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Evaluation of Soil Chemical Properties under Paddy Production System in Central Kenya: Soil Exchangeable Cations

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Abstract

Lowland irrigated schemes contribute the most rice produced in Kenya. However, production is low and highly variable due to management problems. Production could be increased with appropriate soil management which requires that baseline fertility status of the soils and how they vary be known. This study examined the variability of selected soil chemical properties in the Mwea Irrigation Scheme in Central Kenya. Soil samples were collected from the top 0-15 cm depth in August 2013 and 2014 and analysed for pH, electrical conductivity (EC) and the exchangeable cations potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}) and sodium (Na^+). Significant variability in soil EC as well as soil cation concentration was observed among units. Overall results showed soil pH ranged from 4.56 (very strongly acidic) to 8.05 (moderately alkaline). Soil EC varied from 0.17 to 1.52 dS m^{-1} with higher elevation areas recording lower values (< 0.50 dS m^{-1}) and lower elevation areas recording higher EC values (> 0.50 dS m^{-1}). On average, exchangeable Ca^{2+} was 38.17 $cmol_c$ kg^{-1}, Mg^{2+} 23.80 $cmol_c$ kg^{-1}, Na^+ 1.24 $cmol_c$ kg^{-1} and K^+ 0.35 $cmol_c$ kg^{-1}. The soil exchange complex was mainly dominated by Ca^{2+} and Mg^{2+} and cation concentration in the soil was in the order $Ca^{2+} > Mg^{2+} > Na^+ > K^+$. Soil K is low and severe cation imbalances exist with regard to K^+ and other cations thus making K^+ deficient for plant uptake. Management practices and farming systems which enhance soil K status should be encouraged to help boost and sustain rice yield.

Keywords: cation imbalance, mwea irrigation scheme, paddy soil, variability

1. Introduction

Soils are highly variable both spatially and temporally as a result of land use and management strategies and this variability is expressed in soil physical and chemical properties (Bailey, Wang, Jordan, & Higgins, 2001; Jin & Jiang, 2002; Corwin et al., 2003; Cerri et al., 2004). As a consequence, soils can exhibit marked spatial variability at the macro- and micro-scale (Brejda, Karlen, Smith, & Allan, 2000; Vieira & 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).

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, Mati, Kalamwa, Wanjogu, & Kiplagat, 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.

While rice is the third most important staple cereal in Kenya after maize and wheat, the country is only able to produce 20% of its national needs (Ministry of Agriculture [MoA], 2009). Recent years have seen rice grow in importance in Kenya as per capita consumption, particularly in urban areas, has increased far more rapidly than that for other cereal crops (MoA, 2009; European Cooperative for Rural Development [EUCORD], 2012). Approximately 95% of the rice consumed in Kenya is produced from government managed irrigation schemes and the remaining 5% under rain-fed conditions (United States Agency International Development [USAID], 2014). Data from the Ministry of Agriculture indicate that irrigated areas cover approximately 13,000 ha and include irrigation schemes in Nyanza; West Kano and Ahero (3,520 ha), Western Bunyala scheme (516 ha) and Mwea irrigation scheme (9,000 ha) (MoA, 2009).

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, Amin, Lee, & Mohammud, 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 & Vyn, 2006). 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, Ota, & Wanjogu, 2001).

Although knowledge on soil fertility status plays a vital role in enhancing production and productivity of the agricultural sector on sustainable basis, no information is available on rice growing soils of Kenya in general and the specific study area of Mwea irrigation scheme. Therefore, this study was proposed to characterize the fertility status of the rice growing soils in Kenya based on selected soil chemical (soil salinity and exchangeable cations calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}) and potassium (K^{+})) properties in the rice growing soils of Mwea.

2. Materials and Methods

2.1 Description of the Study Area

Mwea Irrigation Scheme is located on the lower slopes of Mt. Kenya, Kirinyaga County in Central Kenya (Figure 1). It is one of the oldest public irrigation schemes in Kenya (Mati, Wanjogu, Odongo, & Home, 2011). It lies within latitudes 37°13′E and 37°30′E and longitudes 0°32′S and 0°46′S with an annual average precipitation of about 950 mm. The area experiences bimodal rainfall with the long rains falling between March and May and short rains between October and December (Kihoro, Bosco, Murage, Ateka, & Makihara, 2013). According to Kenya's agro-climatic zoning by Sombroek, Braun, and van de Pouw (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 0.40 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).

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, but about 80% are in the semi-arid to arid areas (International Board for Soil Research Management [IBSRAM], 1987). According to Muchena and Gachene (1985), these Vertisols are developed on parent materials ranging from Precambrian Basement System rocks, volcanic rocks 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). Kondo et al. (2001) also observed predominant presence of Vertisols in the rice growing fields and Alfisols occurred at higher elevation. Studies in Mwea irrigation scheme by Mukiama and Mwangi (1989) noted 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 of about 12,282 ha of which about 9,000 ha has been developed for paddy production. Mwea irrigation scheme, first developed in 1953 is the largest and is divided into five production sections/units located at different topographical elevation namely Tebere and Mwea covering 1400 and 1300 ha respectively and Thiba, Wamumu and Karaba covering 1200, 1200 and 1100 ha respectively (Njagi, 2012) (Figure 1).

