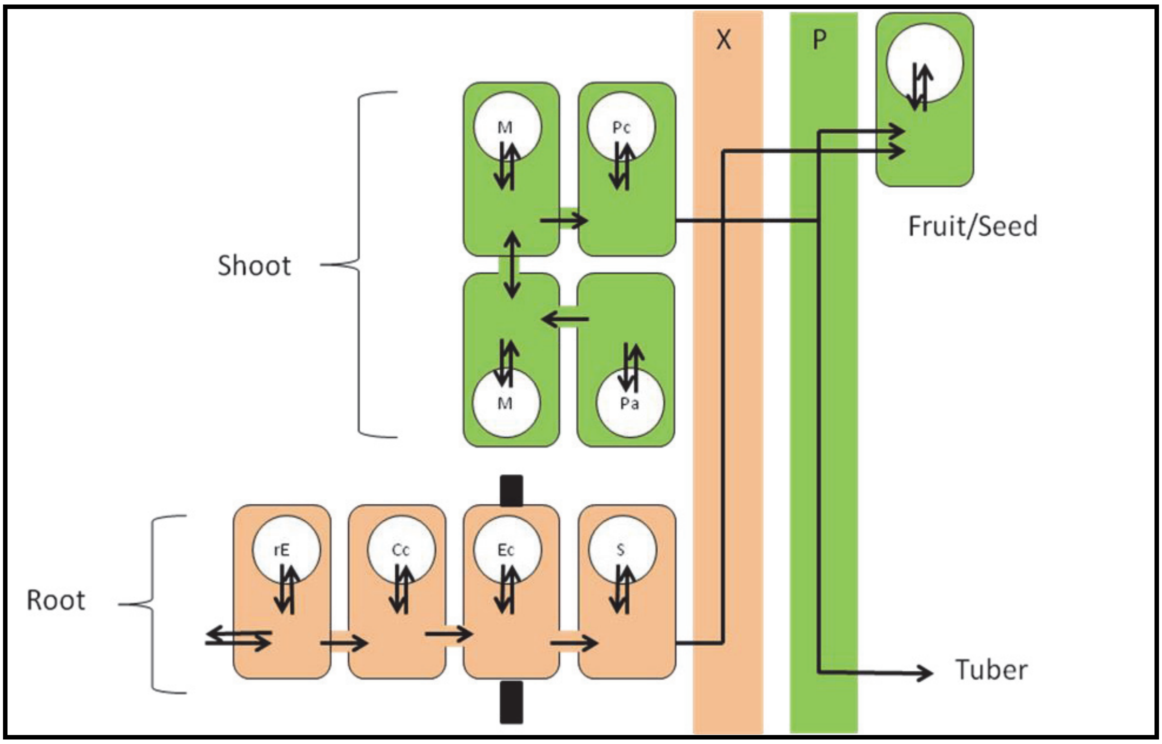

Figure 3. 1: K movement through the plant (Modified from: Karley and White, 2009).

Root epidermal (rE), Cortical (Cc), Endodermal cells (Ec), Stele (S), Xylem (X), Parenchyma cells (Pa), Mesophyll cells (M), Phloem companion cells (Pc), Phloem (P).

Potassium is said to be very mobile in plants and as would be expected, since the straw contents were high, the grain contents would be equally high. However, since K, Mg and P accumulate in the aleurone layer (Ogawa, 1979), it is likely that the high P concentration in form of phytic acid complexes with K thus hindering its accumulation. Furthermore, the soil K concentration in Mwea was low and further exacerbated by the extreme cation imbalance could have led to low accumulation of K in the grain.

Calcium is an critical plant macronutrient and is taken up by the root system from the soil solution in the cationic form (Ca^{2+}) and translocated to the shoot via the xylem at rates consistent with growth (White, 1998, 2001). Its delivery to the xylem is essentially restricted to the apical region of the root (Moore *et al*., 2002). Ca can reach the xylem exclusively via the root apoplast where Casparian bands are absent or via the cytoplasm of unsuberized endodermal cells where Casparian bands are present (White, 2001; Moore *et al*., 2002). Its influx into the root cells is mediated by Ca^{2+}-permeable ion channels in their plasma membranes (White, 2000). Once within the xylem, Ca appears to be transported either as Ca^{2+} or as a complex with organic acids (Welch, 1995; White and Broadley, 2003). Shoot Ca concentration of different taxa grown in the same environment have been shown to correlate well with cell wall chemistry and cation binding capacity (White and Broadley, 2003; White, 2005), nonetheless, Ca concentration found in the leaves is found to depend greatly upon the phytoavailability of Ca in the rhizosphere and the transpirational water flux (White, 2001; White and Broadley, 2003). Since Ca is immobile in the phloem, and fruits, seeds and tubers are fed mainly by the phloem, most of these parts eventually seem to contain low Ca contents (White and Broadley, 2003; Sharma *et al*., 2017) and most is retained in straw. Since Ca cannot be mobilized from older leaves and redistributed via the phloem, developing plant tissues are forced to rely Ca supply from the xylem which is dependent on transpiration. Unfortunately, transpiration in young leaves, enclosed tissues and fruits is low thus low Ca accumulation (White and Broadley 2003). Figure 3.2 illustrates how Ca moves from the soil into the root and through the plant cells.

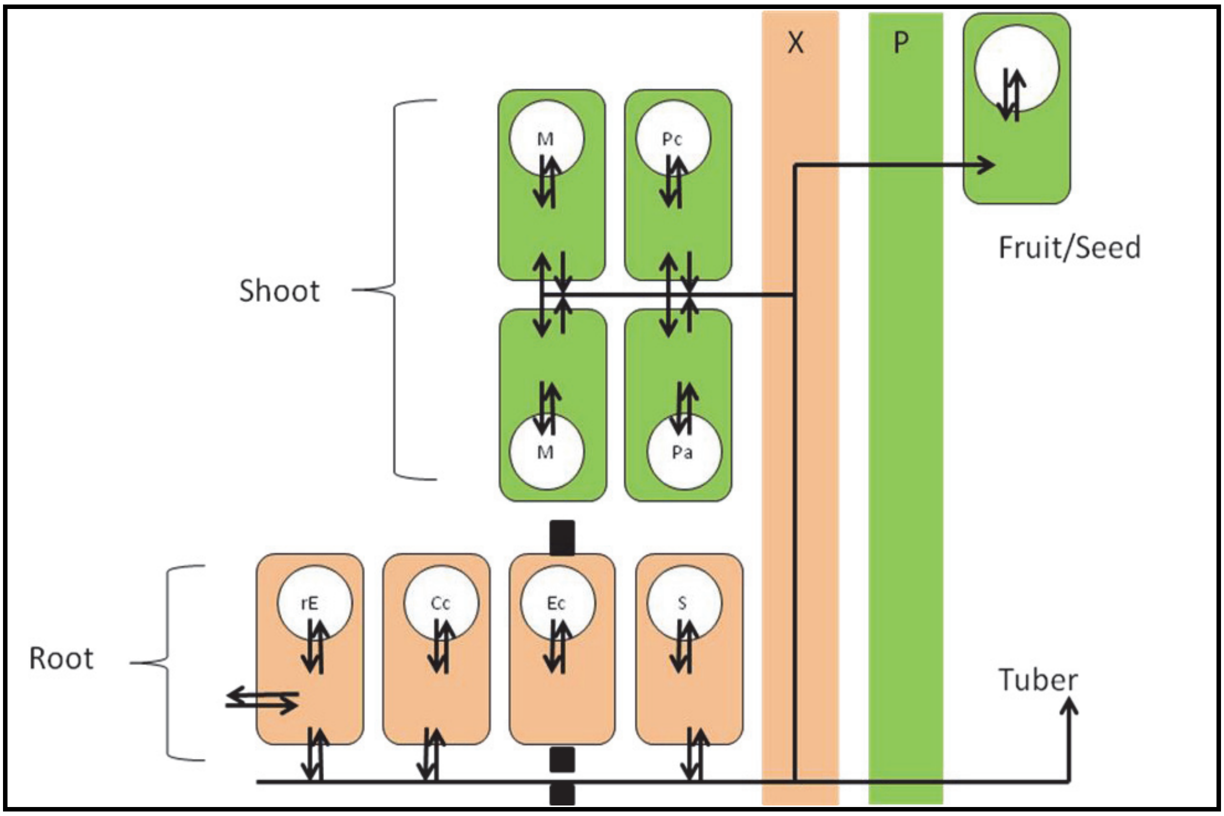

Figure 3. 2: Ca movement through the plant (Modified from Karley and White, 2009).

Root epidermal (rE), Cortical (Cc), Endodermal cells (Ec), Stele (S), Xylem (X), Parenchyma cells (Pa), Mesophyll cells (M), Phloem companion cells (Pc), Phloem (P).

3.3.4.3. Micronutrients (Fe, Mn, Cu and Zn)

Nutrient uptake depends on the plant species and soil availability of each nutrient. For micronutrients such as Fe, Zn and Cu, their availability relies mainly on chemical and physical properties of the soil (Marschner, 2012). As an essential plant micronutrient, Zn has been shown to be the most critical yield limiting micronutrient to rice growth after N (Neue and Mamaril, 1985; Alloway, 2008; Buri *et al*., 2000). Zn deficiency has been shown to decrease cereal yields by as much as 50% according to work done by van Asten *et al*., (2004). Micronutrient amounts in the grain depends much on the amounts taken up by the roots during grain development and redistribution from the vegetative tissues via the phloem; which is determined by how mobile the element is in the phloem (Garnett and Graham, 2005). Accumulation of these micronutrients by plants generally follows the order of C1 > Mn > Fe >Zn > B > Cu > Mo. This order may change among plant species and growth conditions, but is generally correct for lowland rice (Fageria *et al*., 2003).

Root uptake is the initial step in accumulation of Zn in rice grains. However, plant factors such as root architecture, root hairs, root surface area and modification of rhizosphere chemistry can change soil pH thereby improving solubility and diffusion to the rot surface affects Zn uptake by roots (Rose *et al.,* 2013a). On the other hand, soil factors that affect availability of Zn to plants include soil pH, texture, content of organic matter, microbial population and soil mineralogy (White and Broadley, 2011). In rice under flooded (anaerobic) condition, availability of Zn is further affected by the soil redox potential, total sulphur content and soluble bicarbonate (Impa and Johnson-Beebout, 2012).

Although soil is rich in Fe, plants cannot utilize it as it is chiefly present as largely insoluble Fe (III) compounds (Bashir *et al*., 2010). Studies revealed that Fe content in rice has significant differences among genotypes (Zhai *et a*l., 2001) which is further regulated by other environmental factors such as soil and climate (Barikmoa *et al*., 2007; Zuo and Zhang 2011). For example, although it is the second most abundant metal in the earth's crust, its availability to plants is very low under well-aerated calcareous or alkaline soils, since it can be precipitated in the form of hydroxides, oxyhydroxides or oxides (Marschner, 2012). Given the fact that it is insoluble in the soil, application of soil Fe as a fertilizer may not be an effective strategy for increasing its accumulation in the grain (Bashir *et al*., 2013).

Zn is an essential micronutrient with numerous cellular functions in plants and its deficiency represents one of the most serious problems in human nutrition worldwide. While it is an essential micronutrient, Zn can be toxic if its accumulation is in excess (Ishimaru *et al.,* 2011). 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). Its solubility and availability is determined by various factors like high $CaCO_3$, high pH, high clay soils, low organic matter, low soil moisture and high iron and aluminium oxides (Kirk and Bajita, 1995; Cakmak, 2008). Although the concentration of soil available Zn (1 M HCl-extractable Zn) was below the critical deficiency level, it was necessary for the plants to induce changes in the soil to solubilize Zn. Given the changes that occur in the soil immediately following flooding, it is possible that there was a substantial accumulation of Zn associated with organic matter and amorphous ferric hydroxide within the rhizosphere which could have contributed to the high Zn accumulation in the root and aboveground biomass. Prolonged flooding however significantly reduces Zn as well as Fe availability because of precipitation in calcareous soils conditions (Broadley *et al*., 2007; Marschner, 2012).

Considerable disparity in seed Fe concentration has been reported in rice and high grain Fe as well as Zn was reported in aromatic rice varieties (Gregorio *et al*., 2000). In plants, ferritin is the known storehouse of bioavailable Fe with the ability to accumulate up to 4, 500 Fe within its cavity and also functions in maintaining cellular Fe homeostasis (Briat *et al*., 2010). Ferritin has been thus established as an effective dietary Fe source in alleviating Fe deficiency used in biotechnology and its over-expression in rice has resulted in an increase in grain Fe as well as enhanced Zn accumulation in transgenic Basmati rice (Paul *et al*., 2012). Allocation of Zn and Fe within rice plants greatly occurs through xylem transport, transfer from xylem to phloem and retranslocation in the phloem (Ishimaru *et al*., 2011). Transport through the xylem is simply directed from roots to shoots in the transpiration stream while phloem transport that occurs from old to new leaves is selective and dependent on how mobile the element is in the phloem (Sperotto, 2013). However in relation to their phloem mobility, Zn and Fe are considered intermediate or conditionally mobile (Fernández and Brown, 2013). Zn translocation to roots xylem occurs via symplast and apoplast; although high levels have been detected in the phloem, an indication that Zn is translocated through both the xylem and phloem tissues (Broadley *et al*., 2007).

During rice grain filling process, Zn remobilization from the leaves has been shown to be less important than its uptake by roots (Jiang *et al*., 2007). Surprisingly at the same time, Jiang *et al*., (2008) demonstrated that increased root uptake does not necessarily result in enhanced Zn grain accumulation. In yet another separate scenario, Wu *et al*. (2010) showed that the large amounts of Zn contained in rice grains at maturity had been retranslocated from other plant parts and not directly acquired by rice roots. Recently in Japan while assessing Cd, Zn and Fe transport into rice grains, Yoneyama *et al*. (2010) reported that Zn in rice grains may be actively supplied via the phloem after mobilization from the leaf blades of flag and upper leaves and also by xylem to phloem transfer in the nodes while Fe stored in the leaves maybe transported to the grain via phloem. Iron stored in the flag and upper leaves may also be transported to the grains via the phloem. Grain Fe and Zn may share similar protein-dependent mechanisms for translocation to or storage into the grain, and thus an indication of positive correlation between Fe and Zn grain concentrations (Sperotto *et al*., 2012a) and in a separate experiment it was shown the mineral remobilization from green tissues can be severely affected by Fe status (Sperotto *et al*., 2012b).

Mineral remobilization from vegetative tissues in rice seems to be affected by plant Zn and Fe nutrition as different supplies alter remobilization levels. Different rice genotypes with different efficiencies in Zn and Fe use coupled with different levels of Zn and Fe in the seed can alter remobilization patterns with source-sink communication changes (Jiang *et al*., 2008; Wu *et al*., 2010; Impa *et al*., 2013).

While observing the effect of different Fe supplies on mineral partitioning and remobilization in rice, Sperotto *et al.*, (2012b) observed that rice plants supplied with a high Fe concentration showed no Fe remobilization from flag leaves, non- flag leaves and stems/sheaths. On the other hand when supplied with low Fe concentration, the highest Fe remobilization from stems/sheaths was observed probably due to reduced uptake from the roots during seed filling stage. When Fe was sufficiently supplied, high level of mineral remobilization mostly from flag leaves but also from stems/sheaths was observed. Nonetheless, as the flag leaves mineral content is much lower than the stems/sheaths content, the maximum possible contribution to seed mineral content is, in general, higher from stems/sheaths than from flag leaves (Sperotto *et al.*, 2012b). It seems that abundant Fe supply at the root level promotes continued uptake during seed fill, which may have reduced the need for remobilization to serve as a source of Fe for seeds. A similar pattern was observed for Zn (Jiang *et al*., 2007, 2008; Impa *et al*., 2013).

According to Jiang *et al*. (2007), in rice plants grown under sufficient or surplus Zn supply, most of the Zn accumulated in the grain originates from uptake by roots after flowering and not from Zn remobilization from leaves. It was also shown that, at lower Zn supply levels, the Zn taken up by the roots after flowering seems to accumulate mostly in the grain, which is accompanied by net Zn remobilization from the leaves and transport to the grain. However, at higher Zn supply levels, Zn content in all non-grain organs remained constant (roots, leaves and sheaths) or continued to increase after flowering, and grain Zn accumulation could be fully accounted for by Zn uptake during grain filling (Jiang *et al*., 2008).

It is clear that Zn and Fe remobilization from vegetative tissues can occur in rice plants; however, remobilization is not required for seeds to acquire minerals. Contrasting results may be due to different rice genotypes behaving differently. Thus, there may not be only one way for rice to load Zn/Fe into grain, but genotype- specific variations. Additionally, the process depends on plant Zn and Fe nutrition (Sperotto, 2013).

In relation to the findings by different authors (Jiang *et al*.,2007, 2008; Wu *et al*., 2010; Yoneyama *et al*., 2010; Sperotto *et al*., 2012b; Impa *et al*., 2013), an anticipated representation for Zn and Fe allocation to the grain is shown in Figure 3.3.

Under Zn-sufficient conditions (Figure 3.3a), the grain is supplied with Zn from root continuous uptake during grain-filling and to a lesser extent remobilized from stem and flag leaves. When Zn supply is limited (Figure 3.3b), both continuous root uptake and remobilization from plant tissues occur but remobilization from the stem is higher.

Under high Fe conditions (Figure 3.3c), continuous root uptake can fully account for grain Fe loading although there is risk of excess uptake that could lead to toxicities. Under sufficient Fe supply (Figure 3.3d), continuous root uptake but with some remobilization from stems and flag leaves contribute to grain total Fe. A greater amount is however contributed from flag lead remobilization. When Fe is limiting, (Figure 3.3e), grain Fe can be satisfied by remobilization from stems/sheaths of the earlier taken up Fe and with continuous root uptake.

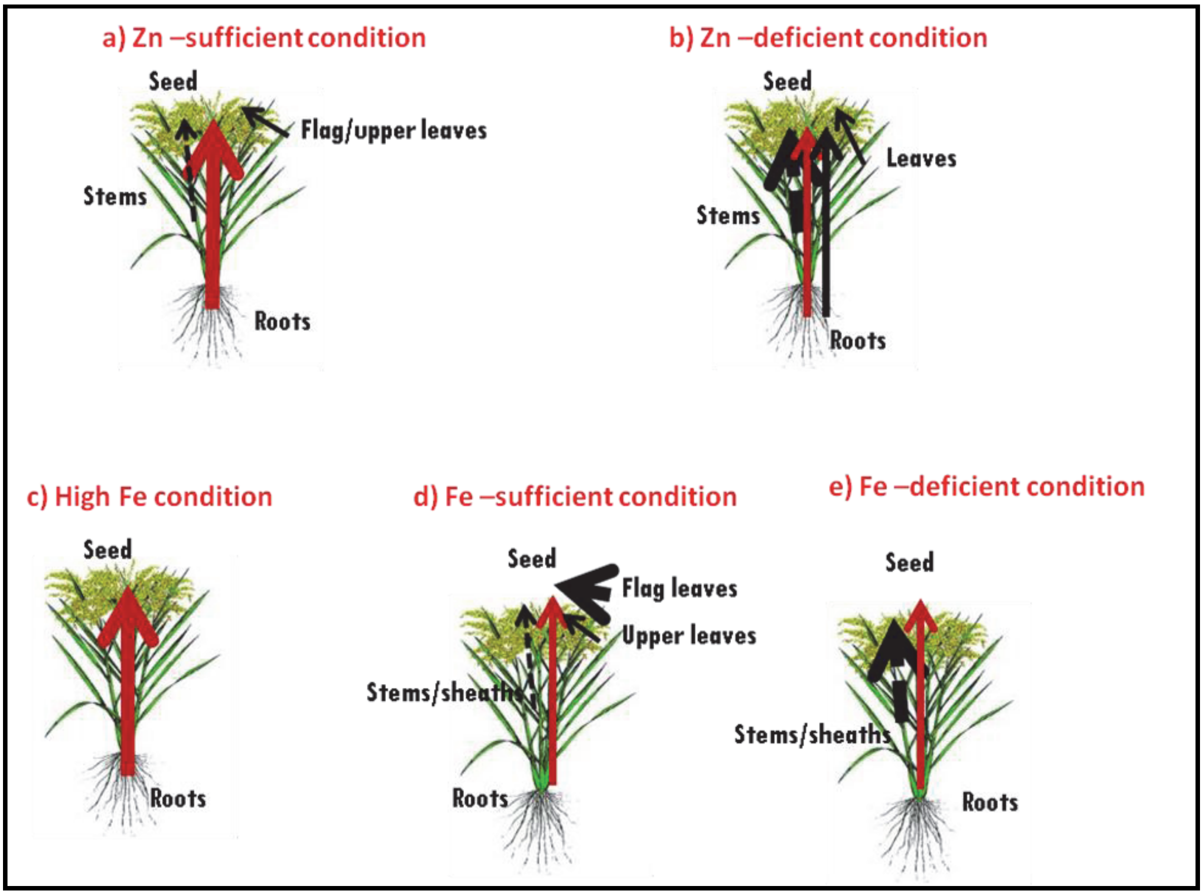

Figure 3. 3: Proposed Zn and Fe loading into grain under different soil supplies (Continuous uptake through xylem-**RED** colour and phloem remobilization-**BLACK** colour). Modified from Sperotto, (2013).