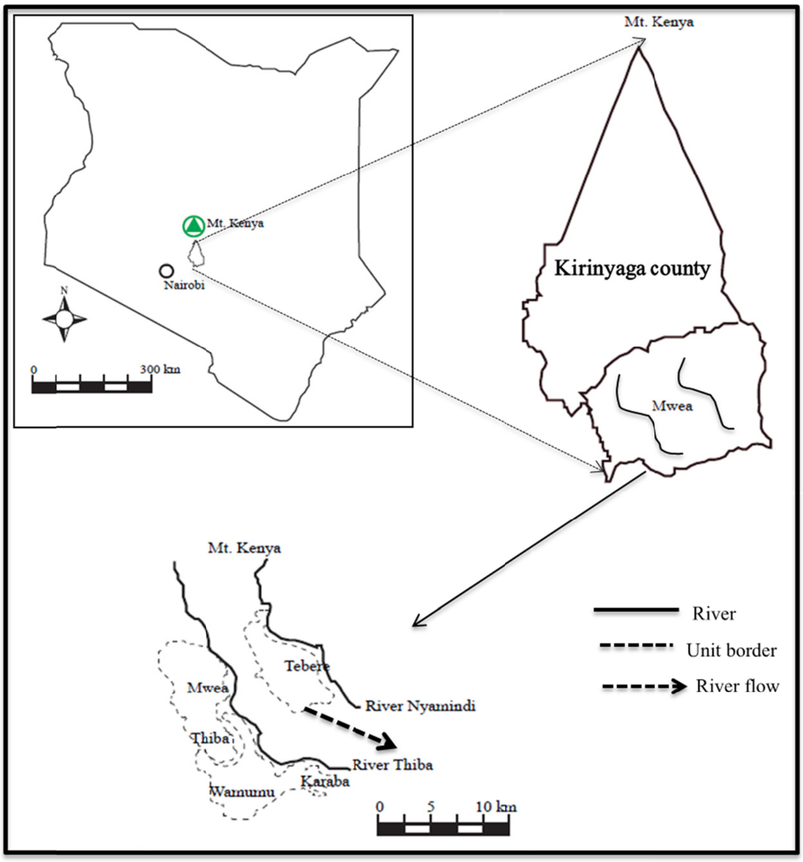

Figure 1. Location and layout of Mwea irrigation scheme

Mwea and Tebere sections are the largest and oldest to be developed while Karaba, the smallest located at the end of the scheme was the last to be developed in 1973 (Kabutha & Mutero, 2002). The irrigation scheme gets its waters from two rivers; the Nyamindi and Thiba which have no storage facilities. River Nyamindi mainly serves the Tebere (T) section, while river Thiba serves Mwea (M), Thiba (H), Wamumu (W) and Karaba (K) sections (Figure 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 & Mutero, 2002; Abdullahi, Mizutani, Tanaka, Goto, & Matsui, 2003).

2.2 Soil Sample Collection, Preparation and Analysis

Surface (0-15 cm) soil samples were collected in August 2013 and 2014 cropping period from Mwea rice fields. 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 a total of 166 fields were marked. Three to five representative soil samples were collected from fields averaging about 0.4 ha using a soil auger at a depth of 0-15 cm. The samples were mixed thoroughly and a composite sample from each field taken for evaluation. Transparent polythene bags were used to keep the samples and each labelled. The samples were dried, ground and passed through a 2mm sieve in readiness for chemical analysis. The samples were exported to Japan and analysed in the Soil and Ecological Engineering laboratory, Faculty of Life and Environmental Science, Shimane University. The samples were analysed for pH, electrical conductivity (EC) and exchangeable cations (Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}). Soil pH was measured potentiometrically using a glass electrode pH meter (HORIBA D-51) in 1:2.5 (w/v) soil-water ratio suspension as described by the International Institute of Tropical

Agriculture [IITA], (1979) and McLean (1982) using 8 g air-dried soil. EC was measured with the conductivity meter (HORIBA D-24) after a soil saturation paste was prepared with a soil-water ratio of 1:5 (w/v) using 5 g of air-dried soil. Exchangeable Ca^{2+}, Mg^{2+}, K^+ and Na^+ in the soil were first extracted by mixing 1.25 g of air dried soil with 25 ml of 1M neutral ammonium acetate (1 M NH_40Ac pH 7.0) and shaking for 60 minutes according to Thomas (1982). The solution was then filtered through ADVANTEC Whatman filter paper No. 6 and the cation concentration in the leachate determined by Inductively Coupled Plasma-Atomic Emission Spectroscopy (ICPE-9000 Shimadzu).

2.3 Data Analysis

Data for all the measured parameters were subjected to statistical analyses using SPSS (IBM SPSS Statistics version 22). Descriptive statistics that included mean, maximum, minimum and standard deviation (SD) were obtained. The coefficient of variation (CV) which is a ratio of standard deviation to mean and expressed as a percentage was also calculated for each measured variable. We used the CV as a measure of variability to gauge the degree of heterogeneity among the studied parameters. Correlation analysis was performed to assess relationships among the soil parameters. The soil fertility status of the study area was evaluated basing on the concentrations of the respective parameters obtained from the laboratory analyses and were compared with established ratings and critical levels for optimum rice growth.

3. Results

3.1 Soil Solution pH and Electrical Conductivity (EC)

Mean values for soil solution pH and EC of the Mwea irrigation scheme paddy fields are presented in Table 1.

Table 1. Mean soil solution pH and EC across the units

Unit name	pH_{water}	pH_{KCl}	EC (dS m^{-1})
Mwea	5.99b	4.52c	0.36ab
Wamumu	6.28ab	4.95abc	0.52a
Karaba	6.65a	5.27a	0.54a
Tebere	6.51ab	5.24ab	0.52a
Thiba	6.11ab	4.68bc	0.20b
Mean	6.27	4.88	0.45
CV (%)	12	15	62

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

The soil pH_{water} values ranged from 4.56 to 8.05 while pH_{KCl} ranged from 3.33 to 6.63 and was consistently less than the values observed for pH_{water} an indication of soils with a net negative charge. Variations within the units were observed in soil solution pH. In the Mwea production unit, soil solution pH_{water} from the sampled fields ranged from 4.56 to 8.05. In Wamumu, the lowest soil solution pH_{water} recorded was 4.91 and the highest value was 7.86. In the Karaba unit block, soil solution pH_{water} varied from 5.53 to 7.99 while in Tebere unit it ranged from 4.90 to 7.74. In Thiba unit, soil solution pH_{water} ranged from 4.90 to 6.96. Unit-wise, Mwea paddy soils had the lowest mean value of 5.99 while the other units had pH values above 6. Compared to Tropical Asia (pH 6.0 and 5.6) and Japan paddy fields (pH 5.4) (Kawaguchi & Kyuma, 1974; Kyuma, 2004) Mwea paddy fields have higher mean pH value (6.27) (Table 1).

Soil EC ranged from 0.08 to 1.52 dS m^{-1} in surface soil samples indicating that these soils have a low content of soluble salts and that there is no risk of salinity. In Mwea unit, soil solution EC ranged from 0.08 to 1.12 dS m^{-1} with field differences. In Thiba, soil EC values recorded ranged from 0.11 to 0.59 dS m^{-1} while in Wamumu fields, it varied from 0.10 to 0.89 dS m^{-1}. Down in Karaba, soil solution EC ranged from 0.13 to 1.22 dS m^{-1} whereas in Tebere, values ranging between 0.10 and 1.52 dS m^{-1} were recorded. On average across the sampled fields in the Mwea rice production mandate have moderately high soil pH and low EC. Coefficient of variation (CV) statistic for pH and EC was 12% and 62% respectively (Table 1).

3.2 Soil Cation Concentration

Variations were observed in the concentration of soil exchangeable cations in the sampled fields. Mean values and deficiency level as described by Dobermann and Fairhurst (2000) for soil exchangeable cations in our study site are shown in Table 2.

Table 2. Soil exchangeable cation concentration across the units

Unit	Exchangeable cations ($cmol_c\ kg^{-1}$)				Ca + Mg/K
	Ex. Ca	Ex. Mg	Ex. Na	Ex. K	
Mwea	31.37c	25.00ab	1.49ab	0.22b	325.86b
Wamumu	36.98bc	20.88b	1.05abc	0.30b	222.46bc
Karaba	47.19a	23.49ab	0.95bc	0.40b	232.93bc
Tebere	41.91ab	25.35ab	1.67a	0.85a	109.94c
Thiba	44.30a	27.36a	0.84c	0.31b	455.03a
Mean	38.17	23.80	1.24	0.35	264.65
CV (%)	27	29	65	83	66
Deficiency level	<1	<1	-	<0.2	>100

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

In the larger Mwea region, soil Ca concentration ranged from 8.66 to 69.60 $cmol_c\ kg^{-1}$, soil Mg from 5.00 to 40.30 $cmol_c\ kg^{-1}$. Soil Na concentration on the other hand ranged from 0.28 to 5.01 $cmol_c\ kg^{-1}$ while exchangeable K ranged from 0.07 to 1.47 $cmol_c\ kg^{-1}$ with unit differences. In Mwea unit, the concentration of soil exchangeable Ca ranged from 8.66 to 51.70 $cmol_c\ kg^{-1}$ with field variations. Exchangeable Mg, K and Na were in the ranges of 5.00 to 40.30 $cmol_c\ kg^{-1}$, 0.07 to 1.26 $cmol_c\ kg^{-1}$ and 0.28 to 5.01 $cmol_c\ kg^{-1}$ respectively. In Thiba unit, soil cation concentration ranged from 37.42 to 51.80 $cmol_c\ kg^{-1}$ for exchangeable Ca, 19.30 to 38.30 $cmol_c\ kg^{-1}$ for exchangeable Mg, 0.32 to 1.78 $cmol_c kg^{-1}$ for exchangeable Na and from 0.08 to 1.26 $cmol_c\ kg^{-1}$ for soil exchangeable K. In Karaba unit, soil cation concentration ranged from 32.46 to 69.60 $cmol_c\ kg^{-1}$, 16.74 to 37.80 $cmol_c\ kg^{-1}$, 0.63 to 1.70 $cmol_c\ kg^{-1}$ and 0.09 to 1.16 $cmol_c\ kg^{-1}$ for exchangeable Ca, Mg, Na and K respectively. In Wamumu unit, soil exchangeable cation concentrations were from 17.17 to 66.40 $cmol_c\ kg^{-1}$ for exchangeable Ca, from 8.25 to 32.93 $cmol_c\ kg^{-1}$ for exchangeable Mg, from 0.52 to 2.56 $cmol_c\ kg^{-1}$ for exchangeable Na and from 0.12 to 0.99 $cmol_c\ kg^{-1}$ for exchangeable K. In Tebere unit, Ca and Mg dominated the exchangeable sites and ranged from 17.70 to 65.60 $cmol_c\ kg^{-1}$ and from 9.76 to 39.20 $cmol_c\ kg^{-1}$ of soil respectively. In the same unit, the concentration of soil exchangeable Na ranged from 0.62 to 3.31 $cmol_c\ kg^{-1}$ and exchangeable K from 0.20 to 1.47 $cmol_c\ kg^{-1}$ of soil. Exchangeable Ca and Mg were the dominant cations and on average, all the exchangeable cations exceeded the deficiency criteria as outlined by Dobermann and Fairhurst (2000). The high level of exchangeable Ca, Mg and low exchangeable K is consistent with the findings of earlier studies by Kondo et al. (2001). Ca + Mg:K ratios exceeding 100 were observed in all units which may indicate low K availability for rice growth. The imbalance was extremely high in Thiba and Mwea units at 455.03 and 325.86 respectively (Table 2). The coefficient of variation statistics indicated that Mwea region is highly heterogeneous in terms of soil exchangeable K and Na with CV of 83% and 65% respectively and least heterogeneous in exchangeable Ca and Mg with CV of 27% and 29% respectively (Table 2).

3.3 Correlation between Soil Analytical Parameters

Correlation analysis was performed to assess relationships among the assessed soil parameters; soil pH, soil electrical conductivity and exchangeable cations of paddy field soils from the Mwea irrigation scheme (Table 3).