In a review by Bashir *et al*., (2013), native soil Zn status is the dominant factor controlling grain Zn accumulation followed by genotype and fertilizer while for Fe, soil pH and carbonate concentration as well as field conditions are more important. Although rice particularly produced in wet cultivation systems is sensitive to Zn deficiency, the results obtained in Mwea contradict the Wissuwa *et al*., (2008) that rice grain both white and brown are known to be low in Zn.

From the insights above, and the fact that grain Zn content in Mwea grains was high, it could be as a result of remobilization from the stems of Zn taken up early during plant growth as the soils are deficient in Zn. Furthermore, a reasonably high transfer coefficient of Zn from straw to grain contributed to higher loading in the grain and probably the Mwea variety BASMATI 370 is a Zn-efficient genotype with an ability to tolerate soil Zn deficiency. For the case of Fe, it would have been expected that grain Fe be high but was low across the scheme even with sufficiently high soil Fe concentration. This could be attributed to the prolonged submerged soil conditions and high carbonate accumulation in the Mwea soils as was observed by Kondo *et al*., (2001).

Iwai *et al*., (2012) have shown that phytic acid, the P form found in seeds is a strong chelator especially of Ca, K and Fe. In contrast, Zn is loosely bound and localized not only in the aleurone layer but also in the inner endosperm. Cu is also said to pass rapidly through the aleurone layer without being captured by the phytic acid as it would with other elements making phytate salts with poor bioavailability.

According to Krüger *et al*., (2002) and Shi *et al*., (2012), nitrogen nutrition is likely to have a positive effect on micronutrient translocation especially of Fe and Zn because it is said to be essential in the biosynthesis of nicotianamine (NA) and iron transport peptide (ITP). In wheat, an additional supply of N up to certain level has been shown to enhance accumulation of Fe and Zn in grains (Kutman *et al*., 2010, 2011; Shi *et al*., 2010; Aciksoz *et al*., 2011a; Erenoglu *et al*., 2011). This was partly attributed to the fact that the sufficient supply of N increases grain protein concentrations and in so doing increasing the sink strength of grains for Fe and Zn (Barunawati *et al*., 2013).

The characteristic practice of flooding rice increases Fe but decreases Zn availability. On the other hand, moderate soil aeration improves the uptake of Zn but depresses Fe uptake. However, the use of Zn-and/or Fe containing fertilizers could provide sufficient metals for plant uptake. Furthermore, proper timing of N fertilization has been shown to affect metal accumulation in grains (Slamet-Loedin *et al*., 2015). In China, a greenhouse experiment by Wang *et al*., (2014) observed a decrease in phytic acid content and molar ratio of phytic acid to Zn in rice grains following Zn fertilization. In combination with alternative wet and drying (AWD), $ZnSO_4$ fertilization effectively increased grain yield and Zn accumulation.

Since Fe and Zn are said to have similar protein dependent translocation mechanisms, an enhancement of soil Zn in Mwea through Zn fertilization could accelerate Fe loading as well as enhancing Zn loading into the grain. Further research into this aspect is therefore necessary to elucidate this on Mwea soils and Kenyan rice varieties. In addition, appropriate field management practices like mid-season drainage as well as sufficient N supply are important options to employ.

Manganese (Mn) is a crucial element for plants intervening in several metabolic processes mainly in photosynthesis and as an enzyme antioxidant-cofactor. However, an excess of it is toxic to plants manifested in a reduction of biomass and photosynthesis and biochemical disorders (Millaleo *et al*., 2010). Furthermore, excessive Mn concentrations in plant tissues can alter various processes, such as enzyme activity, absorption, translocation and utilization of other mineral elements such as Ca, Mg, Fe and P (Ducic and Polle, 2005; Lei *et al*., 2007). Mn toxicity is favoured under acid soil conditions (Kabata-Pendias, 2011). As the pH decreases, the amount of Mn mainly in the Mn^{2+} form increases in the soils solution. This Mn form is available for plants and can be readily transported into the root cells and translocated to the shoots where it accumulates (Marschner, 2012).

3.3.5. Correlation between Soil and Plant Nutrient elements

In order to illustrate how soil and plant nutrient contents relate, a Pearson correlation was performed. Many of the variables correlated negatively with few showing positive correlations. Even though the correlations were moderately weak, they give an indication of what can be done to avoid the negative associations or improve on the positive associations. An understanding of soil test results and plant analysis data is crucial for development of nutrient management strategies. Soil and plant tissue nutrient concentrations are expected to be positively correlated because the concentration of a particular nutrient in plant is generally greater when the concentration in the soil is high.

Figure 3.4 shows how soil, straw and grain nutrients related with each other.

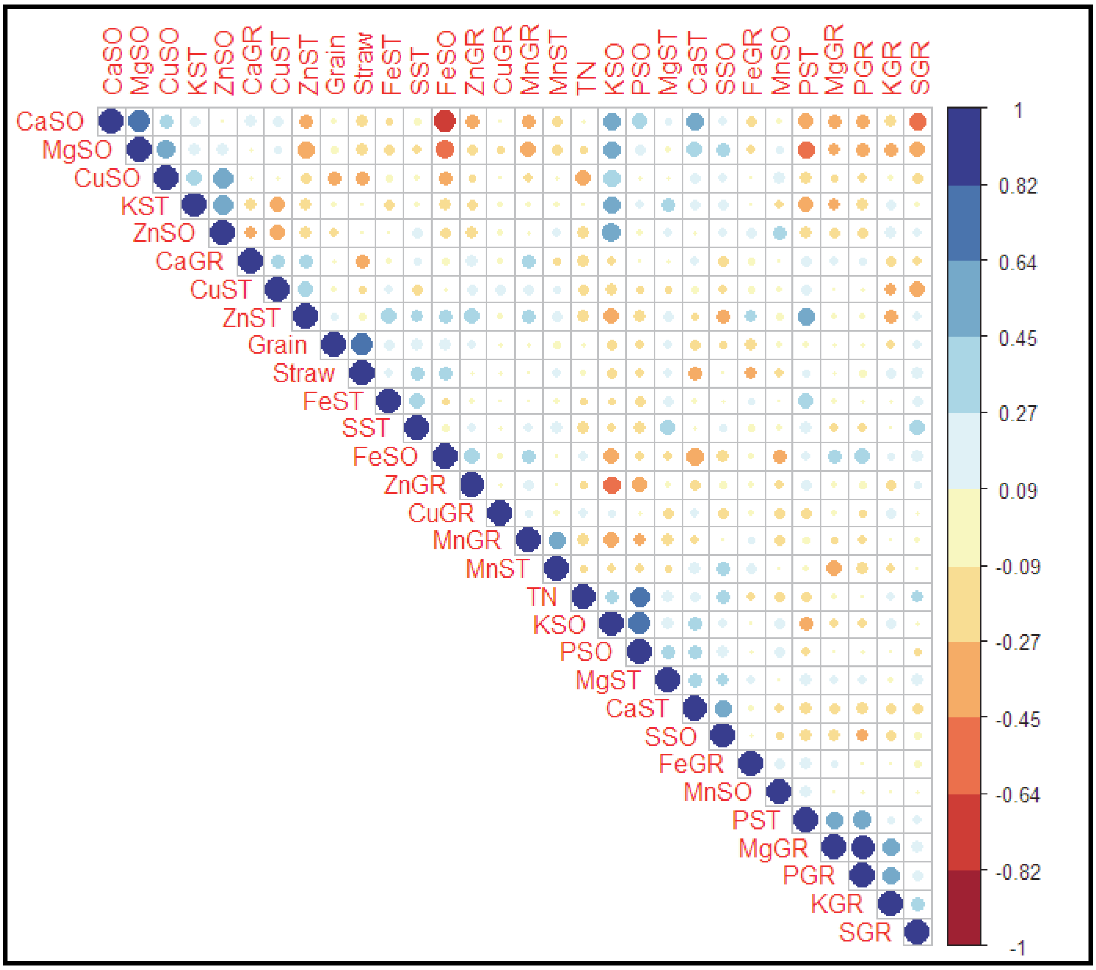

Figure 3. 4: Correlation matrix between soil and plant nutrients

Soil Fe, Mn and Zn showed a negative association with their straw and grain contents that was insignificant ($p>0.05$) except in Zn which was significant at $p<0.05$ for both straw and grain content (Table 3.6a and b). Soil Mg showed a significant ($r=-0.28, p<0.05$) depressing effect on grain Mg concentration while soil S had an insignificant depressing effect on grain S content (Table 3.6b). On the other hand, soil Ca, K and Cu all showed a positive association with their straw and grain nutrient contents. It was however insignificant for Cu but highly significant for the case of Ca ($p<0.05$ and $p<0.001$) for grain and straw. Soil K showed significant positive correlation with straw K ($r=0.052$, $p<0.001$) and insignificant with grain K content (Table 3.6a). Soil Mg and S both showed positive but insignificant relationship with their straw contents.

Soil TN showed positive but insignificant effects on grain and straw yield, straw total Ca and Mg as well as grain total Cu, K, Mg and P_2O_5. The effect was however significant ($r=0.28$, $p=<0.05$) on grain S content (Table 3.6a). On the other hand, soil total nitrogen had depressing effects although insignificant ($p>0.05$) on straw total Cu, Mn, K, Fe, S, P_2O_5 and Zn as well as grain total Fe, Mn and Zn (Tables 3.6a and b). The depressing effect was however significant on grain total Ca (*r=-0.26*, $p<0.05$). According to Swamy *et al*., (2016), the effect of nitrogen fertilizer application on rice has shown inconsistent results on grain Zn concentration but studies on wheat have shown that increasing N application beyond certain levels negatively influences grain Zn (Gao *et al*., 2010; Shi *et al*., 2010).

In Kenya, broadcast application of fertilizers on irrigated fields is the usual practice for lowland rice; which leads to N losses, thus it is critical for farmers to employ efficient N application methods to avoid losses and enhance soil N status. According to Shi *et al*., (2012), N status can affect the remobilization of micronutrients and particularly for Fe whose export out of source was inhibited under sufficient conditions but stimulated under N-deficient growth conditions. In addition, it has been shown that manipulation of nitrogen nutrition can have a significant positive effect on retranslocation of Zn as well as Fe in cereals (Barunawati *et al*., 2013). While evaluating the effects of N fertilizer placement on grain yield and N recovery efficiency in rice, Wu *et al*., (2017) observed that deep placement of N increased rice yield that was attributed to an increase in the number of productive panicles with coupled with the maintenance of higher N supply in the soil layer during rice growth. However, the effect was higher under balanced N-P-K fertilizer placement.

All in all, nitrogen nutritional status during leaf senescence may display opposing effects on micronutrients particularly Fe, Cu and Zn retranslocation in plants. On one hand, N favours Fe, Cu and Zn acquisition and allocation (Kutman *et al*., 2011; 2010; Shi *et al*., 2010) which in graminaceous species heavily rely on the involvement of phytosiderophores and nicotianamine, both derived from the biosynthesis of methionine (Aciksoz *et al*., 2011b). On the other hand, a high N nutritional status tends to fix Fe in proteins (Marschner, 2012) and thus decreases its availability for retranslocation. In wheat, a high yield and of high quality i.e. high in percent nitrogen was obtained from a high input and uptake of nitrogen (Barraclough *et al*., 2010)

It seems that the N nutritional status of plants is an important factor in improving root uptake, shoot transport and seed accumulation of micronutrients Fe and Zn. Thus soil nitrogen improvement and management could be a promising strategy to explore in improving grain yield and micronutrient accumulation.

Tables 3.6a and b shows a correlation matrix between soil nutrients and rice straw and grain nutrient contents.

Table 3.6a: Pearson Correlation showing correlation coefficients between soil nutrients and rice yield and nutrient contents

	Grain	Straw	TN	CaGR	CaST	CaSO	CuGR	CuST	CuSO	FeGR	FeST	FeSO	KGR	KST	KSO
Straw	0.73***														
TN	0.04ns	0.06ns													
CaGR	-0.04ns	-0.31**	-0.26*												
CaST	-0.22ns	-0.29*	0.18ns	0.13ns											
CaSO	-0.08ns	-0.24*	-0.04ns	0.24*	0.48**										
CuGR	-0.04ns	-0.04ns	0.13ns	0.07ns	0.14ns	-0.02ns									
CuST	0.05ns	-0.09ns	-0.22ns	0.34**	0.09ns	0.21ns	0.17ns								
CuSO	-0.29*	-0.32**	-0.38**	0.04ns	0.21ns	0.29*	0.00ns	0.03ns							
FeGR	-0.25*	-0.28*	-0.13ns	0.09ns	0.06ns	-0.19ns	-0.05ns	0.08ns	0.00ns						
FeST	0.21ns	0.13ns	-0.10ns	-0.05ns	-0.07ns	-0.11ns	0.02ns	0.12ns	-0.09ns	0.11ns					
FeSO	0.23ns	0.30*	0.14ns	-0.08ns	-0.44***	-0.74***	0.08ns	-0.04ns	-0.29*	-0.05ns	-0.10ns				
KGR	-0.16ns	0.18ns	0.12ns	-0.20ns	-0.21ns	-0.26*	0.20ns	-0.28*	-0.08ns	-0.01ns	0.03ns	0.11ns			
KST	-0.08ns	0.00ns	-0.02ns	-0.27*	0.17ns	0.18ns	-0.06ns	-0.39**	0.40***	-0.01ns	-0.18ns	-0.25*	0.17ns		
KSO	-0.21ns	-0.18ns	0.35**	-0.15ns	0.30*	0.47***	0.11ns	-0.23ns	0.44***	0.02ns	-0.11ns	-0.41***	0.19ns	0.52***	
MgGR	0.03ns	0.04ns	0.06ns	0.16ns	-0.19ns	-0.32**	0.05ns	0.02ns	-0.11ns	0.09ns	0.05ns	0.34**	0.50***	-0.27*	-0.13ns
MgST	0.16ns	0.13ns	0.22ns	-0.05ns	0.28*	0.10ns	-0.20ns	-0.11ns	-0.03ns	0.16ns	0.19ns	-0.13ns	0.05ns	0.29*	0.23ns
MgSO	-0.09ns	-0.24*	-0.12ns	0.03ns	0.41***	0.78***	-0.10ns	0.11ns	0.60***	-0.15ns	-0.19ns	-0.55***	-0.31**	0.24*	0.46***
MnGR	0.03ns	0.02ns	-0.23ns	0.32**	-0.16ns	-0.29*	0.11ns	0.20ns	-0.13ns	0.11ns	0.02ns	0.33**	-0.02ns	-0.07ns	-0.36**
MnST	0.08ns	0.15ns	-0.12ns	-0.10ns	0.24*	-0.18ns	0.05ns	0.11ns	-0.04ns	0.19ns	0.06ns	0.01ns	-0.16ns	0.07ns	-0.13ns
MnSO	-0.05ns	-0.12ns	-0.20ns	0.00ns	-0.16ns	0.05ns	-0.21ns	0.06ns	0.26*	0.21ns	0.00ns	-0.29*	-0.02ns	-0.15ns	0.20ns
PGR	0.03ns	0.09ns	0.00ns	0.09ns	-0.23ns	-0.35**	-0.12ns	-0.03ns	-0.14ns	0.01ns	0.04ns	0.37**	0.48***	-0.22ns	-0.16ns
PST	0.07ns	0.10ns	-0.19ns	0.22ns	-0.23*	-0.36**	-0.17ns	0.19ns	-0.24*	0.23ns	0.36***	0.14ns	0.10ns	-0.40***	-0.35**
PSO	0.28*	0.11ns	0.30*	0.02ns	-0.21ns	0.00ns	-0.01ns	-0.01ns	-0.19ns	0.02ns	-0.10ns	0.13ns	0.06ns	-0.10ns	0.31*
SGR	0.13ns	0.23ns	0.28*	-0.15ns	-0.17ns	-0.50***	0.04ns	-0.36**	-0.20ns	0.08ns	0.21ns	0.27*	0.30*	0.06ns	-0.05ns
SST	0.24*	0.29*	-0.22ns	0.11ns	-0.04ns	-0.08ns	-0.04ns	-0.17ns	-0.05ns	0.09ns	0.43***	-0.09ns	-0.02ns	0.08ns	-0.14ns
SSO	-0.12ns	-0.01ns	0.29ns	-0.22ns	0.45***	0.16ns	-0.19ns	-0.15ns	0.16ns	0.05ns	-0.03ns	-0.26*	-0.19ns	0.18ns	0.13ns
ZnGR	0.13ns	-0.03ns	-0.11ns	0.23ns	-0.18ns	-0.34**	0.04ns	0.20ns	-0.10ns	0.06ns	0.07ns	0.37**	-0.21ns	-0.20ns	-0.49***

ZnST	0.12ns	-0.09ns	-0.23ns	0.30*	-0.10ns	-0.31**	0.05ns	0.38**	-0.17ns	0.28*	0.36**	0.31**	0.31*	-0.26*	-0.40***
ZnSO	-0.15ns	-0.01ns	-0.27*	-0.28*	-0.05ns	0.01ns	-0.05ns	-0.40***	0.62***	0.20ns	0.02ns	-0.20ns	0.26*	0.64***	0.57***

*Significance levels are noted by ***: p≤ 0.001; **: p≤0.01; *: p≤0.05; ns (not significant): p> 0.05*

Table 3.6b: Pearson Correlation showing correlation coefficients between soil nutrients and rice yield and nutrient contents

	MgGR	MgST	MgSO	MnGR	MnST	MnSO	PGR	PST	PSO	SGR	SST	SSO	ZnGR	ZnST	ZnSO
MgGR															
MgST	0.16ns														
MgSO	-0.28*	0.05ns													
MnGR	-0.11ns	-0.23ns	-0.39**												
MnST	-0.35**	-0.11ns	-0.22ns	0.51***											
MnSO	0.02ns	-0.01ns	0.09ns	-0.20ns	-0.02ns										
PGR	0.91***	0.14ns	-0.32**	-0.12ns	-0.26*	-0.03ns									
PST	0.50***	0.25*	-0.49***	-0.08ns	-0.06ns	0.22ns	0.57***								
PSO	0.29*	0.12ns	0.03ns	-0.38**	-0.35**	0.34**	0.27*	0.12ns							
SGR	0.26*	0.24*	-0.39**	-0.08ns	-0.01ns	-0.03ns	0.17ns	0.13ns	0.21ns						
SST	-0.12ns	0.38**	-0.15ns	0.15ns	0.24*	-0.06ns	-0.12ns	0.26*	-0.17ns	0.37**					
SSO	-0.27*	0.28*	0.30*	-0.02ns	0.29*	-0.12ns	-0.28*	-0.22ns	-0.46***	-0.08ns	0.11ns				
ZnGR	0.06ns	-0.06ns	-0.17ns	0.21ns	0.02ns	-0.16ns	0.09ns	0.18ns	-0.07ns	0.10ns	0.12ns	-0.09ns			
ZnST	0.06ns	0.22ns	-0.44***	0.29*	0.18ns	-0.09ns	0.08ns	0.48***	-0.12ns	0.13ns	0.28*	-0.30*	0.36**		
ZnSO	-0.18ns	0.12ns	0.22ns	-0.04ns	0.12ns	0.31*	-0.18ns	-0.25*	-0.07ns	0.12ns	0.18ns	0.13ns	-0.24*	-0.24*	

*Significance levels are noted by ***: p≤ 0.001; **: p≤0.01; *: p≤0.05; ns (not significant): p> 0.05*

(Grain=grain yield, Straw=straw yield, suffix ~SO=soil concentration, ~ST=straw content, ~GR=grain content, TN=total nitrogen (soil), prefix-Ca=calcium, Cu=copper, Fe=iron, K=potassium, Mg=magnesium, Mn=manganese, P=phosphorus (P_2O_5), S=sulphur, Zn=zinc)

As shown in Tables 3.6a and b, soil phosphorus showed a positive relationship with rice grain and straw yield, grain total Ca, Fe, K, Mg, P_2O_5 and S as well as straw total Mg and P_2O_5. Although the relationship was insignificant in most cases, it was highly significant with rice grain yield (*r=0.28, p<0.05*), grain total Mg (*r=0.29, p<0.05*) and grain total P_2O_5 (*r=0.27, p<0.05*). Similar linear increase in rice yield with soil phosphorus was reported by Saleque *et al*., (1998) in Bangladesh.