Table 3. Pearson correlation between soil analytical parameters assessed

	EC	pH_{water}	pH_{KCl}	Ex Ca	Ex Mg	Ex Na	Ex K
EC							
pH_{water}	.143						
pH_{KCl}	$.237^{**}$	$.973^{**}$					
Ex Ca	.139	$.578^{**}$	$.588^{**}$				
Ex Mg	$-.197^{*}$	.061	.026	$.323^{**}$			
Ex Na	$.233^{**}$	$.370^{**}$	$.307^{**}$	$.154^{*}$	$.210^{**}$		
Ex K	$.333^{**}$	.040	.120	$.285^{**}$	$.215^{**}$	.096	

Note. *and **: significant at 0.05 and 0.01 levels respectively.

There was a positive correlation between soil solution EC and other measured soil parameters except with exchangeable Mg which showed a negative but significant correlation (r = -0.197, $p < 0.05$). The correlation was significant but weak with pH_{KCl}, exchangeable Na and exchangeable K (r = 0.237, r < 0.233 and r = 0.333, $p < 0.01$). Soil solution pH_{water} showed a very good correlation with pH_{KCl} (r = 0.973, $p < 0.01$), exchangeable Ca (r = 0.578, $p < 0.01$) and exchangeable Na (r = 0.370, $p < 0.01$). Among the exchangeable cations, Mg and Ca showed moderate positive correlation with each other (r = 0.323, $p < 0.01$) and positively correlated with exchangeable K and Na (r = 0.285, $p < 0.01$ and r = 0.154, $p < 0.05$). Exchangeable K showed a significant and positive correlation with exchangeable Ca (r = 0.285, $p < 0.01$) and exchangeable Mg (r = 0.215, $p < 0.01$).

4. Discussion

The degree of soil acidity or alkalinity is expressed as soil pH and is a master variable affecting a wide range of soil chemical and biological properties. It also influences greatly the availability and uptake of many elements both nutrients and toxins by plant roots (Brady & Weil, 2014). It plays an important role in soil microbial activity and decomposition of mineral substances and organic matter thus influences the release, fixation and migration of soil nutrients (Fageria & Baligar, 1999). Across the units in the scheme, soil pH was moderately high tending towards neutral (pH 7). Soil pH of the paddy fields ranged from very strongly acid to mildly alkaline. The maximum pH observed was 8.05 and minimum 4.56 with a mean of 6.27 (Table 1). On average, the lowest pH value was recorded for Mwea unit soils (5.99) and the highest for Karaba unit (6.65). It was noticeable that soil pH gradually increased from the high elevation areas of Mwea towards the low topographical fields in Karaba. The Kenya Soil Survey (KSS) 1987 classification of soil reaction (Table 4) was used to categorize the soils from our study on the basis of pH.

Table 4. Key to soil reaction (KSS, 1987)

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

As per the KSS 1987 rating (Table 4), the soils of Mwea region have a medium acidic to slightly acidic reaction with a medium level soil pH. In all sampled fields, pH values measured in water were higher relative to pH values in salt solutions; an indication that our study site has soils with a net negative charge. This moderately high soil pH condition had also been reported by Kondo et al. (2001) who attributed it to high carbonate concentration in the soils of this semi-arid region. Kawaguchi and Kyuma (1974) in their studies associated the occurrence of high soil pH to climate and/or parent material noting that drier conditions coupled with calcareous parent material favor higher pH. Additionally Murthy, Bhattacharjee, Landey, and Pofali (1982) related soil pH to the nature of the parent material, climate and topographic situations adding that elements of climate and topography remaining the same, Vertisols develop from parent materials rich in alkaline earths thus higher pH values. Descriptive statistics showed a low variance in soil pH with a CV of 12%. Similar low variance in soil solution pH has been reported elsewhere for instance Aimrun, Amin, Ahmad, Hanafi, and Chan, (2007); Abu and Malgwi (2011) and Addis, Klik, and Strohmeier (2015). This is because pH values are indicated on log scale of proton concentration in soil solution; otherwise there would be a much higher variability if soil acidity is expressed in terms of proton concentration directly (Sun, Zhou, & Zhao, 2003). Given the results generated and from the low CV statistics, we can construe that the soils in the study site are relatively homogenous in view of their pH status and this could be attributed to the homogeneous calcareous parent material and the drier climate in the area.

Soil EC is one of the major parameters in assessing salinity status of a soil because it indicates the presence of soluble salts in a soil. Saline soils refer to soils with an EC above 4 dS m^{-1}, exchangeable sodium percentage (ESP) values less than 15% and pH_{water} values less than 8 and usually contain sufficient soluble salts that adversely affect growth and yield of crops (Yoshida, 1981; Dobermann & Fairhurst, 2000; Kyuma, 2004; Fairhurst, Witt, Buresh, & Dobermann, 2007; Allotey, Asiamah, Dedzoe, & Nyamekye, 2008). The soluble salts are mainly chlorides and sulphates of sodium, calcium and magnesium (Allotey et al., 2008). According to Corwin, Rhoades, and Simunek (2007), salinity and sodicity affect a significant fraction of irrigated soils in semi-arid climates. Nayanaka, Vitharana, and Mapa (2010) further added that salinity is a problem situation in soils where there is excess accumulation of soluble salts as a result of high evapotranspiration, poor drainage and poor quality irrigation water. The application of soil EC to agriculture has its origin in the measurement of soil salinity, which is an arid-zone problem associated with irrigated agricultural land and with areas having shallow water tables. The condition is however influenced by a combination of physico-chemical properties including soluble salts, clay content and mineralogy, soil water content, bulk density, organic matter, and soil temperature. As a result, measurements of EC have been used to map out variation of several edaphic properties such as soil salinity and soil nutrients (Tao 1998; Corwin et al., 2003; Godwin & Miller, 2003; Corwin & Lesch, 2005).

Rice has been regarded as moderately salt tolerant crop but an EC of 6-10 dS m^{-1} decreased yield by up to 50% (Yoshida, 1981; van Mensvoort, Lantin, Brinkman, & van Breemen, 1985). Salt tolerance however varies with rice growth stage and variety (Kyuma, 2004) and sensitivity to salt is reported to be high during the seedling and heading stages. Rice yields in the Mwea region do not exceed 5 ton ha^{-1} and varies greatly from farmer to farmer. This low yield is far below the optimum of about 10 ton ha^{-1} according to MoA (2009). This low yield has been attributed to several factors such as lack of newly improved and adapted varieties, certified seeds, high input costs, climate change, soil chemical and physical degradation due to continuous mono-cropping and an over-reliance by farmers on production techniques that are inefficient (Kimani, Tongoona, Derera, & Nyende, 2011; Nyamai et al., 2012).

The EC values ranged from 0.08 to 1.52 dS m^{-1} in the study area. On average, the lowest value was found in Thiba unit soil (0.20 dS m^{-1}) and highest in Karaba (0.54 dS m^{-1}). Lower values of EC were recorded for upstream and topographically higher areas of Mwea and Thiba. According to the KSS 1987 key to salinity classes, the soils of Mwea region are categorised as non-saline (Table 5) with EC lower than 4 dS m^{-1} and therefore no salinity related risks. The low EC in our study site shows that the presence of salts in these soils is negligible.

Table 5. Key to salinity classes (KSS, 1987)

EC value (dS m^{-1})	Salinity description
0-4	Non-saline
4-8	Slightly saline
8-15	Moderately saline
15-30	Strongly saline
> 30	Excessively saline

In our results, the soil EC coefficient of variation statistic of 62% observed indicates that the Mwea region soils are heterogeneous in terms of salt concentration which could be attributed to the differences in topographical elevation where high elevation areas of Mwea and Thiba soils showed EC values of < 0.5 dS m^{-1} while in the lower position areas it was > 0.5 dS m^{-1}. Similar diffences in salt accumulation with respect to elevation has been reported in Vietnam by Nguyen, Watanabe & Funakawa 2014 where they observed differences in soil salinity over very small elevation differences.

Magnesium (Mg), Calcium (Ca) and Potassium (K) constitute macronutrients required by plants for growth and metabolism. Sodium (Na) is termed a beneficial element because it stimulates growth but is not essential or is only essential for certain plant species or under specific conditions (Marschner, 2012). Mg is a component of chlorophyll and is involved in photosynthesis and protein synthesis. It activates several enzymes and regulates cellular pH and cation-anion balance. Mg is very mobile and is retranslocated readily from old to young leaves. In rice plants, Mg deficiency that can be exacerbated by Fe toxicities can result in reduced spikelet number, reduced grain weight and reduced grain quality (Dobermann & Fairhurst, 2000; Fairhurst et al., 2007; Marschner, 2012). A critical deficiency level of 1 $cmol_c$ kg^{-1} soil is recommended for rice (Dobermann & Fairhurst, 2000; Fairhurst et al., 2007). In our study area, the soil solution concentration of Mg was above the critical deficiency level and hence sufficient for rice production. According to Murthy et al. (1982) and IBSRAM (1987), parent material that is primarily basic in nature and containing a high proportion of alkaline earths, favour the development of Vertisols and soils of vertic subgroups.

Ca is a constituent of Ca pectates which are important cell wall constituents involved in bio membrane maintenance (Dobermann & Fairhurst, 2000). It is important for cell wall and membrane stabilization, osmoregulation and as second messenger allowing plants to regulate developmental processes in response to environmental stimuli. It is less mobile in rice plants and is required in the maintenance of cation-anion balance in cells (Dobermann & Fairhurst, 2000; Fairhurst et al., 2007; Marschner, 2012). An adequate supply of Ca to plants increases its resistance to diseases such as bacterial leaf blight or brown spot (Dobermann & Fairhurst, 2000; Fairhurst et al., 2007; Marschner, 2012). A soil concentration of below 1 $cmol_c\ kg^{-1}$ results in deficiency and can result in impaired root function and predispose rice plants to Fe toxicity. Under extreme deficiency cases, plant stunting and death of growing points may occur. However according to Dobermann and Fairhurst (2000) and Fairhurst et al. (2007), Ca 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. From our study, Ca and Mg concentration in the soil solution is sufficiently enough and therefore it is unlikely that their deficiency can occur in this region. On average, soil Ca and Mg content in our study site was very high (Table 2) according to KSS 1987 criteria (Table 6).

Table 6. Key to fertility classes for exchangeable cations (KSS, 1987)

	Soil cation concentration ($cmol_c\ kg^{-1}$)		
	K	**Ca**	**Mg**
Very high	> 3.5	> 20	> 20
High	2.0 - 3.5	10 - 20	6 - 12
Moderate	1.0 - 2.0	6 - 10	3 - 6
Low	0.3 - 1.0	2 - 6	1 - 3
Very low	< 0.3	< 2.0	< 1.0

In our results, it was observed that soil Ca and Mg concentration was very high which could be attributed to the parent material composition. The high content of exchangeable Ca and Mg of these soils corroborate the findings of Kondo et al. (2001) who observed Ca and Mg as the dominant cations in the region. Furthermore, Muriithi, Karoki, and Gachanja (2012) while studying the mineral composition of Mwea clays also observed that the clays contained substantial amounts of Mg and Ca oxides. Karaba unit in the lower elevation had the highest mean soil Ca concentration that are likely to have been leached from the upslope and subsequently deposited there. Additional basic cations are also supplied through irrigation water movement and thus a higher concentration especially in the depression areas. Fageria, Caryalho, Santos, Ferraira, and Knupp (2011) further reiterated that calcium and magnesium deficiencies are rare in lowland rice and changes in their concentrations are infinitesimal in flooded soils. In our study site, exchangeable Ca and Mg were very high compared to Tropical Asian and Japanese paddy soils; which could be attributed to differences in parent material composition and climate. With such high calcium levels, the pH of soils is expected to be high. In our results, the soils in the Mwea production unit had lower exchangeable Ca that could be attributed to its higher topographical elevation and low pH that promote leaching thus less cation retention. Funakawa, Tanaka, Kaewkhongkha, Hattori, and Yonebayashi (1997) showed that in soils where pH is less than 6, there is a limited negative charge thus limited cation retention. On the contrary, where soil pH is higher than 6, there is an increase in the amount of variable negative charge thus an increase in the retention of exchangeable cations.