On the other hand, soil phosphorus had an insignificant (*p>0.05*) negative effect on straw total Ca, straw and grain total Cu, straw total Fe, straw total K, straw total S as well as straw and grain total Zn. The depressing effect was however highly significant on straw (*r=-0.35, p<0.01*) and grain (*r=-0.38, p<0.01*) total Mn (Table 3.6b). The relationship between soil phosphorus and straw/grain P_2O_5, Mg, Cu, Zn and K agrees with the findings of Rose *et al*., (2016) with a contradiction in the association between soil P_2O_5 and straw Ca which was negative in Mwea and positive in their work done in the Philippines. Similarly, in their work, they reported a positive association between soil P_2O_5 and straw and grain Mn while in Mwea, soil P_2O_5 showed a depressing effect on plant Mn content. The differences observed could be attributed to the differences in soil chemical properties and probably rice genotype differences as they used a non-Basmati IR variety while the Mwea case is a Basmati variety. Elsewhere in Bangladesh, Saleque *et al*., (2001) also observed similar associations between soil phosphorus and straw/grain K and Mg content. These findings imply that phosphorus nutrition not only affects phosphorus uptake by rice but also the uptake and accumulation of other nutrient elements.

From Tables 3.6a and b, soil exchangeable cations Ca^{2+}, K^{+} and Mg^{2+} all showed a depressing effect on rice straw and grain yield and was significant between soil exchangeable Ca^{2+} and Mg^{2+} and straw yield (*r=-0.24*, *p<0.05*). Soil exchangeable Ca^{2+} showed a significant depressing effect on straw total P_2O_5 (*r=-0.36, p<0.01*) and Zn (*r=-0.31, p<0.01*) as well as grain total K (*r=-0.26, p<0.05*), Mg (*r=-0.32, p<0.01*), Mn (*r=-0.29, p<0.05*), P_2O_5 (*r=-0.35, p<0.01*), S (*r=-0.50, p<0.001*) and Zn (*r=-0.34, p<0.01*).

Soil Fe and Zn both showed negative association with their straw and grain contents although it was insignificant in Fe and significant (*p<0.05*) in Zn. The negative relationship between soil available Zn and accumulation in straw and grain shows that straw and grain Zn accumulation is as a result of remobilization rather than continuous root uptake from the soil. Similarly, a negative association although insignificant (Table 3.6a) between soil available Zn and grain and straw yield indicated that there is need to strictly and carefully regulate soil Zn availability, thus more studies in this aspect are required.

Soil S is known to affect availability of Fe and its uptake by rice through regulation of Fe root surface plaque formation in rice (Hu *et al*., 2007; Gao *et al*., 2010; Fan *et al.,* 2010), influence Fe uptake by rice (Wu *et al.,* 2015), and influence the formation of phytosiderophore, which is closely linked with Fe uptake by plants (Cao *et al*. 2002; Yehuda *et al*. 1996; Jin *et al*., 2005). On the contrary, S can increase Fe transport in the xylem (Na and Salt, 2011) and phloem, as well as accelerate the activation of deposited Fe in the apoplast (Holden *et al*. 1991; Toulon *et al*. 1992). The observations in Mwea seem to agree with these findings as soil S showed a negative association with soil ($r=-0.26, p<0.05$) and straw ($r=-0.03, p>0.05$) Fe but positive with grain Fe (Table 3.6a). In China, Wu *et al*., (2014) reported that S input in farmlands through S-containing fertilizers (e.g., calcium superphosphate) and atmospheric S deposition may decrease the accumulation of Fe especially in brown rice when cultivated on high S- soils.

3.4. Conclusions and Recommendations

This is the first study that assessed the relationship between soil properties and yield quality in lowland rice in Kenya. Although reasonably high grain yields are observed, grain quality is compromised this means that the consuming population is affected with certain nutritional deficiencies. In the current study, rice grain showed deficiencies in S, K, Ca, Mg and Fe which were probably affected by soil factors and /or element remobilization. With respect to the grain S, K and Mg accumulation, the high soil concentration of divalent cations could have had a depressing effect. Thus, targeting of the soil resource as an agronomic intervention for increased and timely mineral nutrition supply could help in their accumulation in the panicles and consequently in the grain. The results highlight the need for soil nutritional balance in terms of major and micronutrients which can be achieved through fertilizer application coupled with proper field management practices that are specific to the different units. It will be possible to improve the soil contents of the limiting nutrients like Zn, K and nitrogen through proper and timed fertilization depending on the extent of limitation.

Therefore combinations of proper agronomic management approaches are essential to improve the soil health conditions to enhance the root uptake of mineral nutrients from the soil.

3.5. References

Aciksoz SB, Yazici A, Ozturk L, Cakmak I, 2011a. Biofortification of wheat with iron through soil and foliar application of nitrogen and iron fertilizers *Plant Soil,* 349, 215-225.

Aciksoz SB, Ozturk L, Gokmena OO, Römheld V, Cakmak I, 2011b. Effect of nitrogen on root release of phytosiderophores and root uptake of Fe (III)-phytosiderophore in Fe-deficient wheat plants *Physiologia Plantarum*, 142, 287-296.

Ahmad I, Maathuis FJM, 2014. Cellular and tissue distribution of potassium: Physiological relevance, mechanisms and regulation *Journal of Plant Physiology,* 171, 708-714.

Alloway BJ, 2008. *Zinc in Soils and Crop Nutrition* (2^{nd} Ed.) IFA and IFIA, Brussels, Belgium and Paris, France.

Barikmoa I, Ouattara E, Oshaug A, 2007. Differences in micronutrients content found in cereals from various parts of Mali *Journal of Food Composition and Analysis* 20, 681-687.

Barraclough PB, Howarth JR, Jones J, Lopez-Bellido R, Parmar S, Shepherd CE, Hawkesford MJ, 2010. Nitrogen efficiency of wheat: Genotypic and environmental variation and prospects for improvement *European Journal of Agronomy*, 33(1), 1-11.

Barunawati N, Giehl RFH, Bauer B, von Wirén N, 2013. The influence of inorganic nitrogen fertilizer forms on micronutrient retranslocation and accumulation in grains of winter wheat *Frontiers in Plant Science*, 4, 320.

Bashir K, Ishimaru Y, Nishizawa NK, 2010. Iron Uptake and Loading into Rice Grains *Rice* 3, 122-130.

Bashir K, Takahashi R, Nakanishi H, Nishizawa NK, 2013. The road to micronutrient biofortification of rice: progress and prospects *Frontiers in Plant Science*, 4, 15.

Bi J, Liu Z, Lin Z, Alim MA, Rehmani MI, Li G, Wang Q, Wang S, Ding Y, 2013. Phosphorus accumulation in grains of *japonica* rice as affected by nitrogen fertilizer *Plant and Soil* 369, 231–240.

Briat JF, Duc C, Ravet K, Gaymard F, 2010. Ferritins and iron storage in plants *Biochimica et Biophysica Acta,* 1800, 806-814.

Broadley MR, White PJ, Hammond JP, Zelko I, Lux A, 2007. Zinc in plants *New Phytologist* 173, 677-702.

Buri MM, Masunaga T, Wakatsuki T, 2000. Sulphur and zinc levels as limiting factors to rice production in West Africa lowlands *Geoderma, 94*, 23-42.

Cakmak I, 2008. Enrichment of cereal grains with zinc: Agronomic or genetic biofortification? *Plant and Soil,* 302, 1-17.

Cao H, Han ZH, Xu XF, Zhang Y, 2002. Iron nutrition in higher plants *Plant Physiology Communications* 38 (2), 180-186.

Clarkson DT, Smith FW, Vanden Berg PJ, 1983. Regulation of Sulphate transport in tropical legume *Macroptilium atropurperum,* cv. Siratro *Journal of Experimental Botany,* 34 (148), 1463-1483.

Dučić T, Polle A, 2005. Transport and detoxification of manganese and copper in plants *Brazilian Journal of Plant Physiology,* 17(1), 103-112.

Dobermann A, Cassman K, Cruz PS, Adviento M, Pampolino M. 1996. Fertilizer inputs, nutrient balance and soil nutrient supplying power in intensive, irrigated rice system. III. Phosphorus *Nutrient Cycling in Agroecosystems* 46, 111–125.

Dobermann A, Cassman KG, Mamaril CP, Sheehy JE, 1998. Management of phosphorus, potassium and sulphur in intensive, irrigated lowland rice *Field Crops Research*, 56, 113-138.

Dobermann A, Fairhurst T. 2000. Rice: Nutrient disorders & nutrient management Manila, Philippines: Potash & Phosphate Institute and International Rice Research Institute

Erenoglu EB, Kutman UB, Ceylan Y, Yildiz B, Cakmak I, 2011. Improved nitrogen nutrition enhances root uptake, root-to-shoot translocation and remobilization of zinc (^{65}Zn) in wheat *New Phytologist,* 189, 438-448.

Fageria NK, Wright RJ, Baligar VC, 1988. Rice cultivar evaluation for phosphorus use efficiency *Plant and Soil,* 111, 105-109.

Fageria NK, Slaton NA, Baligar VC, 2003. Nutrient Management for improving lowland rice productivity and sustainability *Advances in Agronomy,* 88, 63-152.

Fairhurst T, Witt C, Buresh R, Dobermann A, 2007. *Rice: A practical guide to nutrient management*, 2nd ed. International Rice Research Institute.

Fan JL, Hu ZY, Ziadi N, Xia X, Wu CYH, 2010. Excessive sulphur supply reduces cadmium accumulation in brown rice (*Oryza sativa* L.) *Environmental Pollution* 158, 409-415.

Fernández V, Brown PH, 2013. From plant surface to plant metabolism: the uncertain fate of foliar-applied nutrients *Frontiers in Plant Science* 4, 289.

Forieri I, Wirtz M, Hell R, 2013. Toward new perspectives on the interaction of iron and sulfur metabolism in plants *Frontiers in Plant Sciences,* 4, 357.

Garnett TP, Graham RD, 2005. Distribution and Remobilization of Iron and Copper in Wheat *Annals of Botany*, 95, 817-826.

Gao X, Brown KR, Racz GJ, Grant CA, 2010. Concentration of cadmium in durum wheat as affected by time, source and placement of nitrogen fertilization under reduced and conventional-tillage management *Plant Soil*, 337, 341-354.

Gierth M, Mäser P, 2007. Potassium transporters in plants- Involvement in K^+ acquisition, redistribution and homeostasis *FEBS Letters,* 581, 2348-2356.

Gregorio GB, Senadhira D, Htut H, Graham RD, 2000. Breeding for trace mineral density in rice *Food and Nutrition Bulletin*, 21, 382-386.

Guo W, Nazim H, Liang Z, Yang D, 2016. Magnesium deficiency in plants: An urgent problem *The crop Journal*, 4, 83-91.

Holden MJ, Luster DG, Chaney RL, Buckhout TJ, Robinson C, 1991. Fe^{3+}-Chelate Reductase Activity of Plasma Membranes Isolated from Tomato (*Lycopersicon esculentum* Mill.) Roots : Comparison of Enzymes from Fe-Deficient and Fe-Sufficient Roots *Plant Physiology*, 97(2), 537-544.

Hu ZY, Zhu YG, Li M, Zhang LG, Cao ZH, Smith FA, 2007. Sulphur (S)-induced enhancement of iron plaque formation in the rhizosphere reduces arsenic accumulation in rice (*Oryza sativa* L.) seedlings *Environmental Pollution* 147, 387–393.

Impa SM, Johnson-Beebout SE, 2012. Mitigating zinc deficiency and achieving high grain Zn in rice through integration of soil chemistry and plant physiology research *Plant and Soil*, 361, 3-41.

Impa SM, Morete MJ, Ismail AM, Schulin R, Johnson-Beebout SE, 2013. Zn uptake, translocation and grain Zn loading in rice (*Oryza sativa* L.) genotypes selected for Zn deficiency tolerance and high grain Zn *Journal of Experimental Botany* 64, 2739-2751.

Ishimaru Y, Bashir K, Nishizawa NK, 2011. Zn uptake and translocation in rice plants *Rice* 4, 21-27.

Iwai T, Takahashi M, Oda K, Terada Y, Yoshida KT, 2012. Dynamic changes in the distribution of minerals in relation to phytic acid accumulation during rice seed development *Plant Physiology* 160, 2007-2014.

Jiang W, Struik PC, Lingna J, van Keulen H, Ming Z, Stomph TJ, 2007. Uptake and distribution of root-applied or foliar-applied ^{65}Zn after flowering in aerobic rice *Annals of Applied Biology,* 150, 383-391.

Jiang W, Struik PC, van Keulen H, Zhao M, Jin LN, Stomph TJ, 2008. Does increased zinc uptake enhance grain zinc mass concentration in rice? *Annals of Applied Biology,* 153, 135-147.

Jin CW, Yu XH, Zhao SJ, 2005. Latent function of microorganisms on plant iron acquisition *Plant Nutrition and Fertilizer Science,* 11, 688-695.

Juliano BO, Ibabao MGB, Perez CM, Clark RB, Maranville JW, Mamaril CP, Choudhury NH, Momuat CJS, Corpuz IT, 1987. Effect of soil sulphur deficiency on sulphur amino acids and elements in brown rice *Cereal Chemistry,* 64, 27-30.

Julia C, Wissuwa M, Kretzschmar T, Jeong K, Rose T, 2016. Phosphorus uptake, partitioning and redistribution during grain filling in rice *Annals of Botany* 118, 1151–1162.

Kabata-Pendias A, 2011. *Trace elements in soils and plants* (4th Ed.) CRC Press, Taylor and Francis Group, LLC.

Karley AJ, White PJ, 2009. Moving cationic minerals to edible tissues: potassium, magnesium, calcium *Current Opinion in Plant Biology,* 12, 291-298.

Kennedy G, Burlingame B, Nguyen VN, 2002. Nutritional contribution of rice and impact of biotechnology and biodiversity in rice-consuming countries 20th International Rice Commission, Bangkok Thailand 23rd to 26th July.

Khurana N, Gupta J, Chatterjee, 1999. Sulphur deficiency influences metabolism and grain quality of Rice *Indian Journal of Plant Physiology,* 4, 277-281.

Kihoro J, Njoroge JB, Murage H, Ateka E, Makihara D, 2013. Investigating the impact of rice blast disease on the livelihood of the local farmers in greater Mwea region of Kenya *SpringerPlus*, 2, 308-320.

Kirk GJD, Bajita JB, 1995. Root-induced iron oxidation, pH changes and zinc solubilization in the rhizosphere of lowland rice *New Phytologist,* 131, 129-137.

Kondo M, Toshinari OTA, Wanjogu R, 2001. Physical and chemical properties of Vertisols and soil nutrient management for intensive rice cultivation in the Mwea area in Kenya *Japanese Journal of Tropical Agriculture,* 45, 126-132.

Koyama T, Sutoh M, 1987, Simultaneous multi-element determination of soils, plant and animal samples by inductively coupled plasma emission spectrometry *Japanese Journal of Soil Science and Plant Nutrition*, 58,578-585 (In Japanese).

Krüger C, Berkowitz O, Stephan UW, Hell R, 2002. A metal-binding member of the late embryogenesis abundant protein family transports iron in the phloem of *Ricinus communis* L. *The Journal of Biological Chemistry,* 277(28), 25062-25069.

Kutman UB, Yildiz B, Cakmak I, 2011. Effect of nitrogen on uptake, remobilization and partitioning of zinc and iron throughout the development of durum wheat *Plant Soil,* 342, 149-164.

Kutman UB, Yildiz B, Ozturk L, Cakmak I, 2010. Biofortification of Durum Wheat with zinc through Soil and Foliar applications of Nitrogen *Cereal Chemistry,* 87(1), 1-9.

Lei Y, Korpelainen H, Li C, 2007. Physiological and biochemical responses to high Mn concentrations in two contrasting *Populus cathayana* populations *Chemosphere,* 68, 686-694.

Maathius FJM, 2009. Physiological functions of mineral macronutrients *Current Opinion in Plant Biology,* 12, 250-258.

Maranguit D, Guillaume T, Kuzyakov Y, 2017. Effects of flooding on phosphorus and iron mobilization in highly weathered soils under different land-use types: Short-term effects and mechanisms *Catena*, 153, 161-170.

Marschner P, (ed.) 2012. Marschner's mineral nutrition of higher plants, 3rd Ed. Academic Press, San Diego, CA, USA

McAinsh MR, Pittman JK, 2009. Shaping the calcium signature *New Phytologist,* 181, 275-294.

Millaleo R, Reyes-Díaz M, Ivanov AC, Mora ML, Alberdi M, 2010. Manganese as essential and toxic element for plants: Transport, accumulation and resistance mechanisms *Journal of Soil Science and Plant Nutrition,* 10(4), 476-494.

Moore CA, Bowen HC, Scrase-Field S, Knight MR, White PJ, 2002. The deposition of suberin lamellae determines the magnitude of cystosolic Ca^{2+} elevations in root endodermal cells subjected to cooling *The Crop Journal,* 30(4), 457-465.

Moritsuka N, Yanai J, Umeda M, Kosaki T, 2004. Spatial relationships among different forms of soil nutrients in a paddy field *Soil Science and Plant Nutrition*, 50(4), 565-573.

Na GN, Salt DE, 2011. The role of sulphur assimilation and sulphur-containing compounds in trace element homeostasis in plants *Environmental and Experimental Botany,* 72(1), 18-25.

Neue HE, Mamaril CP, 1985. Zinc, sulphur and other micronutrients in wetland soils In *Wetland Soils: Characterization, Classification and Utilization* (p307-319). IRRI, Los Banos, Laguna, Philippines.

Newell-McGloughlin M, 2008. Nutritionally improved agricultural crops *Plant Physiology,* 147, 939-953

Ning HF, Liu ZH, Wang QS, Lin ZM, Chen SJ, Li GH, Wang SH, Ding YF, 2009. Effect of nitrogen application on grain phytic acid and protein concentrations in japonica rice and its variations with genotypes *Journal of Cereal Science,* 50, 49-55.

Ogawa M, Tanaka K, Kasai Z, 1979. Accumulation of phosphorus, magnesium and potassium in developing rice grains: followed by electron microprobe X-ray analysis focusing on the aleurone layer *Plant and Cell Physiology,* 20, 19–27.

Paul S, Ali N, Gayen D, Datta SK, Datta K, 2012. Molecular breeding of *Osfer2* gene to increase iron nutrition in rice grain *GM Crops & Food,* 3(4), 310-316.

Ponnamperuma FN, 1972. The Chemistry of Submerged Soils *Advances in Agronomy*, 24, 29-96.

Raboy V, 2007. The ABCs of low-phytate crops *Nature Biotechnology,* 25, 874-875.

Raboy V, 2009. Approaches and challenges to engineering seed phytate and total phosphorus *Plant Sciences,* 177, 281-296.

Rakotoson T, Amery F, Rabeharisoa L, Smolders E, 2014. Soil flooding and rice straw addition can increase isotopic exchangeable phosphorus in P-deficient soils *Soil Use and Management,* 30, 189-197.

Rakotoson T, Six L, Razafimanantsoa MP, Rabeharisoa L, Smolders E, 2015. Effects of organic matter addition on phosphorus availability to flooded and non-flooded rice in P-deficient tropical soil: a greenhouse study *Soil Use and Management*, 31, 10-18.

Rakotoson T, Rabeharisoa L, Smolders E, 2016. Effects of soil flooding and organic matter addition on plant accessible phosphorus in a tropical paddy soil: an isotope study *Journal of Plant Nutrition and Soil Science*, 179,765-774.

Randal PJ, Freney JR, Spenser K, 2003. Diagnosing sulfur deficiency in rice by grain analysis *Nutrient Cycling in Agroecosystems,* 65, 211-219.

Richardson AE, Lynch JP, Ryan PR, Delhaize E, Smith FA, Smith SE, Harvey PR, Ryan MH, Vneklaas EJ, Lambers H, Oberson A, Culvenor RA, Simpson RJ, 2011. Plant and microbial strategies to improve the phosphorus efficiency of Agriculture *Plant Soil,* 349, 121-156.

Rosanoff A, 2013. Changing crop magnesium concentrations: impact on human health *Plant Soil*, 368, 139-153.

Rose TJ, Impa SM, Rose MT, Pariasca-Tanaka J, Mori A, Heuer S, Johnson-Beebout SE, Wissuwa M, 2013a. Enhancing phosphorus and zinc acquisition efficiency in rice: a critical review of root traits and their potential utility in rice breeding *Annals of Botany*, 112, 331-345.

Rose TJ, Krestzschmar T, Liu L, Lancaster G, Wissuwa M, 2016. Phosphorus Deficiency Alters Nutrient Accumulation Patterns and Grain Nutritional Quality in Rice *Agronomy,* 6, 52.

Rose TJ, Liu L, Wissuwa M. 2013b. Improving phosphorus efficiency in cereal crops: is breeding for reduced grain phosphorus concentration part of the solution? *Frontiers in Plant Science,* 4, 444.

Rose TJ, Pariasca-Tanaka J, Rose MT, Fukuta Y, Wissuwa M, 2010. Gynotypic variation in grain phosphorus concentration and opportunities to improve P-use efficiency in rice *Field Crops Research,* 119, 154-160.

Saleque MA, Abedin MJ, Panaullah GM, Bhuiyan NI, 1998. Yield and phosphorus efficiency of some lowland rice varieties at different levels of soil-available phosphorus *Communications in Soil Science and Plant Analysis*, 29(19-20), 2905-2916.

Saleque MA, Abedin MJ, Ahmed ZU, Hasan M, Panaullah GM, 2001. Influences of phosphorus deficiency on the uptake of Nitrogen, Potassium, Calcium, Magnesium, Sulfur and Zinc in Lowland Rice varieties *Journal of Plant Nutrition*, 24(10), 1621-1632.

Sharma A, Patni B, Shankhdhar D, Shankhdhar SC, 2013. Zinc-An Indispensable Micronutrient *Physiology and Molecular Biology of Plants*, 19, 11-20.

Sharma D, Jamra G, Singh UM, Sood S, Kumar A, 2017. Calcium Biofortification: Three Pronged Molecular Approaches for Dissecting Complex Trait of Calcium Nutrition in Finger Millet (*Eleusine coracana*) for Devising Strategies of Enrichment of Food Crops *Frontiers in Plant Science,* 7, 2028.

Shi RL, Weber G, Köster J, Reza-Hajirezaei M, Zou C, Zhang F, von Wirén N, 2012. Senescence-induced iron mobilization in source leaves of barley (*Hordeum vulgare*) plants *New Phytologist*, 195, 372-383.

Shi RL, Zhang YQ, Chen XP, Sun QP, Zhang FS, Römheld V, Zou CQ, 2010. Influence of long-term nitrogen fertilization on micronutrient density in grain of winter wheat (*Triticum aestivum* L.) *Journal of Cereal Science*, 51, 165-170.

Shoji K, Kawamura T, Horio H, 2005. Variability of micro-elevation, yield and protein content within a transplanted paddy field *Precision Agriculture*, 6, 73–86.

Slamet-Loedin IH, Johnson-Beebout SE, Impa S, Tsakirpaloglou N, 2015. Enriching rice with Zn and Fe while minimizing Cd risk *Frontiers in Plant Science,* 6, 121.

Sperotto RA, 2013. Zn/Fe remobilization from vegetative tissues to rice seeds: should I stay or should I go? Ask Zn/Fe supply! *Frontiers in Plant Science*, 4, 464.

Sperotto RA, Ricachenevsky FK, Waldow VA, Fett JP, 2012a. Iron biofortification in rice: It's a long way to the top *Plant Science,* 190, 24-39.

Sperotto RA, Vasconcelos MW, Grusak MA, Fett JP, 2012b. Effects of different Fe supplies on mineral partitioning and remobilization during the reproductive development of rice (*Oryza sativa* L.) *Rice* 5, 27.

Swamy BPM, Rahman MA, Inabangan-Asilo MA, Amparado A, Manito C, Chadha-Mohanty P, Reinke R, Slamet-Loedin IH, 2016. Advances in breeding high grain Zinc in Rice *Rice*, 9, 49.

Toulon V, Sentenac H, Davidian JC, Moulineau C, Grignon C, 1992. Role of apoplast acidification by the H^+ pump: Effect on the sensitivity to pH and CO_2 of iron reduction by roots of *Brassica napus* L. *Planta* 186, 551-556.

van Asten PJA, Barro SE, Wopereis MCS, Defoer T, 2004. Using farmer knowledge to combat low productive spots in rice fields of Sahelian irrigation scheme *Land Degradation and Development, 15*, 383-396.

Vandamme E, Rose TJ, Saito K, Jeong K, Wissuwa M, 2016. Integration of P acquisition efficiency, P utilization efficiency and low grain P concentrations into P-efficient rice genotypes for specific target environments *Nutrient Cycling in Agroecosystems,* 104, 413-427.

Wang F, Rose T, Jeong K, Kretzschmar T, Wissuwa M, 2016. The knowns and unknowns of phosphorus loading into grains, and implications for phosphorus efficiency in cropping systems *Journal of Experimental Botany* 67, 1221–1229.

Wang YY, Wei YY, Dong LX, Lu LL, Feng Y, Zhang J, Pan FS, Yang XE, 2014. Improved yield and Zn accumulation for rice grain by Zn fertilization and optimized water management *Journal of Zhejiang University- Science B (Biomedicine & Biotechnology)*, 15(4), 365-374.

Waters BM, Sankaran RP, 2011. Moving micronutrients from the soil to the seeds: Genes and physiological processes from biofortification perspective *Plant Science* 180, 562-574.

Welch RM, 1995. Micronutrient nutrition of plants *Critical Reviews in Plant Science* 14, 49–82.

White PJ, 1998. Calcium channels in the Plasma Membrane of Root Cells *Annals of Botany,* 81, 173-183.

White PJ. 2000. Calcium channels in higher plants *Biochimica et Biophysica Acta (BBA) Biomembrane,* 1465, 171-189.

White PJ, 2001. The pathways of calcium movement to xylem *Journal of Experimental Botany*, 52(358), 891-899.

White PJ, Broadley MR. 2003. Calcium in plants *Annals of Botany* 92, 487-511.

White PJ, Broadley MR, 2005. Biofortifying crops with essential mineral elements *Trends in Plant Science* 10, 586-593.

White PJ, Broadley MR, 2009. Biofortication of crops with seven mineral elements often lacking in human diets- iron, zinc, copper, calcium, magnesium, selenium and iodine *New Phytologist,* 182, 49-84.

White PJ, Broadley MR, 2011. Physiological limits to zinc biofortification of edible crops *Frontiers in Plant Science*, 2, 80.

White PJ, Cooper HD, Earnshaw MJ, Clarkson DT, 1990. Effects of low temperature on the development and morphology of rye (*Secale cereale*) and wheat (*Triticum aestivum*) *Annals of Botany* 66, 559-566.

Wilkinson SR, Welch RM, Mayland HF, Grunes DL, 1990. Magnesium in plants: Uptake, distribution, function, and utilization by man and animals, In *Metal Ions in Biological Systems* Sigel H, Sigel A, (eds), 26, 33-56.

Wissuwa M, Ismail AM, Graham RD, 2008. Rice grain zinc concentration as affected by genotype, native soil-zinc availability and zinc fertilization *Plant Soil*, 306, 37-48.

Wu CY, Lu LL, Yang XE, Feng Y, Wei YY, Hao HL, Stoffella PJ, He ZL, 2010. Uptake, translocation, and remobilization of zinc absorbed at different growth stages by rice genotypes of different Zn densities *Journal of Agricultural Food Chemistry,* 58, 6767-6773.

Wu CYH, Lu J, Hu ZY, 2014. Influence of Sulphur Supply on the Iron Accumulation in Rice Plants *Communications in Soil Science and Plant Analysis*, 45, 1149–1161.

Wu M, Li G, Li W, Liu J, Liu M, Jiang C, Li Z, 2017. Nitrogen Fertilizer Deep Placement for Increased Grain Yield and Nitrogen Recovery Efficiency in Rice Grown in Subtropical China *Frontiers in Plant Science*, 8, 1227.

Wu Z, Zhang C, Dai C, Ge Y, 2015. Sufficient sulphur supply promotes seedling growth, and alleviates oxidation stress and regulates iron uptake and translocation in rice *Biologia Plantarum,* 59(4), 788-792.

Yehuda Z, Shenker M, Romheld V, Marschner H, Hadar Y, ChenY, 1996. The role of ligand exchange in the uptake of iron from microbial siderophores by gramineous plants *Plant Physiology,* 112, 1273-1280.

Yoneyama T, Gosho T, Kato M, Goto S, Hayashi H, 2010. Xylem and phloem transport of Cd, Zn and Fe into the grains of rice plants (*Oryza sativa* L.) grown in continuously flooded Cd-contaminated soil *Soil Science and Plant Nutrition,* 56, 445-453.

Zhai CK, Lu CM, Zhang X, Sun JG, Lorenz KJ, 2001. Comparative study on nutritional value of Chinese and North American wild rice *Journal of Food Composition and Analysis* 14, 371–382.

Zuo YM, Zhang FS. 2011. Soil and crop management strategies to prevent iron deficiency in crops *Plant and Soil* 339, 83–95.

CHAPTER 4

Paddy Soil Properties of Ahero and West Kano Irrigation Schemes in the Lake Victoria Basin of Kenya

4.1. Introduction

The demand for rice in Kenya continues to soar as more people show progressive changes in their eating habits, which is coupled with urbanization. Rice is currently the third most important cereal crop after maize and wheat. Most of the rice in Kenya is grown in irrigation schemes established by the Government, which include Mwea in central Kenya, three irrigation schemes (Ahero, West Kano and Bunyala) in western Kenya. On the other hand, a smaller quantity of rice is produced along major river valleys, located in the coast and lake basin regions (Cheserek *et al*., 2012). In Kenya, about 80% of rice is grown under continuous flooding as is typified in gravity operated Mwea irrigation scheme and in the three western Kenya irrigation schemes that are pumps operated (JICA, 1988, MoA, 2009). The remaining 20% is produced under rain-fed conditions (MoA, 2009).

The increasing gap between rice production and consumption has become a burden to the country's economy. Rice consumption increased by 360, 468 tonnes between 2010 and 2013, whereas the production increased only by 39,720 tonnes during the same period (FAOSTAT, 2017). The lack of self-sufficient rice production is supplemented by importation, which eats hugely on Kenya's economy. It is anticipated that rice demand will continue to increase given the high rates of population growth and rapid urbanization, which have resulted in a shift in consumer preferences in favour of rice (Balasubramanian *et al*., 2007); therefore increasing the total rice production is an urgent issue to avert further economic burden and food insecurity in the country. This increase can be achieved by a good balance between area expansion and production improvement per unit area. The yield gap between potential and actual yields exists in Kenya (Kondo *et al.,* 2001) and fortunately, there are opportunities to help increase on total rice production while reducing the yield gap. Lowland ecosystems provide an appropriate environment for realizing increased productivity. This is because this environment can hold water resources and is said to be relatively fertile compared to upland environment (Buri *et al*., 1999). Furthermore, the use of lowlands for rice cultivation does not cause competition with other crops. A recent review on rice production in West Africa by Abe *et al*., (2010) suggested that because of their high productivity, lowland ecosystems should be the focus rather than upland ecosystems to help meet the increasing rice demand.

Faced with rapid population growth and increasing per capita rice consumption, increased production is required to meet the future demand for rice in Kenya. Improving farmers' efficiency in rice production therefore has a potential of increasing rice production in the country; which will hopefully have direct effect on increased output hence food security, increased incomes and reduction in supply-demand gap consequently reducing the rice import bill (Omondi and Shikuku, 2013).

An understanding how variable the soil is in terms of its fertility is fundamental for enhancing rice productivity through developing appropriate management practices in the current irrigation schemes in Kenya. Thus against this backdrop, the focus is on western Kenya irrigation schemes of Ahero and West Kano that are underutilized.

4.2. Materials and Methods

4.2.1. Site Description

This work was carried out in two rice irrigation schemes in Western Kenya namely; Ahero, West Kano that are both managed by the Kenya National Irrigation Board (NIB). The area is characterized by bimodal rainy season averaging 1175 mm annually and isolated heavy storms due to the influence of Lake Victoria. Annual temperatures range from 22.1^{0}C in June to 23.5^{0}C in March. The irrigated fields in the schemes are underlain by deep black cotton soils with very high clay content that swell or shrink and crack accordingly when they are hydrated or dried (Cheserek *et al*., 2012).

Ahero Irrigation Scheme (AIS) is located in Kisumu County in the outskirts of Kisumu city on a landscape that consists of a wide alluvial plain and draws water from river Nyando (Figure 4.1); a feeder river of Lake Victoria using pumps and flows to the fields by gravity. The area experiences seasonal flooding from river Nyando causing water logging due to the flat terrain. Nearly all irrigated farmland is used for paddy cultivation (Omondi, 2014).

The scheme was commissioned in 1969 and covers a net area of about 880 ha sub-divided into 13 blocks (Cheserek *et al*., 2012; Omondi and Shikuku, 2013). The scheme however stalled in 1999/2000 due to depletion of funds but later in 2003, the government through the Ministry of Water and Irrigation funded its rehabilitation by buying two pumps (Omondi, 2014).

Rice is the main crop and the varieties grown are mainly IR 2793 and ITA 310 although BASMATI 217 and 370 are also grown. After harvesting rice, a small number of farmers plant maize and tomatoes. Inputs such as seeds and fertilizer are supplied by the NIB although farmers are allowed to buy from any other source (Omondi, 2014).

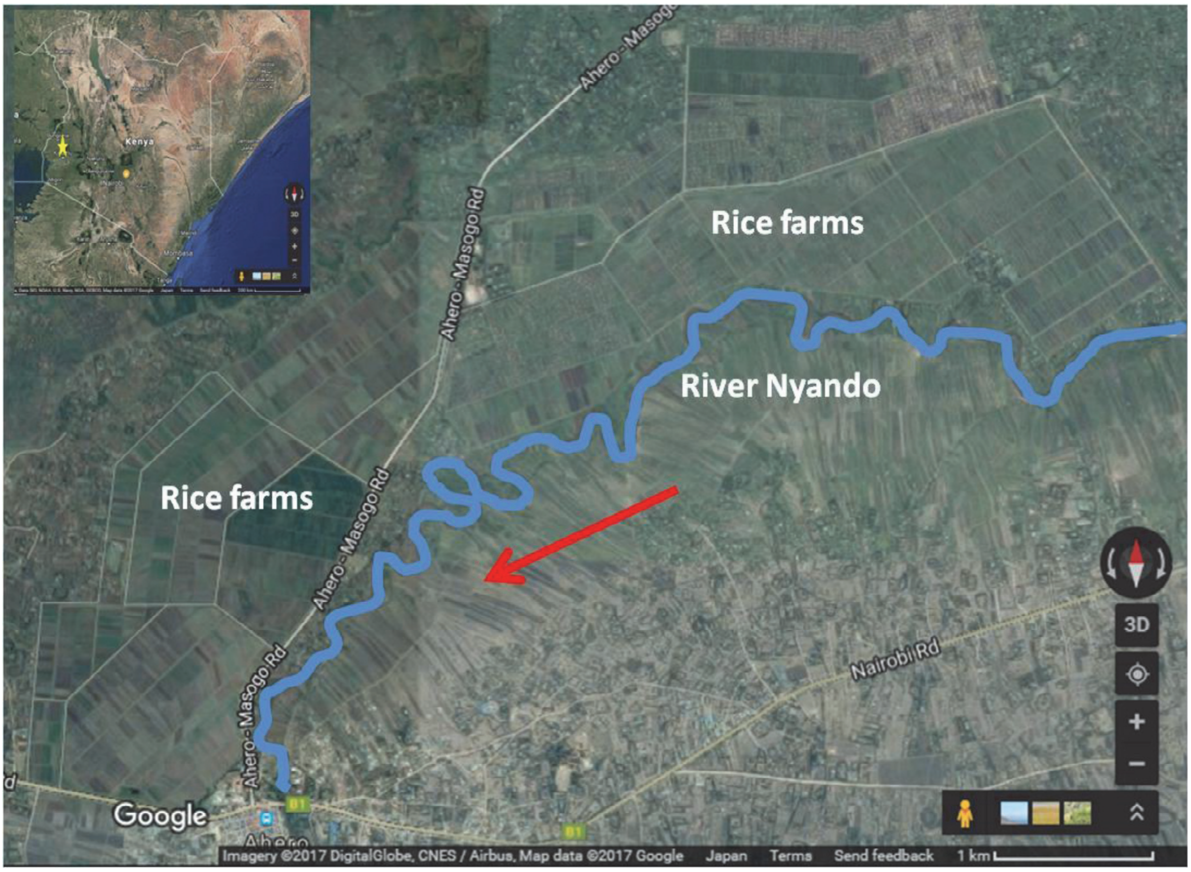

Figure 4. 1: Location and layout of Ahero Irrigation Scheme

West Kano Irrigation Scheme was started in 1975 and is located on the shores of Lake Victoria (Figure 4.2). The scheme is bounded to the west by Lake Victoria, to the north and south by Nyando and Nyabondo escarpments respectively and to the east by the footsteps of Tinderet highlands occupying the major part of Kano plains (Afullo, 2009). The area was initially put under rice and sugarcane cultivation but sugarcane cultivation stopped when it proved uneconomical. The scheme lies in a depression and water is pumped in and out of the depression during a crop cycle (Onjala, 2001). The scheme covers a net area of approximately 900 ha and draws its water from Lake Victoria using pumps.

According to Cheserek *et al*., (2012), some of the major challenges facing the western Kenya irrigation schemes are the lack of effective water supply system, lack of water storage to guarantee adequate supply during the dry period, slow acceptance of participatory irrigation management by the farming community, combating water-borne and other related diseases, environmental stability and lack of clean drinking water.

Figure 4. 2: Location and layout of West Kano Irrigation Scheme

4.2.2. Soil sampling and Analysis

Soil samples were collected from nine blocks out of the 12 blocks in Ahero irrigation scheme. In West Kano, soil samples were taken from eight blocks. Surface 0-15 cm representative samples were collected from each plot, mixed thoroughly and a composite sample per field taken for evaluation. The composite samples collected were air-dried, ground and passed through a 2mm sieve for laboratory analysis. Soil samples were analysed for pH, electrical conductivity (EC), total carbon (TC), total nitrogen (TN), available silica (SiO_2), available sulphur (S), available phosphorus (P_2O_5), available micronutrients (Fe, Mn, Cu and Zn) and exchangeable cations (Ca^{2+}, Mg^{2+}, Na^+ and K^+) using standard procedures for soil analysis.

4.2.3. Statistical Analysis

All data collected from laboratory analyses were subjected to statistical analysis using R software version 3.4.0 for windows with means compared at $p \leq 0.05$. Soil fertility status was evaluated basing on the concentrations of the respective parameters obtained from the laboratory analyses compared with established ratings for rice production.

4.3. Results and Discussions

4.3.1. Soil Chemical Properties

Soil solution pH in the scheme ranged from 6.2 to 8.0 in Ahero and from 5.4 to 7.5 in West Kano irrigation scheme. EC on the other hand had values ranging from a minimum of 0.3 to 0.9 dS/m and from 0.3 to 1.05 dS/m in Ahero and West Kano respectively.

Soil total carbon ranged from a minimum of 14.6 g/kg in West Kano to a maximum of 38.5 g/kg while in Ahero, values from 10.9 g/kg to a maximum of 25.5 g/kg was recorded. Total nitrogen on the other hand varied from 0.7 g/kg to 2.1 g/kg in Ahero and from 1.1 g/kg to 2.9 g/kg in West Kano. On average, TC and TN contents observed for Ahero and West Kano paddy soils were higher than what was observed in Mwea, central Kenya where straw removal is a common practice.

Soil available phosphorus is enriched in the two schemes and values varying from 79.9 mg/kg to 482 mg/kg were recorded in Ahero irrigation scheme. In West Kano, available P_2O_5 ranged from 107 mg/kg to 2701.3 mg/kg. Ahero and West Kano soils seem highly enriched with phosphorus exceeding the deficiency level for rice and were 3-5 times the average in Mwea.

Soil available SiO_2 in Ahero varied from 564.5 mg/kg to 1094.2 mg/kg while in West Kano, values recorded varied between 199.3 mg/kg to 967.5 mg/kg. Available S exceeded the deficiency level for rice and ranged from 24.1 mg/kg to 60.3 mg/kg in Ahero and from 20.6 mg/kg to 42.8 mg/kg in West Kano.

In terms of exchangeable cations, Ca^{2+} occurred in higher concentration followed by Mg^{2+}, K^+ and Na^+. In Ahero, exchangeable Ca^{2+} ranged from 20.9 $cmol_c$/kg to 40.8 $cmol_c$/kg while Mg^{2+} varied from 6.4 $cmol_c$/kg to a maximum of 9.5 $cmol_c$/kg. Exchangeable Na^+ and K^+ ranged from 0.6 $cmol_c$/kg to 3.2 $cmol_c$/kg and from 1.1 $cmol_c$/kg to 3.4 $cmol_c$/kg respectively. In West Kano, exchangeable Ca^{2+} varied from 13.3 $cmol_c$/kg to 40.6 $cmol_c$/kg. On the other hand, values from 4.4 $cmol_c$/kg to 11.4 $cmol_c$/kg, 0.5 $cmol_c$/kg to 2.2 $cmol_c$/kg and from 0.9 $cmol_c$/kg to 4.9 $cmol_c$/kg were recorded for exchangeable Mg^{2+}, Na^+ and K^+ respectively. All exchangeable cations exceeded the deficiency criteria for rice and exchangeable Ca^{2+} was comparable to the levels observed in the Mwea irrigation scheme. On the contrary, exchangeable Mg^{2+} was much higher in Mwea than in Ahero and West Kano while exchangeable K^+ was enriched in Ahero and West Kano than in Mwea scheme.

In terms of micronutrients, available Fe ranged from 19.5 mg/kg to 799.8 mg/kg in Ahero while in West Kano available Fe ranged from 41.6 mg/kg to 901.1 mg/kg. Available Mn ranged from 63.6 mg/kg to 813.6 mg/kg in Ahero and from 78.5 mg/kg to 468.6 mg/kg in West Kano. Available Cu was high and ranged from 1.6 mg/kg to 8.5 mg/kg in West Kano and from 0.6 mg/kg to 9.9 mg/kg in Ahero irrigation scheme. Available Zn on the other hand ranged from 2.3 mg/kg to 6.2 mg/kg in Ahero and from 3.1 mg/kg to 13.2 mg/kg in West Kano. Soil available Zn in the two schemes exceeded the values recorded in Mwea several times-fold.