Na is one of the most mobile elements in the soil and according to Kawaguchi and Kyuma (1974), where climate is humid; it is leached out of all soils regardless of their physiographic position. In our study area, soil exchangeable Na is comparable to Tropical Asian soils with almost similar soil concentration probably due to the dry climate or alternating wet and dry conditions. The case is however different for Japanese soils, whose mean Ex-Na content was low at 0.4 $cmol_c\ kg^{-1}$ as discovered by Kawaguchi and Kyuma (1974), and Kyuma, (2004).

Exchangeable K represents the fraction of potassium which is adsorbed on external and accessible internal soil surfaces. K has a main role in osmoregulation and affects loading of sucrose and the rate of mass flow-driven solute movement within the plant. It provides strength to plant cell walls and is involved in lignification of sclerenchyma tissues. It increases leaf area and leaf chlorophyll content, delays senescence and thus contributes to greater canopy photosynthesis and crop growth. In rice plants, K increases the number of spikelets per panicle, percentage of filled grains and grain weight. It also improves tolerance to adverse climatic conditions, lodging, insect pest and diseases (Dobermann & Fairhurst, 2000; Fairhurst et al., 2007). Depending on soil texture, clay mineralogy and K input from natural sources, a critical concentration for deficiency to occur is set in the range of 0.1 to 0.4 $cmol_c\ kg^{-1}$ but a soil concentration of 0.2 $cmol_c\ kg^{-1}$ is commonly used (Dobermann & Fairhurst, 2000; Fairhurst et al., 2007). In the Mwea region paddy fields, soil K content ranged from 0.07 (very low) to 1.47 $cmol_c\ kg^{-1}$ (moderate) according to KSS 1987 (Table 6). On average in the units, soil K content was very low in Mwea unit and low in Thiba, Wamumu, Tebere, and Karaba (Table 2) and therefore not sufficient enough for plant growth.

Furthermore, Dobermann and Fairhurst (2000) noted that a Ca+Mg:K ratio exceeding 100 may indicate low K availability for rice growth because of stronger K adsorption to cation exchange sites thus reduced K concentration in the soil solution for plant uptake. In our study site, the Ca+Mg:K ratios were high over 100 in all units (Table 2) thus an indication that K uptake by rice is limited in Mwea paddy soils. Dobermann, Sta Cruz, and Cassman (1996a), and Dobermann, Cassman, Sta Cruz, Adviento, and Pampolino (1996b) also indicated that excessive Ca and Mg compared to K reduces K uptake by rice. In addition, management practices like removal of straw and excessive use of N or N and P fertilizers with insufficient K application further exacerbates K deficiency problems. During our survey in the area, we noted that while a few farmers were using K fertilizers, rice straw was removed from the fields after harvest; a common practice that has been going on as was reported by Kondo et al. (2001). With the increasing mining of native soil K without additional reserves, there is bound to be a continuous increase in K deficiency and cation imbalance ratios especially with Ca and Mg in relation to K in the Mwea irrigation scheme. A Study by Dobermann, Cassman, Mamaril, and Sheehy (1998) observed that most rice-based production systems have been known to have a negative K balance that was attributed to the lack of K fertilizer use in correspondence with the increased use of nitrogen fertilizers. Moreover, the practice of removing all straw from farms by many resource poor farmers in most rice growing countries for fuel and cattle feed or burning for easy tillage operation further exacerbates the removal of nutrients. Similar negative K balances were observed by Ghiri and Abtahi (2011) in their study on K dynamics in calcareous Vertisols in Southern Iran.

5. Conclusion

Soil chemical property variability in the Mwea Irrigation Scheme is evident. The soils of Mwea irrigation scheme have slightly high pH, have low salt accumulation and the soil exchange complex is rich in exchangeable bases predominantly the divalent cations (exchangeable Ca^{2+} followed by Mg^{2+}). In addition, high cation imbalance exists. In view of the variability and cation imbalance, the soils are deficient in K availability for rice uptake. Soil management practices and farming systems which enhance long term soil K availability should be encouraged to help boost and sustain rice yield. Understanding soil nutrient patchiness is essential in applying location-specific management strategies because the more variable the properties, the more variable the crop growth and yield.

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References

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*(8), 60-67.

Abu, S., & Malgwi, W. (2011). Spatial Variability of Soil Physico-chemical Properties in Kadawa Irrigation Project in Sudan Savanna Agroecology of Nigeria. *International Journal of Agricultural Research, 6*(10), 714-735. http://dx.doi.org/10.3923/ijar.2011.714.735

Addis, H. K., Klik, A., & Strohmeier, S. (2015). Spatial Variability of Selected Soil Attributes under Agricultural Land Use System in a Mountainous Watershed, Ethiopia. *International Journal of Geosciences, 6*, 605-613. http://dx.doi.org/10.4236/ijg.2015.66047

Aimrun, W., Amin, M. S. M., Ahmad, D., Hanafi, M. M., & Chan, C. S. (2007). Spatial Variability of Bulk Soil Electrical Conductivity in a Malaysian Paddy Field: key to Soil Management. *Paddy Water Environ, 5*, 113-121. http://dx.doi.org/10.1007/s10333-007-0072-z

Allotey, D. F. K., Asiamah, R. D., Dedzoe, C. D., & Nyamekye, A. L. (2008). Physico-Chemical Properties of Three Salt-Affected Soils in the Lower Volta Basin and Management Strategies for their Sustainable Utilization. *West African Journal of Applied Ecology, 12*, 163-182. http://dx.doi.org/10.4314/wajae.v12i1.45776

Bailey, J. S., Wang, K., Jordan, C., & Higgins, A. (2001). Use of Precision Agriculture Technology to Investigate Spatial Variability in Nitrogen Yields in Cut Grassland. *Chemosphere, 42*, 131-140. http://dx.doi.org/10.1016/S0045-6535(00)00118-1

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.