Mean values for soil parameters in Ahero and West Kano irrigation schemes are presented in Table 4.1 with deficiency criteria for rice production according to Dobermann and Fairhurst (2000).

Table 4.1: Mean values for soil chemical parameters in Ahero and West Kano schemes

Parameter/Scheme	Ahero	West Kano	Deficiency criteria*
pH	6.8	6.5	
EC (dS/m)	0.54	0.50	
TC (g/kg)	20.2	20.7	
TN (g/kg)	1.52	1.62	
C/N ratio	13.5	12.7	
Avail. SiO_2 (mg/kg)	751.9	575.9	<86
Avail. S (mg/kg)	37.4	31	<9.0
Avail. P_2O_5 (mg/kg)	211.9	347.4	<12-20
Ca^{2+} ($cmol_c$/kg)	30.5	28.0	<1.0
Mg^{2+} ($cmol_c$/kg)	8.4	8.4	<1.0
Na^+ ($cmol_c$/kg)	1.09	1.30	
K^+ ($cmol_c$/kg)	1.67	1.81	<0.2
(Ca+Mg)/K ratio	24	22	>100
Avail. Fe (mg/kg)	357.3	285.2	<5.0
Avail. Mn (mg/kg)	364.8	196.7	<30.0
Avail. Cu (mg/kg)	5.69	4.61	<1.0
Avail. Zn (mg/kg)	4.80	4.72	<2.0

*Dobermann and Fairhurst, (2000)

As pointed out in soil results in Table 4.1, soil pH is near neutral in both schemes. Such high pH was also reported by van Engelen, (1987) in the same region. The values observed for EC indicate that soils contain low concentration of soluble salts and hence considered non saline similar to the case in Mwea.

On average, TC was moderately high which could be attributed to the retention of straw in the fields in the two irrigation schemes. Furthermore, the somewhat long cultivation history coupled with good soil drainage conditions could also contribute to organic matter accumulation. We also observed that livestock grazed freely in the fields after harvest. Soil TN is slightly higher than the values observed in Mwea while the C:N ratio fall within the acceptable range of agricultural soil.

Averagely, available SiO_2 and P_2O_5 exceeded the 86 mg kg^{-1} and 12-20 mg kg^{-1} deficiency level for rice production respectively (Table 4.1). The high P_2O_5 levels could be as a result of the dissolution of Ca-P by the Bray II extractant (Mamo *et al.*, 1988). On the other hand, the high available SiO_2 is attributed to Si-rich parent material. Rice retains about 86% of silica taken up from the soil in straw (Klotzbücher *et al.*, 2015; Marxen *et al.*, 2016); therefore the high values of SiO_2 observed could also be because of retention of straw in the two schemes. Furthermore, the high siltation especially in Ahero could also be the reason for the values observed as silt is rich in silica (Brady and Weil, 2014). Additional supply is also known to originate from irrigation water (Desplaques *et al.*, 2006).

Comparing available S concentration in the two schemes with Mwea, results demonstrated that the concentration is lower than Mwea even though it exceeded the deficiency level for rice cultivation. The concentration in Ahero was higher than in West Kano. In our survey during soil sampling, we noticed that straw was burnt in the fields especially in West Kano, a practice that is known to contribute to S losses (Dobermann and Fairhurst, 2000).

The concentration of soil exchangeable cations exceeded deficiency criteria on average. Even though the divalent cations dominated the soil exchange site, exchangeable Mg^{2+} occurred in lower concentration compared to Mwea and thus there was no cation imbalance as observed in Mwea. Soil exchangeable K^+ concentration was much higher than in Mwea even though the soils in the schemes being Vertisols and containing the 2:1 type of clays (van Engelen, 1987). Probably the practice of straw retention in Ahero and West Kano could be the reason for the high soil exchangeable K^+ values observed as opposed to the practice of straw removal in Mwea (Kondo *et al.*, 2001).

In terms of micronutrients, available Cu is sufficient in the soil and so is available Zn unlike in Mwea where available Zn was below the deficiency level. However, Ahero scheme could require close monitoring for Fe and Mn toxicities as it contained high values on average, similar to Thiba unit in the Mwea irrigation scheme.

4.3.2. Correlation Analysis between soil properties

In order to assess how the soil parameters are related, Pearson's correlation coefficients ($p \le 0.001$, $p \le 0.01$ and $p \le 0.05$) were calculated and are shown in Tables 4.2 and 4.3 for West Kano and Ahero irrigation schemes respectively. Mixed and inconsistence correlations were observed. From Table 4.2 for West Kano soils, the Pearson correlation analysis results showed that pH correlated negatively and moderately with TC, TN; and highly with Fe and Cu. In Ahero, pH showed very strong and negative correlation with TC, TN, micronutrients and S ($p<0.001$) (Table 4.3). In Mwea and West Kano, pH and S relationship was insignificant and positive ($p>0.05$). Among the exchangeable cations, Mg^{2+} showed a negative though insignificant correlation with pH and positive significant with Ca^{2+} ($r=0.44$, $p<0.01$) as Na^{+} and K^{+} association was insignificant in West Kano (Table 4.2). Exchangeable cations and pH relations were strongest in Mwea scheme. Soil parameters relationships seem moderately strong in West Kano and very strong in Ahero as compared to Mwea scheme.

Table 4.2: Pearson Correlation showing correlation coefficients among soil parameters in West Kano irrigation scheme

	pH	EC	TC	TN	C/N	P_2O_5	K	Na	Mg	Ca	CaMg/K	Zn	Cu	Fe	Mn	SiO_2	S
pH																	
EC	0.16ns																
TC	-0.31*	0.19ns															
TN	-0.37*	0.18ns	0.96***														
C/N	0.22ns	0.12ns	0.25ns	-0.00ns													
P2O5	0.25ns	0.19ns	-0.01ns	0.05ns	-0.16ns												
K	0.01ns	0.10ns	0.36*	0.36*	0.09ns	0.76***											
Na	0.27ns	0.20ns	-0.03ns	-0.11ns	0.29*	-0.09ns	0.06ns										
Mg	-0.13ns	-0.40**	-0.00ns	-0.09ns	0.24ns	-0.36*	0.00ns	0.46***									
Ca	0.44**	0.07ns	-0.10ns	-0.23ns	0.42**	-0.30*	-0.11ns	0.62***	0.68***								
CaMg/K	0.27ns	-0.14ns	-0.44**	-0.48***	0.02ns	-0.55***	-0.77***	0.26ns	0.37**	0.56***							
Zn	-0.20ns	0.02ns	0.31*	0.38**	-0.16ns	0.78***	0.74***	-0.05ns	-0.10ns	-0.39**	-0.56***						
Cu	-0.68***	-0.30*	0.35*	0.37**	-0.05ns	-0.18ns	-0.05ns	-0.21ns	0.15ns	-0.44**	-0.21ns	0.29*					
Fe	-0.64***	-0.13ns	0.50***	0.56***	-0.12ns	0.00ns	0.10ns	-0.34*	-0.18ns	-0.62***	-0.40**	0.39**	0.80***				
Mn	0.01ns	0.30*	0.47***	0.42**	0.33*	0.22ns	0.16ns	-0.16ns	-0.33*	-0.24ns	-0.30*	0.28*	0.28ns	0.44**			
SiO_2	0.62***	0.23ns	-0.02ns	-0.16ns	0.59***	0.04ns	0.18ns	0.33*	0.27ns	0.69***	0.15ns	-0.22ns	-0.44**	-0.48***	0.03ns		
S	0.04ns	0.45**	0.12ns	0.00ns	0.44**	-0.12ns	-0.11ns	0.40**	0.17ns	0.34*	0.21ns	-0.04ns	0.04ns	-0.04ns	0.12ns	0.35*	

*Significance levels are noted by ***: p≤ 0.001; **: p≤0.01; *: p≤0.05; ns (not significant): p> 0.05*

Table 4.3: Pearson Correlation showing correlation coefficients among soil parameters in Ahero irrigation scheme

	pH	EC	TC	TN	C/N	P_2O_5	K	Na	Mg	Ca	CaMg/K	Zn	Cu	Fe	Mn	SiO_2	S
pH																	
EC	0.01ns																
TC	-0.73***	0.22ns															
TN	-0.80***	0.21ns	0.96***														
C/N	0.73***	0.09ns	-0.56***	-0.73***													
P_2O_5	0.33*	0.10ns	-0.09ns	-0.16ns	0.32*												
K	-0.09ns	0.27ns	0.31*	0.23ns	0.03ns	0.29ns											
Na	0.54***	0.16ns	-0.54***	-0.54***	0.45***	0.02ns	-0.22ns										
Mg	0.14ns	0.04ns	-0.39**	-0.40**	0.24ns	-0.18ns	0.09ns	0.36*									
Ca	0.57***	0.25ns	-0.48***	-0.58***	0.66***	0.02ns	0.18ns	0.52***	0.69***								
CaMg/K	0.44**	-0.19ns	-0.63***	-0.60***	0.34*	-0.19ns	-0.75***	0.58***	0.36*	0.42*							
Zn	-0.79***	0.04ns	0.71***	0.78***	-0.74***	-0.09ns	0.01ns	-0.46**	-0.29ns	-0.66***	-0.42**						
Cu	-0.80***	0.07ns	0.64***	0.74***	-0.75***	-0.40**	-0.13ns	-0.40**	-0.19ns	-0.65***	-0.29ns	0.86***					
Fe	-0.74***	0.15ns	0.65***	0.74***	-0.68***	-0.25ns	0.00ns	-0.43**	-0.23ns	-0.62***	-0.40**	0.81***	0.94***				
Mn	-0.43**	0.26ns	0.54***	0.56***	-0.44**	-0.16ns	-0.05ns	-0.50***	-0.41**	-0.57***	-0.37*	0.62***	0.69***	0.72***			
SiO_2	0.73***	0.17ns	-0.55***	-0.63***	0.72***	0.04ns	0.10ns	0.45**	0.34*	0.74***	0.28ns	-0.76***	-0.74***	-0.69***	-0.53***		
S	-0.56***	0.56***	0.52***	0.51***	-0.25ns	-0.26ns	0.23ns	-0.16ns	0.04ns	-0.09ns	-0.34*	0.39**	0.42**	0.38**	0.31*	-0.23ns	

*Significance levels are noted by ***: $p \leq 0.001$; **: $p \leq 0.01$; *: $p \leq 0.05$; ns (not significant): $p > 0.05$*

4.3.3. Extraction of Factors Characterizing Soil Properties

In PCA, factors that contained Eigen values greater than 1 were retained. In Ahero, four components (PC1 to PC4) with eigen values above 1 accounted for about 81 % of total variance (Table 4.4). The first component showed high loadings for TN, Zn, Cu, Fe, TC and negatively for pH. PC2 showed high loading for K similar to Mwea, while PC3 showed high loading for Mg and negatively for P_2O_5 and PC4 loaded highly for EC.

Table 4.4: Factor loadings, eigen values and cumulative contribution ratio in Ahero scheme

Variables	PC1	PC2	PC3	PC4
pH	-0.871	0.032	-0.208	0.293
EC	0.091	0.629	0.429	0.570
TC	0.844	0.313	-0.002	-0.024
TN	0.911	0.197	0.037	-0.026
C/N	-0.805	0.242	-0.054	0.210
Avail. P_2O_5	-0.205	0.364	-0.621	0.229
Ex. K	0.110	0.857	-0.171	-0.352
Ex. Na	-0.635	-0.098	0.373	0.244
Ex. Mg	-0.428	0.078	0.625	-0.448
Ex. Ca	-0.763	0.337	0.417	-0.130
Ex. Ca+Mg/K ratio	-0.588	-0.626	0.355	0.171
Avail. Zn	0.895	-0.095	0.047	0.013
Avail. Cu	0.889	-0.243	0.284	0.044
Avail. Fe	0.875	-0.101	0.180	0.101
Avail. Mn	0.724	-0.031	0.005	0.439
Avail. SiO_2	-0.800	0.300	0.121	0.048
Avail. S	0.487	0.439	0.549	0.099
Eigen-value	8.29	2.34	1.91	1.16
Cumulative contribution (%)	48.7	62.5	73.7	80.6

The first component, PC1, showed high positive loadings for TN, Fe, Zn and TC while pH loaded negatively on the same component. Since N is related to soil and fertilizer management, this first component can be referred to as “soil management factor”. The factors that loaded positively on PC1 showed positive correlation between them but correlated negatively with the negatively loading factors. The negative loading for pH is because pH has strongly affects the activity of soil microbes and the rate of soil carbon and nitrogen cycling. Furthermore, the high pH observed in Ahero is likely to render some essential nutrient elements unavailable for plant uptake. The negative Ca loading effect, which is positively associated with high pH, showed a negative association with TC and TN.

PC3 loaded negatively for P while PC4 loaded positively for EC. A pictorial presentation on how the variables load is shown in Figure 4.3.

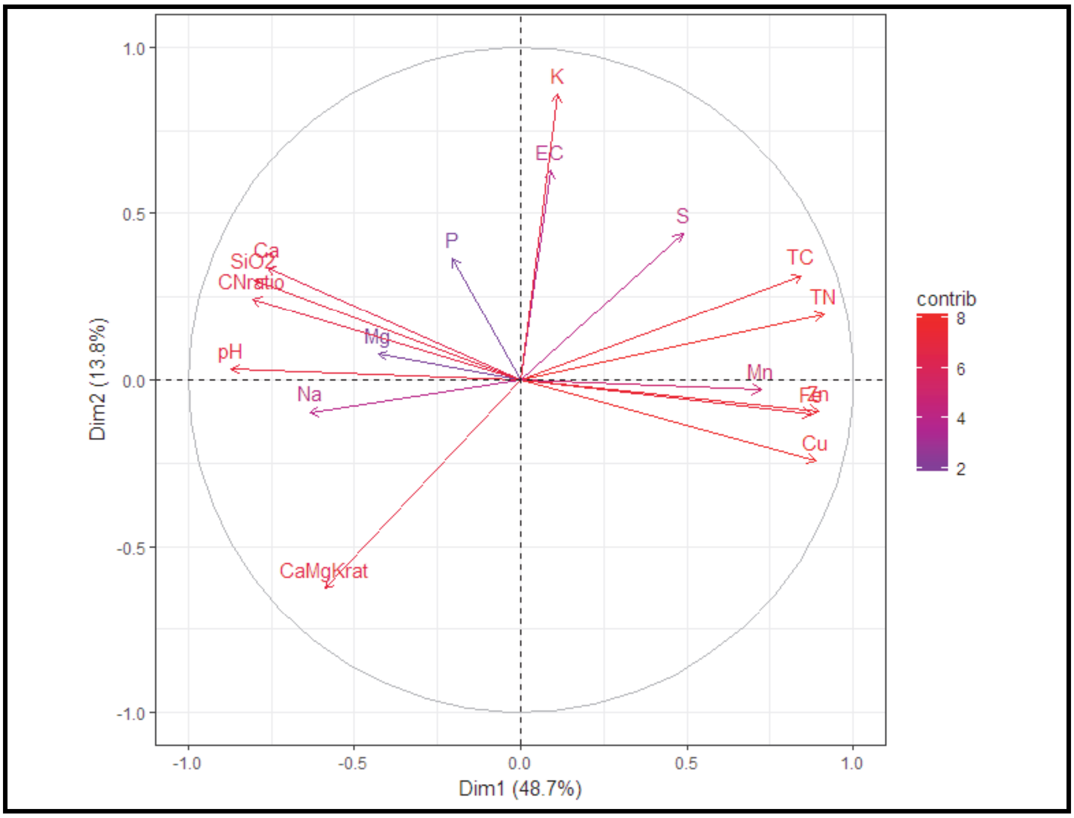

Figure 4. 3: Variable Loading on PCs for Ahero irrigation scheme.

In West Kano, five components (PC1 to PC5) with eigen values above 1 accounted for about 81 % of total variance were produced (Table 4.5). PC1 loaded highly and positively for Fe and negatively for Ca while PC2 loaded highly for K and is therefore the ‘potassium factor’. PC3 indicated high loading for P_2O_5, Mg and TC and can therefore be referred to as the ‘phosphorus factor’ while PC5 loaded highly for EC and thus the ‘salinity factor’.

Table 4.5: Factor loadings, eigen values and cumulative contribution ratio in West Kano

Variables	PC1	PC2	PC3	PC4	PC5
pH	-0.580	0.442	-0.415	-0.174	-0.242
EC	-0.008	0.538	-0.025	-0.591	0.441
TC	0.565	0.403	0.556	-0.051	-0.204
TN	0.666	0.294	0.434	-0.038	-0.135
C/N	-0.269	0.520	0.473	-0.110	-0.310
Avail. P_2O_5	0.390	0.536	-0.647	0.197	0.142
Ex. K	0.450	0.674	-0.263	0.472	-0.054
Ex. Na	-0.480	0.392	0.274	0.284	0.402
Ex. Mg	-0.406	-0.023	0.527	0.703	-0.007
Ex. Ca	-0.802	0.332	0.314	0.234	-0.054
Ex. Ca+Mg/K ratio	-0.748	-0.376	0.219	-0.102	0.111
Avail. Zn	0.667	0.391	-0.209	0.398	0.256
Avail. Cu	0.605	-0.330	0.530	0.148	0.091
Avail. Fe	0.808	-0.193	0.376	-0.054	0.030
Avail. Mn	0.455	0.393	0.224	-0.454	-0.199
Avail. SiO_2	-0.562	0.638	0.095	-0.003	-0.284
Avail. S	-0.248	0.387	0.479	-0.230	0.541
Eigen-value	5.17	3.16	2.63	1.74	1.10
Cumulative contribution (%)	30.4	49.0	64.5	74.7	81.2

A pictorial presentation on how the variables load on the first two components for West Kano irrigation scheme is shown in Figure 4.4.

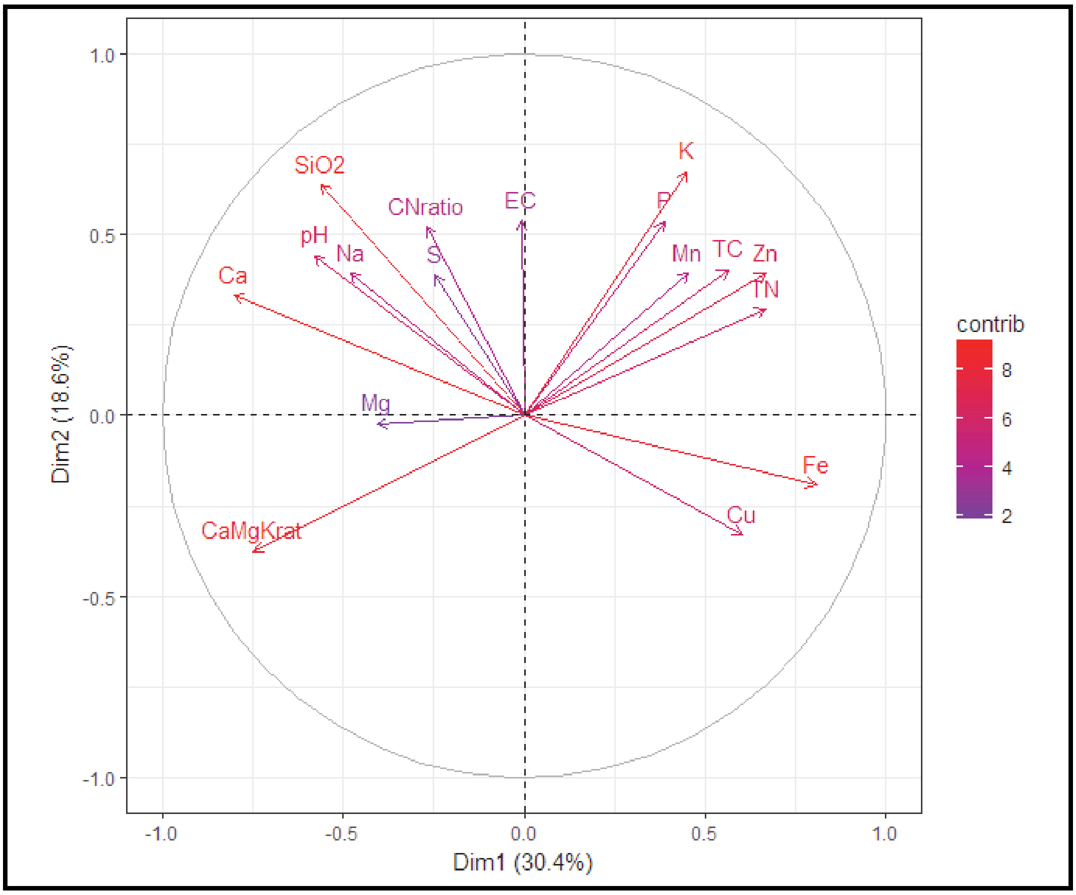

Figure 4. 4: Variable loading on PCs for West Kano scheme

4.4. Conclusions and Recommendations

The two irrigation schemes in Western Kenya seem to be having higher fertility than Mwea in central Kenya with no major constraints thus can be a great potential entry point to enhance rice production in Kenya. However due to problems associated with supply of irrigation water, rice production in the schemes lags behind a great deal. Moreover, the proximity to the Lake Victoria gives farmers an alternative of engaging in fishing rather than farming therefore options of introducing fish-rice cultures could help improve on their incomes while combating food insecurity.

4.5. References

Abe SS, Buri MM, Issaka RN, Kiepe P, Wakatsuki T, 2010. Soil fertility potential for rice production in West African lowlands *Japanese Agricultural Research Quarterly* 44, 343–355.

Afullo OA, 2009. Irrigation Suitability Assessment of Effluents from West Kano Rice Irrigation Scheme, Kisumu, Kenya, *Ethiopian Journal of Environmental Studies and Management,* 2(2).

Balasubramanian V, Sie M, Hijmans RJ, Otsuka K, 2007. Increasing rice production in Sub-Saharan Africa: Challenges and Opportunities *Advances in Agronomy,* 94, 55–133.

Brady NC, Weil RR, 2014. The Nature and Properties of Soils, 14th Edition, Pearson Education Limited.

Buri MM, Ishida F, Kubota D, Masunaga T, Wakatsuki T, 1999. Soils of flood plains of West Africa: General fertility status *Soil Science and Plant Nutrition,* 45, 37–50.

Cheserek GJ, Kipkorir EC, Webi POW, Daudi F, Kiptoo KKG, Mugalavai EM, Kiplagat LK, Songok CK, 2012. Assessment of Farmers Challenges with Rice Productivity in Selected Irrigation Schemes in Western Kenya, *International Journal of Current Research* 4(8), 025-033.

Desplanques V, Cary L, Mouret JC, Trolard F, Bourrié G, Grauby O, Meunier JD, 2006. Silicon transfers in a rice field in Camargue (France). *Journal of Geochemical Exploration*, 88, 190-193.

Dobermann A, Fairhurst T, 2000. *Rice Nutrient Disorders and Nutrient Management*, International Rice Research Institute.

FAOSTAT Database, 2017. Available at www.fao.org/faostat/en/#data/

JICA, 1998. Feasibility Study on the Mwea Irrigation Development Project, NIB Kenya. pp 154, T-59, F-45, A-32.

Klotzbücher T, Marxen A, Vetterlein D, Schneiker J, Türke M, Sihn NV, Manh NH, Chien HV, Marquez L, Villareal S, Bustamante JV, Jahn R, 2015. Plant-available silicon in paddy soils as a key factor for sustainable rice production in Southeast Asia *Basic and Applied Ecology*, 16, 665-673.

Kondo M, Toshinari OTA, Wanjogu R, 2001. Physical and chemical properties of Vertisols and soil nutrient management for intensive rice cultivation in the Mwea area in Kenya. *Japanese Journal of Tropical Agriculture,* 45, 126-132.

Mamo T, Haque I, Kamara CS, 1988. Phosphorus status of some Ethiopian highland Vertisols, In *Management of vertisols in Sub-Saharan Africa, Proceedings of a conference held at ILCA*, Addis Ababa, Ethiopia pp: 232-252.

Marxen A, Klotzbücher T, Jahn R, Kaiser K, Nguyen VS, Schmidt A, Schädler M, Vetterlein D, 2016. Interaction between silicon cycling and straw decomposition in a silicon deficient rice production system *Plant and Soil*, 398, 153-163.

Ministry of Agriculture (MoA), 2009. Government of Kenya *National Rice Development Strategy* (2008-2018).

Omondi SO, Shikuku KM, 2013. An Analysis of Technical Efficiency of Rice Farmers in Ahero Irrigation Scheme, Kenya. *Journal of Economics and Sustainable Development,* 4(10), 9-16.

Omondi SO, 2014. Economic Valuation of Irrigation water in Ahero Irrigation Scheme in Nyando District, Kenya Unpublished MSc Thesis, University of Nairobi.

Onjala J, 2001. Water Pricing Options in Kenya: Cases of Mwea and West Kano Irrigation Schemes. CDR Working Papers.

van Engelen VWP, 1987. Soil conditions in the South-Western Kano Plains (Kisumu District), Kenya Soil Survey, Site Evaluation Report No. P82.

CHAPTER 5

Summary in English

The demand for rice continues to increase owing to continued population growth and it is predicted that a 50-60% increase in rice production will be required to meet the demand from this growth by 2025. In the face of this and with the pressure on available land for cultivation, the increases in rice yields are likely to occur through enhancement of crop production systems.

Successful management of crop production systems requires analysis and design of practices that enhance yield by ensuring that growth limiting factors are minimized or completely eliminated. High availability and efficient utilization of soil nutrients are major determinants of healthy plant growth and realization of optimum yield returns. Thus an assessment of nutrient availability, uptake and utilization by plants is vital for optimized crop productivity.

In Kenya, rice production has stagnated while consumption has greatly escalated in the recent past. About 74% of the rice produced is from government established irrigation schemes namely; Mwea, Ahero, Bunyala and West Kano. In these irrigation schemes however, soil chemical and physical degradation among other factors has led to low productivity. The variability in soil properties in the rice growing irrigation schemes has not been exploited for appropriate targeting of soil fertility investment programs. The hypothesis is that there exists high variability in soil properties which requires fertility based soil management strategy for realization of enhanced productivity.

Three irrigation schemes namely Mwea (Central), Ahero and West Kano (Western Kenya) were identified for this study from where surface 0-15 cm soil samples were collected and prepared for laboratory analysis using standard set procedures. Rice plant samples (straw with rachis branch and grain) were collected at harvest from selected paddy fields in Mwea irrigation scheme and analyzed for total for nutrient. The results obtained for soil and plant were evaluated by comparing with nutrient management guidelines for rice issued by IRRI (2000).

Results showed that soil pH ranged from 6.2 to 8.0 and 5.4 to 7.5 in Ahero and West Kano irrigation schemes respectively, while in Mwea, values from 4.5 to 7.7 were recorded. As per the ratings by the Kenya soil survey, the soil pH was moderately high on average which is attributed to the basaltic parent material and the dry climate which favor the formation of Vertisols that largely cover the sites. In terms of soil salt concentration, the surface soils in all the three schemes are regarded as non-saline as low EC values (< 0.4 dS/m) were observed.

Soil total carbon was moderately high on average across the three sites as farmers usually do apply organic matter in their paddy fields especially in Mwea. Furthermore, although rice straw is removed from the fields at harvest, stubble remained and manure from animal was applied. In Ahero and West Kano, straw and stubble was rarely removed from the paddy fields. Soil total nitrogen contents were averagely low despite widespread use of nitrogen fertilizers probably because of inappropriate N-fertilizer management that leads to N losses.

Exchangeable Ca^{2+}dominated the cation complex followed by exchangeable Mg^{2+}which was in slightly higher concentration in Mwea as compared to Ahero and West Kano schemes. This relatively high level of exchangeable Ca^{2+} and Mg^{2+} is due to the basaltic parent materials. Exchangeable K^+ occurred in higher concentration in Ahero and West Kano compared to exchangeable Na^+. Exchangeable Ca^{2+}, Mg^{2+}, K^+ and Na^+ contents exceeded the deficiency criteria for rice in Ahero and West Kano schemes while 13% of the fields in Mwea showed deficiency in exchangeable K^+(<0.2 $cmol_c$/kg). In Mwea, disproportionate cation distribution with the Ca+Mg/K ratio higher than 100 in about 83% fields indicate high K deficiency risk; thus efforts to enhance soil K availability should be embraced. In Ahero and West Kano, there were no cases of disproportionate cation distribution.

The contents of available P_2O_5 was generally high above the critical deficiency criteria of IRRI with only 1% of the sampled fields in Mwea showing levels below the deficiency limit. The high levels of soil P_2O_5 observed could be because of the soil pH close to neutral and with continuous P fertilization. Soil available SiO_2 was high and exceeded the deficiency criteria for rice in all sites, although Ahero and West Kano values were higher than Mwea perhaps because of high siltation and straw retention. Mean soil available S was above the deficiency level for rice across all sites which could be because of fertilizer widely used in rice production.

Among the soil available micronutrients, soil Fe dominated in Mwea and West Kano while soil Mn dominated in Ahero and Zn was less than 2.0 mg/kg deficiency level, on average in Mwea therefore application of Zn fertilizer should be exploited.

Results of plant nutrient content from Mwea scheme indicated that on average, total Ca contents in straw was high (>0.30%) in Tebere, Wamumu and Karaba and below the deficiency level of 0.30% in Thiba and Mwea units which had slightly lower soil Ca content. In addition, high soil Fe could have contributed to the low Ca accumulation in the straw as they associated negatively. Straw total K was also below the deficiency level in the same two units, which was probably due to high soil (Ca+Mg)/K ratio in the two units. Straw total Mg, Cu, Fe, Mn, P_2O_5 and Zn exceeded the deficiency level on average while Mwea unit showed deficiency in straw total S. Soil and straw nutrient concentrations were positively correlated for most nutrients since the concentration of a particular nutrient in the plant is generally greater when the concentration in the soil is high except for straw total Zn that was high despite the soil concentration being below the critical deficiency level.

Grain samples on the other hand showed deficiency in total Ca, Fe, K, Mg and S in all units while grain total Cu, Mn, P_2O_5 and Zn exceeded deficiency limit. The deficiency in grain total Ca, Fe, K, Mg and S could be attributed to their low transfer coefficients from straw to grain. Furthermore, for the case of Fe, it is known that rice as a plant is inefficient at transporting Fe to grain. Ca is said to be immobile in the phloem and since the seed is mainly fed by the phloem, Ca loading into the seed is hampered.

Soil nutrient concentrations affected nutrient accumulation in the straw and grain at various levels thus there is need to apply nutrient at appropriate timing to ensure maximum use-efficiencies. Furthermore, proper soil fertility management practices should be considered to avoid depletion or excessive accumulation of nutrients for improved quality and quantity of rice yields.

Summary in Japanese

良好な作物生産体系管理には、生育制限要因を縮小・解消させ収量を増加させる農法の解析とデザインが必要である。土壌養分の高い可給性と利用効率は、健全な植物生育と適正収量を実現するための主な決定要因である。したがって、養分の可給性や植物の養分吸収・利用を評価する事は、作物の生産性を最適化する上で不可欠である。

ケニアでは、近年の米消費量の急増に対して、米生産量の増加は停滞している。米の約 74%は、ケニア政府が設立した灌漑地区（Mwea、Ahero、Bunyala、West Kano）で生産されている。しかし、これらの灌漑地区では、複数の要因で土壌の化学性・物理性が劣化し、米生産量を低下さている。灌漑地区における土壌肥沃度改善のために必要な要因解析の土壌特性の変動は十分に調査されていない。土壌特性の変動は大きく、生産性の向上を実現するには肥沃度調査に基づく土壌管理戦略が必要であると考えている。

本研究では、灌漑地区［Mwea（ケニア中央部）、Ahero・West Kano（ケニア西部）］圃場の表層 0〜15cm の土壌サンプルを採取し、標準法に基づいて土壌分析を行った。Mwea 灌漑地区のいくつかの水田から収穫期に稲の茎葉部と籾部を採取し、植物体中の養分含量を測定した。土壌・植物の分析結果を IRRI(2000)の発行する米生産のための養分管理のガイドラインと比較することで評価した。

結果は、Ahero および West Kano の土壌 pH は、それぞれ 6.2-8.0、5.4-7.5 の範囲であったのに対して、Mwea では 4.5- 7.7 であった。ケニアの土壌調査基準によると、土壌 pH は、強酸性（Mwea、West Kano）あるいは弱酸性（Ahero）から弱アルカリ性の範囲であった。3 地区の土壌 pH は、平均的には中程度に高く、これは、これらの地区に広く分布する Vertisols が生成しやすい玄武岩質の母材と乾燥気候に起因する。土壌塩類濃度に関して、3 地区すべての表土は非塩性の低 EC（<0.4 dS / m）であり、稲に塩害を与える危険性はないことが示された。

土壌全炭素は、3 地区において中程度に高い値であった。現地農家は、特に Mwea では、水田に有機物を施用している。収穫期に稲わらが持ち出されていたが、切り株は残され、きゅう肥が施用されていた。Ahero と West Kano では、水田から稲わらと切り株はほとんど取り除かれていなかった。土壌全窒素は、窒素施肥が広く行

われていたにもかかわらず平均して低かった。窒素損失につながる不適切な窒素施肥管理が、低窒素含量の理由と考えられた。

全ての灌漑地区において、交換性 Ca が主要な陽イオンであり、交換性 Mg がそれに次いで高かった。交換性 Mg は、Ahero および West Kano と比較して Mwea でわずかに高い濃度であった。この比較的高濃度の交換性 Ca・Mg は、玄武岩質母材に起因する。一方、Ahero および West Kano において、交換性 K 濃度は交換性 Na と比較して高かった。Ahero と West Kano の交換性 Ca・Mg・K・Na 含量が稲作における基準値を満たしたのに対し、Mwea の 13％の圃場は欠乏レベルの非常に低い交換性 K 含量(<0.2 $cmol_c$/kg)であった。Mwea では、約 83％の圃場で(Ca + Mg)/ K が 100 を超える不均衡な陽イオン分布を示し、K 欠乏リスクを示唆した。このことから、Mwea では土壌 K の可給性を向上する取り組みが必要である。Ahero・West Kano では、陽イオンのバランスに問題はなかった。

土壌中の可給性 P_2O_5 の含量は概して高く、IRRI の基準を満たし、Mwea 圃場でわずか 1%が基準値以下であった。高濃度の可給性 P_2O_5 は、中性に近い土壌 pH と継続的な P 施肥に起因すると考えられる。可給性 SiO_2 は高く、おそらく中性に近い土壌 pH のためであり、すべての地区で基準値を満たしていた。しかし、Ahero・West Kano では、Mwea と比較して、可給性 SiO_2 が非常に高く、豊富なシルト堆積物と水田への茎葉部の還元が考えられた。全ての地区で可給性 S の平均濃度は基準値を満たしており、稲作に広く用いられる硫酸アンモニウム肥料のためと考えられた。

土壌の可給性微量要素は、MweaとWest KanoでFeが多く、AheroでMnが多かった。ZnはMweaでは平均値が欠乏レベルの2.0 mg/kg未満であったが、Ahero・West Kanoでは十分に高い水準であった。したがって、Mweaにおいては、Zn施肥が土壌肥沃度改善の適切な選択肢となると考えられた。

Mwea灌漑地区の植物体元素分析の結果から、Tebere・Wamumu・Karaba区では、茎葉部Ca含量が高く（>0.30％）、土壌Caがわずかに低いThiba・Mwea区では基準値である0.30％を下回った。さらに、濃度分布がCaと反対の傾向を示す土壌Fe含量の高さが茎葉部Caを低下させた可能性がある。Mwea・Thiba区において茎葉部Kが基準値以下であった。これはおそらく高い土壌(Ca+Mg)/K比のためである。茎葉部Mg・Cu・Fe・Mn・P_2O_5・Zn含量は基準値を満たしたが、Mwea区では茎葉部Sが欠乏水準であった。

土壌の養分濃度は、茎葉部や籾部の養分の蓄積にさまざまなレベルで影響を及ぼす。そのため、適切な時期に施肥を行い施肥効率を最大限にすることが求められる。さらに、養分欠乏や過剰な蓄積を避け、米の質と収量を向上させるために、適切な栽培管理作業を検討する必要がある。

List of Publications

Kundu C. A., Ishii M., Sato K., Masunaga T., Wanjogu R. K., Njagi R. E., Yamauchi A. and Makihara D. (2016). Evaluation of Soil Chemical Properties under Paddy Production System in Central Kenya: Soil Exchangeable Cations, *Journal of Agricultural Science* 8 (8): 136-148. (**Chapter 2**).

Kundu C. A., Ishii M., Sato K., Wanjogu R. K., Makihara D., Yamauchi A., and Masunaga T. (2017). An Assessment of Paddy Production System in Central Kenya with Special Reference to Micronutrients, *Journal of Agricultural Science* 9 (6): 49-63. (**Chapter 2**)

APPENDICES

Appendix 1

Soil chemical properties of Mwea irrigation scheme

			Total (g/kg)			Available (mg/kg)			Exchangeable cations ($cmol_c/kg$)					Available micronutrients (mg/kg)			
Unit	pH	EC (dS/m)	C	N	C/N ratio	P_2O_5	S	SiO_2	Ca^{2+}	Mg^{2+}	Na^+	K^+	Ca+Mg/K ratio	Fe	Mn	Cu	Zn
Mwea	5.1	0.21	20.3	1.2	17.1	20.3	32.5	108.4	26.7	23.4	0.4	0.2	263.4	326.9	430.6	1.3	1.4
Mwea	6.3	0.45	12.6	0.7	19.4	14.7	63.1	309.2	31.3	25.6	0.6	0.2	334.9	381	849.2	1.5	0.6
Mwea	6.0	0.42	17.3	0.9	18.4	26.6	65.3	330.6	27.1	25.2	0.9	0.2	256.1	48.8	93.3	0.9	1.6
Mwea	7.3	0.56	12.1	0.7	18.2	26.6	37.1	380.9	33.5	27	4.1	0.2	356.8	55.4	55.9	1.6	0.9
Mwea	6.1	0.54	17.5	1.0	17.5	21.2	66.7	302	37.5	23.6	2.6	0.2	395.2	29.8	66.7	1.7	1.3
Mwea	5.0	0.24	34.1	3.2	10.6	216.6	29.6	150.4	8.8	5.8	0.3	0.3	46.4	935.7	120.7	1.9	4.1
Mwea	4.9	0.24	21.2	1.3	16.6	28.3	55.5	194.8	20.3	18.8	0.3	0.2	211.7	339	333.9	1.4	1.6
Mwea	7.6	1.09	12.3	0.6	19.7	202.7	84.2	320.1	35.1	19.5	4.3	0.2	297.8	20.6	37.5	0.8	1.2
Mwea	5.3	0.5	21.8	1.4	16.1	58.1	95.4	194.8	18.9	15.8	0.5	0.2	203.7	748.7	420.6	2	1.5
Mwea	7.0	0.51	15.4	1.0	15.5	41.9	26.1	608.1	20.1	14.4	1.1	0.2	217.6	82.5	154.8	2.5	1.1
Mwea	5.2	0.36	17.4	1.0	18	45.5	50.6	192.9	26.1	25.6	0.9	0.6	84.4	193.4	309.9	0.9	1.7
Mwea	6.5	0.57	22.9	1.6	14.5	21.1	58	318.9	33.2	22.7	2.8	0.2	269.5	31.6	101.1	2.4	2.1
Mwea	5.3	0.47	27.5	2.0	13.5	35.8	69.8	399.9	25.9	17.6	1.2	0.4	123	1047.3	211.7	5.5	2.3
Mwea	6.7	0.44	12	0.6	19.1	47.3	39.1	397.3	37.7	22.7	3.5	0.2	397.3	25	70.5	1.1	1.3
Mwea	5.7	0.33	16.5	1.0	16.8	108.5	51.1	204.9	33.1	25.5	1.1	0.2	282	90.8	68.2	1.9	1.3
Mwea	6.5	0.89	12.9	0.7	18.5	20.8	90.4	368.3	43.6	27.5	5	0.2	385.7	24.2	68.9	1.5	1.3
Mwea	6.1	0.27	14.6	0.9	16.5	27.6	25.1	317.9	37.1	27.2	2.1	0.2	309.4	98	75.3	2.3	1.3
Mwea	5.4	0.32	19.2	1.1	16.9	38.4	8.1	221.2	27.4	22.7	1.8	0.2	267.1	313.4	131.7	2.8	0.6
Mwea	6.9	0.51	16.7	1.0	16.3	55.8	38	520.2	41.2	21.8	3.2	0.2	315	40.8	90	1.3	1.4
Mwea	8.1	1.12	16.8	1.0	17.6	50.1	54.9	728.5	37.8	23.9	3.7	0.2	378.8	3.8	103.2	0.8	1.2