Brady, N. C., & Weil, R. R. (2014). *The Nature and Properties of Soil* (14th ed.). Pearson New International Edition.

Brejda, J. J., Karlen, D. L., Smith, J. L., & Allan, D. L. (2000). Identification of Regional Soil Quality Factors and Indicators: II. Northern Mississippi Loess Hills and Palouse Prairie. *Soil Sci. Soc. Am. J., 64*, 2125-2135. http://dx.doi.org/10.2136/sssaj2000.6462115x

Cerri, C. E. P., Bernoux, M., Chaplot, V., Volkoff, B., Victoria, R. L., Melillo, J. M., … Cerri, C. C. (2004). Assessment of Soil Property Spatial Variation in an Amazon Pasture: Basis for Selecting an Agronomic Experimental Area. *Geoderma, 123*, 51-68. http://dx.doi.org/10.1016/j.geoderma.2004.01.027

Chan, C. S., Amin, M. S. M., Lee, T. S., & Mohammud, C. H. (2008). Apparent Soil Electrical Conductivity as Indicator of Paddy Soil Productivity. *J. Trop. Agric. and Fd. Sc., 36*, 145-153.

Corwin, D. L., Kaffka, S. R., Hopmans, J. W., Mori, Y., van Groenigene, J. W., van Kessel, C., … Oster, J. D. (2003). Assessment and Field-Scale Mapping of Soil Quality Properties of a Saline-Sodic Soil. *Geoderma, 114*, 231-259. http://dx.doi.org/10.1016/S0016-7061(03)00043-0

Corwin, D. L., & Lesch, S. M. (2005). Apparent Soil Electrical Conductivity Measurements in Agriculture. *Computers and Electronics in Agriculture, 46*, 11-43. http://dx.doi.org/10.1016/j.compag.2004.10.005

Corwin, D. L., Rhoades, J., & Simunek, J. (2007). Leaching Requirement for Soil Salinity Control: Steady-state versus transient Models. *Agricultural Water Management, 90*, 165-180. http://dx.doi.org/10.1016/j.agwat.2007.02.007

Dobermann, A., Sta. Cruz, P. C., & Cassman, K. G. (1996a). 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. http://dx.doi.org/10.1007/BF00210219

Dobermann, A., Cassman, K. G., Sta. Cruz, P. C., Adviento, M. A., & Pampolino, M. F. (1996b). 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. http://dx.doi.org/10.1007/BF00210220

Dobermann, A., Cassman, K. G., Mamaril, C. P., & Sheehy, J. E. (1998). Management of Phosphorus, Potassium and Sulfur in Intensive Irrigated Lowland Rice. *Field Crops Research, 56*, 113-138. http://dx.doi.org/10.1016/S0378-4290(97)00124-X

Dobermann, A., & Fairhurst, T. H. (2000). *Rice: Nutrient disorders and nutrient management*. International Rice Research Institute, Manila, Philippines.

European Cooperative for Rural Development [EUCORD]. (2012). *Rice Sector Development in East Africa: A desk study prepared for the Common Fund for Commodities*. European Cooperative for Rural Development.

Fageria, N. K., & Baligar, V. C. (1999). Growth and Nutrient Concentrations of Common Bean, Lowland Rice, Corn, Soybean and Wheat at Different Soil pH on an Inceptisol. *Journal of Plant Nutrition, 22*(9), 1495-1507. http://dx.doi.org/10.1080/01904169909365730

Fageria, N. K., Caryalho, G. D., Santos, A. B., Ferraira, E. P. B., & Knupp, A. M. (2011). Chemistry of Lowland Rice Soils and Nutrient Availability. *Communications in Soil Science and Plant Analysis, 42*, 1913-1933. http://dx.doi.org/10.1080/00103624.2011.591467

Fairhurst, T. H., Witt, C., Buresh, R. J., & Dobermann, A. (2007). *Rice: A Practical Guide to Nutrient Management* (2nd ed.). International Rice Research Institute, International Plant Nutrition Institute and International Potash Institute, Manila, Philippines.

Ferguson, R. B., Hergert, G. W., Schepers, J. S., Gotway, C. A., Cahoon, J. E., & Peterson, T. A. (2002). Site-Specific Nitrogen Management of Irrigated Maize: Yield and Soil Residual Nitrate Effects. *Soil Sci. Soc. Am. J., 66*, 544-553. http://dx.doi.org/10.2136/sssaj2002.0544

Funakawa, S., Tanaka, S., Kaewkhongkha, T., Hattori, T., & Yonebayashi, K. (1997). Physicochemical Properties of the Soils Associated with Shifting Cultivation in Northern Thailand with Special Reference to Factors Determining Soil Fertility. *Soil Sci. Plant Nutr., 43*(3), 665-679. http://dx.doi.org/10.1080/00380768.1997.10414792

Ghiri, M. N., & Abtahi, A. (2011). Potassium Dynamics in Calcareous Vertisols of Southern Iran. *Arid Land Research and Management, 25*(3), 257-274. http://dx.doi.org/10.1080/15324982.2011.565857

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

Godwin, R. J., & Miller, P. C. H. (2003). A Review of the Technologies for Mapping Within-field Variability. *Biosystems Engineering, 84*(4), 393-407. http://dx.doi.org/10.1016/S1537-5110(02)00283-0

Hartemink, A. E. (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 August 1-6, 2010, Brisbane, Australia.

International Board for Soil Research and Management Inc. [IBSRAM]. (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.

Jin, J., & Jiang, C. (2002). Spatial Variability of Soil Nutrients and Site-Specific Nutrient Management in the P. R. China. *Comput. Electron. Agric., 36*, 165-172. http://dx.doi.org/10.1016/S0168-1699(02)00099-6

Kabutha, C., & Mutero, C. (2002). From government to farmer-managed smallholder rice schemes: The unresolved case of the Mwea Irrigation Scheme. In H. G. Blank, 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.

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

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

Kihoro, J., Bosco, N. J., 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. *Springer Plus, 2013*(2), 308. http://dx.doi.org/10.1186/2193-1801-2-308

Kimani, J. M., Tongoona, P., Derera, J., & Nyende, A. B. (2011). Upland Rice Variety Development through Participatory Plant Breeding. *ARPN Journal of Agricultural and Biological Science, 6*(9), 39-49.

Kondo, M., Ota, T., & Wanjogu, R. (2001). Physical and Chemical Properties of Vertisols and Soil Nutrient Management for Intensive Rice Cultivation in the Mwea Area in Kenya. *Jpn. J. Trop. Agric., 45*(2), 126-132.

Kyuma, K. (2004). *Paddy Soil Science*. Kyoto University Press, Kyoto.

Marschner, P. (2012). Ed. *Marschner's Mineral Nutrition of Higher Plants* (3rd ed.). Academic Press.

Mati, B. M., Wanjogu, R., Odongo, B., & Home, P. G. (2011). Introduction of the System of Rice Intensification in Kenya: Experiences from Mwea Irrigation Scheme. *Paddy Water Environ, 9*, 145-154. http://dx.doi.org/10.1007/s10333-010-0241-3

McLean, E. O. (1982). Soil pH and lime requirement In A. L. Page, R. H. Miller, & D. R. Keeney (Eds.), *Methods of soil analysis Part 2 - Chemical and microbiological properties* (2nd ed., pp. 199-223, Agronomy, 9).

Ministry of Agriculture [MoA]. (2009). *National Rice Development Strategy 2008-2018*. Republic of Kenya.

Muchena, F. N., & Gachene, C. K. K., (1985). Properties, Management and Classification of Vertisols in Kenya. 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, T. K., & Mwangi, R. W. (1989). Field Studies of larval *Anopheles arabiensis* Patton of Mwea Irrigation Scheme, Kenya. *International Journal of Tropical Insect Science, 10*(1), 55-62. http://dx.doi.org/10.1017/S1742758400003349

Muriithi, N. T., Karoki, K. B., & Gachanja, A. N. (2012). Chemical and mineral analyses of Mwea clays. *Int. J. Phys. Sci., 7*, 5865-5869.

Murthy, R. S., Bhattacharjee, J. C., Landey, R. J., & Pofali, R. M. (1982). Distribution, Characteristics and Classification of Vertisols. *Transactions of the 12th International Congress of Soil Science, Managing Soil Resources to Meet the Challenges to Mankind, Vertisols and Rice Soils of the Tropics*. New Delhi, India.

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 Sci. Soc. Am. J., 69*, 1572-1579. http://dx.doi.org/10.2136/sssaj2005.0062

Nayanaka, V. G. D., Vitharana, W. A. U., & Mapa, R. B. (2010). Geostatistical Analysis of Soil Properties to Support Spatial Sampling in a Paddy Growing Alfisol. *Tropical Agricultural Research, 22*(1), 34-44. http://dx.doi.org/10.4038/tar.v22i1.2668

Nguyen, L., Watanabe, T., & Funakawa, S. (2014). Spatiotemporal variability in soil salinity and its effects on rice (*Ozyra sativa* L.) production in the north central coastal region of Vietnam. *Soil Sci. Plant Nutr., 60*, 874-885. http://dx.doi.org/10.1080/00380768.2014.961030

Njagi, T. N. (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, B. M., Home, P. G., Odongo, B., Wanjogu, R., & Thuranira, E. G. (2012). Improving land and water productivity in basin rice cultivation in Kenya through System of Rice Intensification (SRI). *Agric Eng Int: CIGR Journal, 14*, 1-9.

Nyang'au, W. O., Mati, B. M., Kalamwa, K., Wanjogu, R. K., & Kiplagat, L. K. (2014). Estimating Rice Yield under Changing Weather Conditions in Kenya Using CERES Rice Model. *International Journal of Agronomy, 2014*. http://dx.doi.org/10.1155/2014/849496

Omonode, R. A., & Vyn, T. J. (2006). Spatial Dependence and Relationships of Electrical Conductivity to Soil Organic Matter, Phosphorus and Potassium. *Soil Science, 171*, 223-238. http://dx.doi.org/10.1097/01.ss.0000199698.94203.a4

Sanchez, P. A. (2002). Soil Fertility and Hunger in Africa. *Science, 295*, 2019-2020.

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

Sombroek, W. G., Braun, H. M. H., & van der Pouw, B. J. A. (1982). The exploratory soil map of Kenya and Agro-Climatic Zone Map of Kenya scale 1:1 million. *Exploratory Soil Survey Report No. E1*. Kenya Soil Survey, Nairobi.

Sun, B., Zhou, S., & Zhao, Q. (2003). Evaluation of Spatial and Temporal Changes of Soil Quality Based on Geostatistical Analysis in the Hill Region of Subtropical China. *Geoderma, 115*, 85-99. http://dx.doi.org/10.1016/S0016-7061(03)00078-8

Tao, S. (1998). Factor score mapping of soil trace element contents for the Shenzhen area. *Water, Air and Soil Pollution, 102*, 415-425.

Thomas, G. W. (1982). Exchangeable cations. In Page et al. (Eds.), *Methods of Soil Analysis* (Part 2, 2nd ed., Agron. Monogr. 9). ASA and SSSA, Madison, WI.

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

van Mensvoort, M. E., Lantin, R. S., Brinkman, R., & van Breemen, N. (1985). Toxicities of Wetland Soils. *Wetland Soils: Characterization, Classification and Utilization: Proceedings of the 1984 Workshop* (pp. 123-138). IRRI, Los Banos, Laguna, Philippines.

Vieira, S. R., & Gonzalez, A. P. (2003). Analysis of the Spatial Variability of Crop Yield and Soil Properties in Small Agricultural Plots. *Bragantia, Campinas, 62*(1), 127-138. http://dx.doi.org/10.1590/S0006-87052003000100016

Yoshida, S. (1981). *Fundamentals of Rice Crop Science*. International Rice Research Institute, Los Banos, Philippines.

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