Mwea	5.1	0.26	35.5	3.2	11.2	417.4	43.1	162.5	8.7	5	0.3	0.2	57.7	1360.6	250.5	4.1	8
Mwea	6.8	0.38	11.5	0.6	18.6	56.9	35.6	381.2	47	28.4	2.8	0.2	372.2	26.8	82.9	1.1	1.2
Mwea	6.5	0.36	13.7	0.7	20.8	26.4	44.1	372.3	26.7	27.1	1.3	0.2	260.9	25.2	72.4	0.8	1.4
Mwea	5.2	0.22	18.6	1.3	14.8	98.1	30.2	173.7	31.1	20.9	1	0.2	261	177.5	128.6	2.6	2.1
Mwea	6.5	0.28	14.1	0.7	20.8	17.1	26.5	328.5	36.6	36.9	1.1	0.2	377.1	5.2	263.9	0.1	0.9
Mwea	5.5	0.38	17.9	1.0	18.4	41.8	73.7	226.7	30.1	27.8	1.1	0.2	283.7	87.5	176.7	2.7	1.3
Mwea	6.9	0.33	12.5	0.6	21.2	16.7	18.1	617.4	31.7	29.2	0.5	0.2	299.8	17.7	514	0.4	0.8
Mwea	5.4	0.23	19.6	1.1	18.2	29.2	31.4	245.5	25.1	21.7	0.4	0.2	239.4	416.6	695.3	1.8	2.4
Mwea	5.0	0.3	25.1	1.5	16.9	37.2	53.8	188.2	29.7	32.3	0.7	0.3	225.8	535.6	355.3	1.3	2
Mwea	6.3	0.32	17.2	0.9	19.6	22	34.4	315	33	34.6	1.2	0.2	292.6	12.6	80.1	0.7	1.3
Mwea	5.7	0.33	19.1	1.0	18.6	29.1	50.8	278.7	30.7	30.5	1.1	0.3	217.3	77.3	135.5	1.2	1.8
Mwea	6.2	0.33	15.3	0.9	16.9	10.7	33	400	31.7	27.1	2.1	0.2	263.4	63.3	79.1	2	1
Mwea	5.0	0.24	22.4	1.5	15.4	30.5	51.9	202.1	25	22.4	1.1	0.2	196.1	556.6	176	3.9	1.3
Mwea	6.5	0.41	15.0	0.7	21.1	15.4	46.8	351.8	35.8	39	1.8	0.3	299.2	19.2	83.2	0.7	1.2
Mwea	5.4	0.39	21.6	1.3	16.7	43.8	70.7	195.8	30.5	32.1	1.2	0.3	201.9	124.2	135.6	1.4	2.2
Mwea	4.9	0.46	31.2	2.5	12.6	50.1	66.8	163.3	17.4	14.6	0.8	0.3	101.8	808.9	474.9	2.2	5.6
Mwea	5.0	0.42	25.8	1.8	14.7	45.1	86.6	209.3	26.6	24.5	0.8	0.2	218.4	376.2	400.7	1.6	1.8
Mwea	6.0	0.22	16.1	0.8	21.2	15.9	21.4	363.2	34	32.4	0.6	0.2	311.1	125.6	520.2	1	1.1
Mwea	6.0	0.28	17.1	1.1	15.9	31.3	31.8	215.4	37.5	24.9	1.6	0.2	310.6	43.7	83.8	1.5	1.2
Mwea	6.5	0.57	14.3	0.7	19.9	88.2	58	268.5	41.8	24.3	3.2	0.2	318.9	36.2	65.8	1.4	1.1
Mwea	4.6	0.58	28.8	2.0	14.6	46.6	156.2	440.1	24.3	20.9	0.7	0.2	190.2	707.4	318.1	2.1	1.5
Mwea	5.6	0.34	18.7	1.0	18.1	24.3	57.3	219.7	29	28.4	1	0.2	295.4	50.6	173.6	0.7	1.2
Mwea	6.8	0.44	15.0	0.7	21.6	10.9	55.3	363	37.4	37.3	1.8	1.3	59.3	8.7	102.7	0.4	1
Mwea	6.5	0.27	13.2	0.6	22.4	15.2	20.6	496.6	37.8	34.7	0.6	0.2	355.4	-5.3	138	-0.1	2.1
Mwea	5.4	0.21	21.1	1.3	16.3	30.5	28.8	213.4	28.5	21.2	1	0.2	266.1	363.2	187.9	3.3	1.4
Mwea	5.8	0.36	19.1	1.1	17.5	90.8	47.6	213.2	40.2	23	2.2	0.2	302.1	133.4	115	2.4	1.7
Mwea	5.7	0.30	17.9	1.1	16.9	36.7	40.5	309.4	37	22.7	2.2	0.2	306.8	74.6	102.2	2	1.6
Mwea	5.3	0.17	20.7	1.1	18	20.4	26.4	175.6	29.7	29.6	0.6	0.2	258.8	115.5	215.4	0.7	0.8
Mwea	6.8	0.6	17.7	1.0	18	58.5	53	547.8	41.8	24.1	3.7	0.2	289.6	41.9	74.1	1.5	1.7
Mwea	5.8	0.24	16.1	0.8	20.8	13.3	33	356.3	29.5	26.4	0.5	0.2	293.1	70.5	388.8	0.9	0.9

Mwea	5.4	0.26	20.3	1.3	15.1	69.2	38.7	205.3	30.5	22.5	0.9	0.2	224.9	170.2	131.4	2.6	1.7
Mwea	6.3	0.12	17.9	1.0	18.4	31.6	52.1	378	42.8	40.3	0.7	0.2	550.3	82.6	171	1.9	0.5
Mwea	6.5	0.11	17.0	0.9	18.7	43.4	33.7	440	51.7	23.9	0.7	0.1	794.1	107	97.8	1.6	0.3
Mwea	5.9	0.14	19.8	1.1	17.5	18.6	62.6	379	33.4	36.4	1.4	0.1	920.8	97	104	0.6	0.3
Mwea	6.5	0.10	16.4	0.8	20.5	19.8	42.5	363	31.5	30.2	0.7	0.1	828.2	61.8	150	0.8	0.3
Mwea	5.6	0.08	19.8	1.1	18.2	30.3	52.5	301	26.8	21.4	0.4	0.1	681.8	66	121	0.4	0.2
Mwea	6.3	0.10	20.8	1.4	14.7	109	40.7	418	24.3	18	0.5	0.1	582.6	121	83.2	3.3	0.1
Mwea	6.2	0.11	21.7	1.5	14.5	56	40.7	372	28	22.4	1.2	0.1	450	47.5	1.5	2.8	0.5
Mwea	5.9	0.15	22.5	1.6	13.7	109	70.2	418	23.1	20	0.8	0.1	497.7	174	37.6	1.5	0.2
Mwea	7.1	0.25	19.4	1.0	18.8	36.5	47.9	512	41.9	24.9	3	0.1	796.2	81.7	177	3.8	0.6
Mwea	5.1	0.45	28.3	2.0	14.1	83	39.7	259.4	29.1	22.7	0.4	0.2	219	230.3	334.9	1.4	4.7
Thiba	6.0	0.14	20.4	1.2	17	123	51.5	435	41.7	21.7	0.4	0.1	532.8	94.8	198	1.1	0.3
Thiba	6.5	0.15	16.4	0.9	18.3	96.4	53.8	484	47.6	19.5	0.7	0.1	554.5	69	191	2.6	0.7
Thiba	6.6	0.13	16.2	0.9	19	168	44.6	457	47	19.3	0.5	0.1	498.5	22.1	313	2.3	0.5
Thiba	6.7	0.11	15.6	0.7	21.7	121	29.7	480	51.8	20.1	0.5	0.1	923	43	260	2.6	0.5
Thiba	7.0	0.17	19.3	1.1	17.7	30.6	42.5	512	49.5	38.3	1.7	0.3	299.7	76.3	188	4.2	0.6
Thiba	6.4	0.19	17.3	0.9	18.4	22.8	73.9	423	41.6	33.4	1.1	0.1	590.6	63.4	207	2.5	0.4
Thiba	5.8	0.12	21.6	1.2	18	92.5	49.6	406	45.1	26	0.3	0.3	232.4	112	63.6	0.7	0.1
Thiba	6.2	0.12	15.1	0.9	17.7	29	48.6	410	39.3	37.5	0.7	0.1	768.8	101	136	1.7	0.5
Thiba	5.1	0.44	22.5	1.5	15.1	137	44.5	286.6	33	15.5	0.5	0.1	330.3	593.2	859.2	3.1	3.6
Thiba	5.6	0.42	23.5	1.5	16.1	72.7	43	273.6	37.3	24.1	1.1	0.2	329.1	231.7	307.8	2.6	3.1
Thiba	5.0	0.31	27.3	1.4	18.8	97.4	28.1	252.4	29.9	19.8	0.5	0.3	178.1	457.6	484.9	2.4	3.6
Thiba	4.5	0.4	24	1.5	16.1	56.3	41.2	315.9	30	31.6	0.4	0.2	306.6	538.3	176.8	2.3	3.4
Thiba	4.9	0.6	22	1.3	17.2	108.9	85.1	401.8	36.5	21.4	0.7	0.2	277.6	702	563.4	3.1	4.1
Thiba	5.2	0.53	25.8	1.7	15.1	138.9	53.1	427.6	36.5	16.7	0.6	0.2	220	766.6	759.7	3.2	4
Thiba	5.1	0.59	26.5	1.8	14.9	178.6	56.2	327	34.4	15.2	0.6	0.6	88.4	347.7	365.6	2.7	2.7
Thiba	4.9	0.32	18.8	1.0	18.7	98.4	40.7	812.4	31.3	20.3	0.5	0.5	110.1	795.4	504.3	2.9	2.7
Tebere	5.6	0.94	27.7	2.0	14.1	64.3	97.6	396.5	44.5	24.9	1.2	1.4	49.1	42	114.6	0.2	1.3
Tebere	6.8	1.02	19.2	1.2	16.7	92.9	78	739.6	46.8	24.9	1.4	1.2	60.6	19.3	114.3	0.3	1.4
Tebere	7.1	1.52	25.2	1.7	15	107.3	73.3	702.4	49.9	33.5	2.2	1.0	85	19.2	110.5	0.2	1.3

Tebere	5.5	0.92	21.4	1.2	17.9	38.3	89.3	521.2	40.3	25.9	1.4	1.0	64.6	89.2	69.4	1.6	2.1
Tebere	5.9	0.81	28.6	1.7	16.4	61.5	77.7	613	42.5	26.8	1.2	1.0	69.2	67.7	207.4	0.9	1.3
Tebere	5.6	0.84	29	2.2	13.3	31.4	108.6	333.5	38.2	21.7	1.2	0.9	66.9	164.2	92.2	2.1	2.6
Tebere	4.9	0.91	28.7	2.2	13	63.1	117.3	303.7	27.6	17	0.6	0.7	61.2	398.8	101.3	3.4	2.2
Tebere	6	0.1	17.4	1.1	15.2	45.9	55.9	765	17.7	9.8	0.8	0.3	81.2	117	73.3	2	0.7
Tebere	6.7	0.22	23	1.5	14.9	20.3	101	441	35.5	22.8	2.8	0.2	291.5	87.3	57.2	2.4	0.5
Tebere	6.8	0.14	22.1	1.1	20.2	80.8	67.3	344	38.9	25.9	1.8	0.3	221.2	128	139	3.4	0.7
Tebere	7.4	0.19	24.5	1.4	17.7	233	29.2	507	49.4	31.8	2.3	1.1	73.8	76.3	183	4.2	0.9
Tebere	6.7	0.25	28.2	1.9	15.1	76.8	105	494	44.1	22.9	2.2	1.5	45.6	161	60.6	3.3	0.7
Tebere	7.7	0.22	31.1	2	16	95.3	62.2	718	48.8	39.2	3.3	1.2	73.9	27	28.5	2.8	0.3
Tebere	7.7	0.34	24.5	1.4	17.4	549	129	558	65.6	30.1	2.4	1.2	79.1	60.5	124	4.5	0.6
Tebere	7.1	0.1	27.4	2	13.7	92.8	28.8	290	34.5	20.2	1.3	0.7	75	124	50.8	2.2	0.5
Tebere	6.9	0.17	27.9	1.5	18.4	68	87.4	455	45.6	24	1.4	0.5	142.3	13.9	380	1.1	0.4
Tebere	6.2	0.11	27.6	1.7	16.7	52.6	66.3	338	42.5	29.5	1.0	0.2	328.8	151	47.6	3.2	1.2
Tebere	6.4	0.91	22.1	1.2	17.9	63.3	86	604	42.3	24.7	1.5	0.5	131.8	63.7	250.7	1.5	2.9
Tebere	5.2	0.59	27.3	1.9	14.6	74.3	79.9	352.6	30.5	20	0.6	0.3	157.4	303	164.8	3	3.9
Tebere	5.7	0.47	26.7	2	13.3	57.9	44.7	364.5	15.8	11	0.9	0.2	161.6	565.8	127.7	3.6	2.8
Tebere	6.2	0.82	29.5	2.2	13.4	69.7	69.7	467	38.5	25.7	1.2	0.3	224.6	473.2	205.8	3	3.8
Tebere	4.7	0.56	29.1	2.4	11.9	127	87.4	259.7	12	7.9	0.4	0.4	56.4	2073.5	117.2	7.1	5.9
Tebere	6.2	0.77	32	2.6	12.4	82.5	49.3	482.9	30.4	25.6	1.5	0.5	115.8	719.7	465.2	3.4	5.1
Tebere	5.7	0.62	25.1	1.5	16.4	64.7	72	414.6	46.3	23.1	1.1	0.4	195	93.7	208.1	1.6	3.1
Wamumu	6.7	0.1	14.3	0.9	15.6	30.4	38.9	510	40	28.9	0.7	0.7	100.7	90.8	132	7.9	0.8
Wamumu	6.5	0.12	12.7	0.7	18.2	46.4	50.3	432	45.1	21.7	0.7	0.2	273.8	102	132	5.9	0.6
Wamumu	6.5	0.12	18.7	1	19.6	34.3	56.9	501	47.1	24.4	0.9	0.2	294.2	87	54.6	5.4	0.7
Wamumu	6.2	0.12	15.3	0.7	21	26.7	55.4	408	49.7	30.1	0.8	0.1	670.6	127	104	4.4	0.6
Wamumu	6.9	0.21	19.5	1.1	18.4	68.3	75.8	500	37.2	18.8	1.4	0.2	264.2	43.6	240	2.8	0.4
Wamumu	7.3	0.24	15.3	0.8	19.6	36.9	77.8	553	42.2	26.8	2.6	0.2	434	49.9	226	4.6	0.6
Wamumu	7.5	0.25	18.4	0.9	21.6	54.9	75.1	584	66.4	28.3	1.1	0.3	319.9	41.2	41.4	2.5	0.4
Wamumu	5.4	0.34	17.6	1	17.3	12.4	70.4	208	17.2	8.3	0.5	0.2	145.3	80.9	56.4	9.3	1.7
Wamumu	7.2	0.68	15.1	1	15.9	29.6	65.5	484.8	35.9	13.6	0.8	0.3	182.3	27.2	64.8	4.3	1.5

Wamumu	7.5	0.75	12.3	0.7	17.7	9.3	75.9	783.1	26.9	11.2	1.2	0.3	149.9	18.4	49.8	4	1.1
Wamumu	5.6	0.66	16.1	0.9	17.6	10.5	105.4	267	24.2	11.8	0.8	0.2	177.5	35	97	5.9	1.5
Wamumu	4.9	0.61	22.9	1.4	16.3	36.9	117.4	219.1	29.1	23.3	0.9	0.2	224.1	433	288.1	3.7	2
Wamumu	7.5	0.89	13.1	0.7	18.2	28.5	100.6	672.4	40.6	16.4	1.2	0.3	186.1	26.2	79.6	3.6	1.6
Wamumu	6.6	0.57	13.8	0.7	19.5	24.9	64.6	373.1	32.5	30.3	1.3	0.2	294.9	27	67.7	2.3	1.7
Wamumu	5.3	0.49	17.1	0.9	18.2	20	98.3	210.8	28	19.5	0.9	0.2	246.1	115.9	97.8	6.1	2.3
Wamumu	5.6	0.31	19.4	1.2	16.4	30.8	33	234.8	29.4	20.2	1.0	0.5	104.5	346	425.8	5.3	2.6
Wamumu	5.3	0.69	22.2	1.3	17.3	126	112.3	186.6	33.6	13.4	0.8	0.2	214	135.6	265.5	2.5	1.8
Wamumu	5.8	0.71	21.9	1.3	16.3	88	77.1	365.5	43.9	18.1	1.2	0.3	230.4	142.8	346.4	2.6	2.4
Wamumu	5.9	0.7	18.3	1.2	15.7	52.7	120	344.4	29.6	13.7	0.9	0.4	121.7	171.3	94.9	8.7	2.8
Wamumu	6.4	0.53	13.9	0.7	19.8	13.2	77.3	455.5	37.8	25.4	1.4	0.2	283.5	24.8	71.5	3.5	1.6
Wamumu	6.1	0.51	23.1	1.5	15.6	64	45.8	384	50.3	22.3	1.0	0.3	208.6	86.5	151.3	1.4	1.6
Wamumu	6.4	0.35	15.2	0.7	20.9	15.4	33.4	557.9	35.4	27.1	0.9	0.2	294.8	24.2	169.7	1.7	1.3
Wamumu	6.2	0.35	14.4	0.7	20.8	14.2	42.4	417.9	37.9	30.8	1.0	0.2	327.7	28.8	101.1	2.4	1.9
Wamumu	5	0.38	19.7	1.1	17.8	34.8	81.9	201.9	30.1	22.3	0.9	0.2	221.1	293.2	181	3.7	1.7
Wamumu	7.5	0.67	14.1	0.8	17.5	14	65.5	563.2	32.6	9.4	1.3	0.3	167.5	20.9	60.1	4.9	1.5
Wamumu	6.2	0.52	12.9	0.6	22	15.3	69.7	483	36.8	28.2	1.1	0.2	277.2	20.2	166.3	1.8	1.6
Wamumu	7.9	0.83	12.2	0.7	16.4	12.2	63.5	581.3	35.6	17.4	0.8	0.3	175.3	16.5	64.8	2.9	1.1
Wamumu	5.6	0.47	20.1	1.1	18.7	31.2	72.3	267.8	31.9	31.6	1.0	0.3	246.2	114	92.8	3.6	2.5
Wamumu	5.6	0.48	21.7	1.3	16.7	32.4	43.1	325	31.4	26.1	1.2	0.6	102.9	281.3	413.5	5.2	2.5
Wamumu	5.9	0.51	20.9	1.2	17	69.1	58.5	437.6	44.2	26.8	1.3	0.4	182.1	172.3	84.6	4.1	1.4
Wamumu	5.5	0.52	22.7	1.2	18.5	32.1	68.1	324	43.1	23.8	0.9	0.4	165.8	142.6	69.5	4.2	1.7
Wamumu	5.4	0.48	22	1.2	18	26.1	60.5	454.3	30.1	21.7	0.9	0.6	81.4	192	275.6	5.2	2.6
Wamumu	6.5	0.69	19.2	1.2	16.5	85.4	74.5	465.6	48.3	21.6	1.4	0.3	211.6	131	433.1	3.2	2.5
Wamumu	6	0.84	22	1.3	17.1	292.2	45	609.6	59.8	25.8	1.0	1.0	86.3	27.6	121.3	1	2
Wamumu	7.6	0.7	12.6	0.7	17.5	12.8	67.2	467.8	38.1	18.2	1.1	0.2	230.2	19	48.6	3.2	1.4
Wamumu	6	0.59	21.2	1.3	16.3	19.8	94.8	368.6	27.8	10.3	1.0	0.3	139.5	45.3	55.5	7.2	2.1
Wamumu	6.9	0.82	13.8	0.7	20.6	68.2	110.6	611.6	43.5	17.4	0.8	0.2	266.6	33.7	97	1.5	1.6
Wamumu	5.8	0.66	20.1	1.2	16.2	18.6	124.1	321.3	29.7	13.3	1.1	0.3	151.7	31	49.9	7	1.9
Wamumu	6.5	0.48	14	0.8	18.2	7.9	61.2	391.8	22.7	11.3	1.0	0.3	133.8	16.3	69.6	6	1.1

Wamumu	7.2	0.86	11.2	0.6	19.8	6.3	83.4	697.5	35.1	16.3	1.4	0.2	224.1	18.4	63	4.5	1.2
Wamumu	5.6	0.31	15.8	0.8	18.8	23.9	49.2	288.6	38.7	32.9	1.0	0.2	294.5	74.9	83.1	3.2	2.1
Wamumu	5.9	0.7	18.3	1.1	16.9	18.6	120.7	285.6	33.6	18.1	1.0	0.2	210.4	69.3	50	6.4	2.2
Wamumu	5.7	0.84	22	1.2	17.8	61.5	81.4	425.1	39.4	22.8	0.8	0.2	259.1	197.6	183.8	4.7	2.9
Wamumu	5.9	1.34	24.4	1.6	15.6	73.3	143.4	458	43.1	29.8	1.6	0.3	217.6	225.9	199.7	2	3
Karaba	7.4	0.24	21.6	1.5	14.7	129	43.4	594	64.4	22.3	0.8	0.5	163.9	43.7	52	3.6	0.4
Karaba	6.6	0.16	14.3	0.7	20.8	31	82.3	441	40.7	30.8	1.2	0.3	269.8	84.2	185	6	0.8
Karaba	6.2	0.16	16.5	0.9	18.3	56.2	72.2	431	44.5	21.6	0.7	0.3	219.6	38.7	266	3.2	0.5
Karaba	6.6	0.13	19.3	1.1	18.2	98.9	46.2	522	50.7	20	0.6	0.5	139.2	36.4	271	3.6	0.7
Karaba	7.2	0.21	16.4	0.8	20.5	67.8	70.8	573	58	20.1	1.1	0.1	854.5	44	82.9	3.4	0.5
Karaba	6.8	0.14	14	0.6	24.5	37.9	61.3	475	40	37.8	1.1	0.3	226.2	98.4	147	6.8	0.6
Karaba	6.7	0.25	14.6	0.8	17.7	28.6	135	466	44.8	37.7	1.7	0.4	211.5	79.8	108	6.7	0.7
Karaba	7.5	0.29	18	1.1	17	49.6	52.9	588	69.6	37.6	0.8	0.5	196.7	41.4	44.4	4.3	0.4
Karaba	6.7	0.45	13.5	0.7	20.3	228.3	61.8	413.8	46.3	21.8	0.9	0.4	159.3	42.1	94.8	1.9	1.9
Karaba	6.9	0.61	12.9	0.7	18.6	200.7	74.3	462.9	43.6	19.1	0.9	0.2	344.5	35.7	126.9	2.2	1.8
Karaba	6.2	0.29	14.6	0.8	19.2	46.9	41.5	240.5	38.9	19.5	0.6	0.2	269.5	22.5	129.9	1.9	1.2
Karaba	6.8	0.62	13.4	0.7	18.1	173.4	67.7	493.1	51.1	17.9	0.9	0.2	305.2	25.6	158.3	2	1.3
Karaba	6.7	0.66	13.6	0.7	19.5	78.6	86.8	483.7	43.4	18.4	0.9	0.2	255	34.3	124.5	2	1.8
Karaba	6.6	1.2	22.8	1.5	15.4	74.2	109.8	614.9	55.8	22	1.1	0.5	157	40	67.1	1.6	1.2
Karaba	7.5	0.59	11.4	0.6	20	199.5	55.7	727.2	51.2	16.7	1.2	0.3	265.3	39.3	121.1	1.7	1.9
Karaba	7.2	0.56	9.6	0.5	19.1	34.9	64.4	513.3	47.7	21.3	0.8	0.2	358.9	24	93.2	1.8	1.7
Karaba	6.2	0.38	14.2	0.7	19.8	56.8	55.8	505.1	38.5	18.7	0.6	0.4	159	20.2	129	1.9	1.8
Karaba	6	0.63	21.9	1.5	14.6	65.2	68.1	470.1	45.9	22.2	0.8	0.4	160.7	95.8	98.2	2.8	2.5
Karaba	6.7	0.65	11	0.6	19.7	174.3	80.4	491.3	47	19.3	0.9	0.2	336.1	26.6	125.2	1.7	1.3
Karaba	7.2	0.46	10.8	0.5	22.7	206.5	58.2	607.9	44.8	20.2	0.9	0.5	143	43.7	62.6	1.6	1.8
Karaba	6.7	0.35	12.1	0.6	20.4	272.9	42	497.3	45.1	23.2	0.8	0.5	140.1	49.5	103.4	2.2	2
Karaba	5.9	0.86	23	1.4	16.8	65.4	63.9	613.4	56	34.1	1.1	1.0	91.7	50.5	90.4	1.9	1.7
Karaba	5.5	1.17	21.7	1.2	17.6	19.3	123	392	37.9	35.5	1.3	0.7	105.6	175.9	92.2	4.7	1.7
Karaba	7.4	0.67	12.6	0.6	21.6	81.6	87.5	622.2	48.1	24	1.2	0.3	282.2	32	56.1	1.5	1.5
Karaba	5.5	0.63	23.4	1.5	15.9	29.4	55	445	32.5	35.1	1.3	0.7	95.8	226.8	292.9	5	2

Karaba	6.6	0.36	14	0.7	20.8	161	43.1	457.1	43.9	21.6	0.9	0.2	286.5	34.4	81.5	1.8	1.6
Karaba	6.1	0.41	14.3	0.7	20.1	102	53.6	337.2	42.9	21.1	0.8	0.2	258.5	41.7	117.2	2.4	1.7
Karaba	6.3	0.65	15.1	0.8	18.2	138	81.5	424.1	48.7	21.3	0.9	0.2	291.9	30.8	206.9	2.8	2.2
Karaba	6.3	0.36	14.5	0.7	20.1	248	47.6	483.5	41.9	20.4	0.8	0.5	116.9	52.4	137.5	2.3	1.9
Karaba	6.5	0.27	10.9	0.5	21.8	71.1	39.3	495.7	45.7	23.2	0.8	0.2	339.4	24.8	56.6	1.8	1.6
Karaba	8	0.93	10.6	0.5	20.7	47.3	59.1	608.5	56.7	23.3	1.0	0.2	334.8	0.5	35.7	0.2	0.9
Karaba	7.3	0.6	12	0.6	19.5	148.5	65.4	560.9	47.6	20.1	1.1	0.2	357.3	33.5	106.8	1.8	1.8
Karaba	7.1	0.93	10.3	0.5	20.5	99.1	112.7	761.1	46	22.5	1.0	1.2	59.3	36.5	108.6	1.8	1.7
Karaba	5.9	0.49	19.2	1	18.4	29.9	68.5	273	40.7	21.7	0.9	0.5	124.8	28.7	292.2	3.4	3.7
Karaba	7.3	0.61	13.7	0.7	20	245.4	57.6	567.5	55	18.8	1.1	0.3	279.9	23.7	115.5	1.6	1.7
Karaba	7	0.61	12.8	0.7	18.9	143.8	63.3	577.4	47.7	17.3	1.1	0.3	198.4	39.6	154.2	1.7	1.3
Karaba	6.3	1.22	17.7	0.9	19.3	88.2	168.5	565.9	42.5	21.1	1.0	1.0	62.4	44.4	261.5	3.2	2.6
Karaba	5.3	0.51	20.6	1.2	16.7	67.5	45.4	394.7	42	34.4	0.8	0.5	142.7	91.1	177.7	3.2	2.8
Karaba	5	0.64	25.9	1.6	16.7	78.2	57.4	365.1	40.8	27.9	0.6	0.3	244.9	394.6	143.5	4.3	2.9

Appendix 2

Soil chemical properties of Ahero irrigation scheme

		EC	Total (g/kg)		C/N	Available (mg/kg)			Exchangeable ($cmol_c$/kg)				(Ca+Mg)/K	Available micronutrients (mg/kg)			
Block	pH	(dS/m)	C	N	ratio	P_2O_5	S	SiO_2	Ca^{2+}	Mg^{2+}	Na^+	K^+	ratio	Fe	Mn	Cu	Zn
A	7.3	0.37	14.2	1.1	13.2	79.9	27.8	764.7	36.2	9.5	1.4	1.5	30.9	181.1	212.5	3.8	3.3
A	7.1	0.39	17.2	1.2	14.7	96.4	35.8	918.3	37.4	9.1	1.1	1.4	33.3	124.4	155.5	3.5	3.6
A	6.7	0.37	24.2	1.8	13.2	341.6	33.9	620	30.1	7.7	0.7	1.4	26.4	317.9	344.6	4.8	5.2
A	7.5	0.44	15	1	15.7	162.2	27.2	1042.5	33.6	7.9	1.3	1.6	26.4	101.5	107.8	2.4	3.1
A	6.6	0.57	23.9	1.7	14	124.4	41.9	766.6	33.1	9.3	0.8	1.8	23.5	339.3	473.1	6.9	4.9
A	6.9	0.54	23.2	1.7	13.4	306.8	32.9	797	26.6	7.5	0.6	1.8	19	321.8	612.3	5	4.6
A	6.6	0.65	24.8	1.8	14	345.6	50.1	661.2	27.1	7.5	0.6	1.6	21	335.4	669.9	5.8	5.9
B	6.9	0.56	23	1.7	13.8	407.5	40.1	729	32.3	8.5	0.8	3.4	11.9	239.2	218.8	3.3	4.3
B	6.7	0.38	20	1.5	13.1	208	34.7	728.2	27.8	7.8	0.7	1.6	22.6	340.4	308.5	5.4	4.9
B	7.7	0.41	13.3	0.8	15.7	288.7	27.8	1094.2	35.6	8.9	0.9	1.8	24.2	64.8	72.3	1.4	2.6
D	6.8	0.5	20.6	1.5	13.4	120.3	39.3	837.8	30.8	8.3	1.3	1.4	27.9	265.9	255.1	5.3	4.4
D	7.7	0.56	13.2	0.9	15.4	207.9	31.1	940.2	36.5	9	3.2	1.2	36.9	116.5	77.3	3.6	3.5
D	7	0.45	19.2	1.4	13.8	117.8	32	855.1	32.3	8.6	1.1	1.6	26	261.7	227.1	4.5	4.3
D	6.2	0.63	21.9	1.6	13.9	128.2	59.8	719.3	31.2	8.7	1.2	1.9	21	352.2	336.1	6	4.9
D	6.7	0.53	23.4	1.7	13.5	180.3	43.1	676.7	34.4	8.9	1.5	1.8	24.4	454.2	251.7	6.5	5
D	6.5	0.52	25.5	2.1	12.4	156.5	42.6	624.5	25.2	7.6	0.9	1.4	23.5	518.7	300.3	7.3	4.9
D	6.4	0.56	24.7	1.8	13.5	284.8	37.1	583.5	29.2	8.2	1	2	18.6	476.8	306.5	6.6	5.4
D	6.6	0.5	23.6	1.8	13.1	218	31.6	651	26.7	7.8	0.6	1.6	21.6	561.5	708.8	7.5	5.3
D	6.8	0.58	20.3	1.4	14.3	109.9	42.2	658.7	31.8	8.6	0.7	1.6	24.8	492	743.2	7.7	5.1
D	7.4	0.66	20.9	1.6	13.5	158	38.2	829.7	30	7.9	1.2	1.9	19.5	244.6	586.6	4.4	4
F	6.7	0.62	21.7	1.7	13	162.7	37.9	897.4	32.4	8.6	1.2	2	20.3	438.1	327.9	6.6	4.8
F	6.7	0.76	21.8	1.7	12.5	117.6	60.3	800.8	33.3	9.3	1.1	1.8	23.3	295.4	355.3	6.1	5.3
F	7.4	0.96	23	1.7	13.7	225	40.6	961.6	37	7.4	1.3	2.1	21.2	230.2	379.7	4	4.4
G	6.5	0.44	19.7	1.5	13.2	143.6	31.9	721.3	33.8	8.9	0.8	1.7	25.7	264.6	247.2	5.2	5

G	7.4	0.45	17.8	1.2	14.3	482	28.6	771.2	32.1	8.7	1.3	1.8	23	153.7	169	3.5	4.8
M	6.4	0.5	23	1.9	12.4	241.3	30.6	674.5	28.1	8.2	0.8	1.8	20.5	556.9	340.7	7.4	6.1
M	6.3	0.57	23.9	1.9	12.8	200.9	36.6	689.2	29	8.5	1.1	1.8	20.8	472	264.2	6.9	5.8
M	6.2	0.67	19	1.5	13.1	192.2	57.9	720.2	31.1	8.8	1.1	1.8	22.4	485.2	407	7.2	5.8
L	6.9	0.41	18.2	1.3	13.7	219	33.3	739.9	27.9	8.1	1	1.9	18.8	384.5	173.9	5.8	4.5
L	6.5	0.5	21.5	1.7	13	211.7	44.8	640.8	25.7	7.8	0.9	1.5	22.1	333.3	167.6	6.1	4.5
L	6.9	0.43	17.7	1.3	13.2	164.6	31.1	660.4	28	8.1	1.6	1.1	32.1	232.8	170.8	5.8	4.6
N	6.4	0.63	22.2	1.8	12	174.6	41	655.5	29.5	9.1	1.1	1.9	20.1	714	575	9	6.2
N	6.5	0.65	21.8	1.8	12.4	166.5	46.4	727.4	29.5	8.6	1	1.5	25.9	436.7	384	6.9	5.1
N	6.9	0.43	15.2	1.2	12.7	201.5	24.9	649.6	29	8.9	1	1.6	24	278.5	411.7	4.7	4.2
O	7	0.51	17.3	1.3	13.2	153.8	33.7	910	30.5	8.8	1.1	1.5	26.9	247.7	276.2	5.4	4.4
O	6.7	0.46	19.9	1.6	12.8	184.3	29.6	603.3	25	7.6	0.8	1.2	27.3	480.3	701.7	7.9	5.9
O	6.7	0.59	21.3	1.7	12.8	164.7	40.6	641.8	27.6	8.7	0.8	1.5	24.4	761.1	662.6	9.9	6.1
K	8	0.93	10.9	0.7	16.4	469.8	30.9	1002.7	40.8	9.4	1.9	1.5	34.1	19.5	63.6	0.6	2.3
K	7.1	0.3	15	1.2	12.7	277.2	24.1	640.7	28.5	8.3	1.2	1.1	34.6	242.9	150.3	5.6	5.1
K	6.5	0.64	24.9	1.9	13.2	150.5	44.1	662	28	8.4	1	1.4	26.9	799.8	813.6	9.1	5.6
K	6.5	0.59	22.7	1.8	12.4	226.6	43.3	620	26.6	8	0.9	1.8	18.7	697.7	625.9	8.3	5.8
K	6.9	0.56	19.9	1.6	12.8	241.3	37.2	564.7	20.9	6.4	0.9	1.4	19.3	507.3	798.3	6.8	5.5

Appendix 3

Soil chemical properties of West Kano irrigation scheme

Block	pH	EC (dS/m)	Total (g/kg)		C/N ratio	Available (mg/kg)			Exchangeable ($cmol_c$/kg)				(Ca+Mg)/K ratio	Available micronutrients (mg/kg)			
			C	N		P_2O_5	S	SiO_2	Ca^{2+}	Mg^{2+}	Na^+	K^+		Fe	Mn	Cu	Zn
A	6	0.49	21.5	1.6	13.2	118.5	42.8	489.4	29.1	9.7	1.6	1.6	24.2	233.8	124.6	5.1	5
A	6.5	0.32	16.8	1.4	11.7	107.3	28.2	566.1	32.3	10.1	1.4	1.1	39.6	106.8	78.5	4.2	4
A	6.5	0.5	16.1	1.3	12.3	130.7	34.9	578	31.9	10.1	2.2	1.4	31	119.8	110.7	3.5	4.1
A	6.6	0.3	18.5	1.6	11.8	135.1	25.8	543.2	35.1	10.9	1.4	1.5	29.8	141.4	87.5	3.9	3.9
B	6.4	0.48	21.9	1.7	13	229.9	28.7	738.7	28.6	9.9	1.3	2.2	17.4	304.8	175.3	6.9	5.1
B	6.1	0.54	25.5	1.9	13.2	171.3	39.4	567.7	34.2	11.4	1.7	2.3	19.5	336.5	133.4	6.5	5
B	6.7	0.5	23.7	1.9	12.3	461.6	26.3	632.7	23.5	7.1	0.9	2.7	11.1	251	172.5	3.6	5
B	6	0.53	21.6	1.6	13.6	324.7	31.2	570.9	23.9	8.4	1.2	2.7	11.8	338.9	185.9	5.7	5.6
C	6.9	0.41	16.8	1.3	12.9	173.8	27.9	567.5	26.2	8	1	1	35.2	212.1	176.6	5.1	3.8
C	6.8	0.41	14.6	1.1	13.3	173.5	39.3	567	29.8	9.6	1.4	1.2	32.1	255.9	158.6	5.5	4.1
C	6.8	0.41	22.7	1.8	12.3	242.1	24.3	587.7	26.9	8.8	1.3	2	17.5	297	181.7	5.1	4.2
C	6.3	0.33	21.6	1.7	12.4	113.1	30.1	492.7	29.2	9	1	1.4	28	216.8	105.7	4.1	4
C	6.3	0.4	17.8	1.5	11.7	224.6	31.5	472.5	28.7	9.6	1.2	1.7	22.6	252.5	114.5	5.7	5
C	7	0.57	19.2	1.6	12.2	2701.3	30.2	606.5	24.4	8.1	1.6	4.9	6.7	220.7	245.9	3.2	13.2
C	6.7	0.43	19	1.5	12.3	465.5	24.3	496.9	22.7	7.1	0.9	2.3	12.7	274.9	246.1	4.2	4.8
C	6.6	0.33	15.5	1.2	12.6	247.4	22.4	290.8	17.6	5.7	0.9	0.9	25.9	408.8	153.4	4.3	3.8
C	6.7	0.45	15.9	1.2	13.3	303.7	27.2	706.9	37.3	10.4	1.9	2.2	21.8	126.5	84.1	2.6	3.5
C	6.4	0.46	18.2	1.4	13.2	191.2	39.6	788.2	30.7	10.2	1.4	1.6	25	509.3	158.6	7.4	4.5
C	6.5	0.46	20.2	1.6	12.6	439.6	29.4	482.4	24.2	8.4	1	1.6	20.4	413.5	330.5	6	4.8
C	6.2	0.42	24.6	2	12.4	430.6	25.4	460.5	20.9	6.8	0.7	2	13.6	381.5	210.7	5.5	5.3
C	5.8	0.57	23.9	1.7	13.8	147.8	42.7	504.9	25.5	8.7	1.1	1.7	20.4	405.9	258.4	6.8	5.2
D	6.5	0.59	20.4	1.7	11.7	1158.7	34	475.3	13.3	4.4	0.5	1.9	9.1	459.9	228.3	5.4	6
D	6.5	0.63	20.3	1.5	13.4	387.9	40.4	481.2	23.6	7.2	1.8	1.7	18.1	321.4	286.4	4.9	5
D	6.3	0.33	23	1.8	12.7	220.7	25.4	367.7	23.8	7.6	1.2	1.3	23.6	356.2	240.4	6	5.2

D	5.4	0.99	19.5	1.7	11.2	270	25.7	199.3	18.4	6.3	0.8	1.3	19.3	366.9	216.2	4.7	4.7
D	6.1	0.42	23.9	1.9	12.5	154.9	28.7	482.1	29.1	9.6	1.7	2	19.7	415.8	211.9	6.5	5.1
D	6.7	0.44	19.5	1.6	12.3	1212.9	20.6	619.7	23.7	7	1	3	10.4	321.5	224.5	4.3	5.1
D	6.8	0.35	18.9	1.5	12.7	322.1	22.4	436.1	27.3	7.9	1.4	1.5	22.9	216.1	201.3	3.7	4.4
D	6.5	0.63	20.4	1.7	12.2	400.9	26.5	505.6	24	7.2	1.4	2	15.4	297.2	212.4	4.1	4.3
D	6.6	0.43	20.3	1.6	12.5	235.2	26.3	574.3	25.8	7.9	1.2	1.4	24.5	296.6	247.9	6.3	5.2
E	5.9	0.53	38.5	2.9	13.1	350	30.7	504.9	23.7	8.3	1.2	3	10.7	826.9	257.5	6.2	7.4
E	6.1	0.48	25.6	2.1	12.2	201.4	27	512.7	20.6	7.4	1.3	1.6	17.4	460.3	141	5.7	5.2
F	6.8	0.61	21.2	1.6	13.3	496.5	34	766.3	28	6.7	0.8	2.3	15.4	98.2	223.8	1.6	3.2
F	7.5	1.07	21.6	1.8	12.2	486	42.2	727.6	33.4	5.6	1.7	1.3	29.1	78	203	1.7	3.6
F	6.6	0.42	19.5	1.4	14.2	218.4	28.8	877.9	34.4	9.5	0.7	1.7	25.4	154	278.5	3.4	3.8
F	6.6	0.59	34.5	2.4	14.1	210.9	35.6	684.2	38	10.8	1.8	2.4	20.1	264.9	383	5.1	5
G	7.3	0.92	20.6	1.5	13.9	349.8	41	967.5	40.6	7.1	1.9	1.6	29.2	41.6	275.5	2	3.4
G	7.5	0.62	22.4	1.6	14.3	406.7	32.2	825.3	33.3	8.3	1.6	1.6	26.6	107.8	359.3	2.8	3.7
G	7.1	0.58	19	1.4	13.5	191.9	36	758.3	31.7	7.7	1.7	1.6	24.3	82.7	131.1	2.5	3.4
H	6.5	0.46	15.9	1.2	13.2	110.3	31.2	730.6	34.5	10.3	1.7	1.9	24	158.4	80.1	2.9	3.1
H	6.5	0.41	17.7	1.5	11.7	179	30.4	531.7	30.9	8.7	1.4	1.4	27.5	175.7	108.1	3.7	3.9
H	6.6	0.35	16.7	1.4	12	166.6	30.1	560.6	28.7	8.7	1.1	1.3	28.6	205.8	133.3	3.4	3.9
H	6.7	0.41	16.1	1.3	12.8	306.4	27.4	537.3	29.9	8	1.5	1.5	25.1	224	139.6	3.9	4
H	6.5	0.41	19.8	1.6	12.1	258.1	29.6	562.5	29.2	9.2	1.4	1.9	20.3	248.5	162.7	4.3	4.7
H	6.9	0.51	17.9	1.4	12.4	170.7	32.1	635.7	38.2	9.8	1.1	1.2	38.9	143.6	146.2	2.7	4.1
H	6.4	0.39	21.4	1.7	12.8	141.2	34.6	603.5	26.9	9.1	1	1.4	25.5	371.4	192.7	5.3	4.6
H	5.9	0.45	23.1	1.9	12.3	185.1	34.5	426.2	20.1	7.5	1.1	1.2	23.9	901.1	468.6	8.5	5.9