Evidence-based Soils Agronomy for Sustainable Crop Production in Muranga County, Kenya

Project Report

Land Health Decisions

World Agroforestry (ICRAF)

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Table of Contents

List of Figures

List of Tables

Executive summary

Small-scale farming in sub Saharan Africa is central in trying to achieve food security. However, subsistence farming is not meeting its role in reducing the current yield gap. Current agronomic recommendations are too broad to be useful and remain largely un-validated. There is therefore growing demand for high precision information on soil conditions and agronomic performance to guide investment decisions on use of Agro-inputs and other land management interventions. We collected 524 soil samples (0-20 and 20-50 cm depth ranges) from 177 farmers' fields, and 205 maize tissue samples from 143 farmers' fields, to study soil and plant health conditions to identify soil health constraints for targeting interventions to improve maize production in Muranga County, Kenya.

The soil nutrient analysis indicated that the soils in the study area were deficient in both macro (N, P, K) and micro (B, Zn, Mn, Cu) nutrients making it marginally suitable for maize production. DAP (18:46:0) and CAN (26:0:0) were the most widely applied fertilizers as basal and top-dressing applications, respectively. Only less than 15% of the farmers apply NPK (17:17:17). This current fertilizer application does not address the potassium which critically deficient in study area. It is therefore advisable to increase the application NPK (17:17:17) to address macro nutrient gaps observed in the study area. It is critical to address all the micro-nutrients deficiency. About 47% of the soils have extremely low Boron content making the fields unsuitable for maize production. About 78% of the top soils have soil organic carbon value of less than 2%.

More than 85% of the farmers apply dry and fresh manure which could help to improve the soil organic carbon stocks. The organic fraction of manure plays an important role in increasing soil organic matter, improving soil structure and water infiltration. Many of the nutrients in the manure, however, are tied up in the organic fraction and must go through a decomposition process to be converted to the inorganic forms available for plant uptake. The relative nutrient concentration of cattle manure is quite low compared to commercial fertilizers. The low concentration of nutrients in cattle manure requires large application rates to apply an equivalent amount of nutrients. We found soil carbon significantly correlated with all macro and micro-nutrients thus increasing the soil carbon level thought sustainable land management practices is important to improve crop response to fertilizers. The pH ranges are optimum but future management should consider maintaining the current level.

The plant tissue test at silking to tasseling stage also indicated deficiency in N, P, and K but no micro nutrient deficiency were detected. The plant tissue analysis at early stage (V3) showed deficiency in N and P but sufficient for K and micro nutrients (Cu, Fe Mn, and Zn). We found soil carbon significantly correlated with all macro and micro-nutrients thus increasing soil organic matter level through sustainable land management practices is important to improve crop response to agricultural inputs including fertilizers. We found a mean maize grain yield of about 2.5 t/ha. The variation in yield is wide ranging between 0.6 and 6.1 t/ha. This indicates the study area has the potential to increase yield at least for those who produce lower than the mean/median values with some inputs and improved land management practices.

1. INTRODUCTION

It is projected that feeding the world population of 9.1 billion in 2050 would require food production as of 2005/7 to be increased by about 70%. Eighty-five percent of the increase in yield will be expected from increased crop intensity and yields (FAO, 2009) . However, crop yields seem to have stagnated at 80 and 20% of the potential yield in irrigated and rainfed systems, respectively (Lobell, Cassman, & Field, 2009). Over 80% of food consumed in sub-Sahara Africa is produced by resource poor small holder farmers (DeVries, 2017) with at least 95% of the farmed land relying of rainfall (Wani, Sreedevi, Rockström, & Ramakrishna, 2009). Sub-Sahara Africa is the only region in the world with stagnant per capita food production (Muchena, Onduru, Gachini, & de Jager, 2005; Pedro A. Sanchez, 2002). Four to seven percent yearly increase in food production is required from the current 3% if Africa is to rely on agriculture for economic development and food production (Tittonell & Giller, 2013). There is prevalence of hunger especially in the rural areas and it is behind other regions towards achieving Sustainable Development Goals (SDGs) (Gowing & Palmer, 2008). In Kenya, agriculture directly contributes 26% to the GDP and indirectly another 27%. It employs over 40% of the population and accounts for 65% of exports (FAO, 2018).

Declining soil fertility as a result of little to no input continuous cultivation have been cited as one of the major challenges to crop production (Heerink, 2005; Kung'u, 2007; Tittonell & Giller, 2013). Large amounts of nutrients have been removed without replenishment over the past few decades; it is estimated that average yearly depletion rates for N, P and K are 22, 2.5, and 15 kg/ha respectively in 37 African countries for the last 30 years (Pedro A. Sanchez, 2002). Phosphorus and N have been identified as the main nutrients limiting food production in SSA (Kang & Mulongoy, 1992).

Soil analysis attempts to quantify the amount of nutrients available to plants based on chemical extractions. However, absorption of nutrients follows laws of plant physiology and biochemistry (Sillanpää, 1982). This can result in lack of conformity between soil and plant analysis in addition to other determining factors like crop variety, environmental and soil properties (Cox, 1987). Also, such extraction procedure can disrupt equilibrium between phases which complicates result interpretation (Viscarra Rossel, Walvoort, McBratney, Janik, & Skjemstad, 2006). In a study Maman, Idriss, & Wortmann (2018) poor relation between soil test values and crop nutrient responses were reported. This could also be caused by adoption

of soil extraction techniques without following the required correlation and calibration steps when selecting the extractant to use. A combination of plant and soil analysis is a better indicator of soil nutrients status (Sillanpää, 1982). In this study analysis of soil and plant was done in Maragwa, Kangema and Kigumo Sub counties in Muranga County, Kenya to determine maize nutrient status.

2. METHODS

2.1. Study area

Muranga County is located within the Upper Tana catchment which covers Mount Kenya and the Aberdares highlands and with approximate area of 12,500 km^2. It lies between latitudes 0^o 34' South and 10^0 7' South and Longitudes 36^o East and 37^o 27' East (*Figure 1*). The elevation in the study area ranges between 1080 and 1660 masl. The rainfall pattern in the County is a clearly separated bimodal with the first rains occurring between March and May and the second rains occurring between October and November. The average annual rainfall ranges from less than 800 mm in the south-east to about 2600 mm in the North-West.

The soils of Muranga are dominantly Nitisols developed from basic igneous rocks. Nitisols are generally clay-rich and are characterized by a good open soil structure good for deep crop root penetration (Ministry Of Agricultre, 1987). Their high fertility is contributed to by the high clay contents which can retain considerable amounts of plant nutrients and have favorable water holding capacity. The soil factor maps reveal that the eastern sides of Kigumo and Kangema sub counties have high clay contents probably owed to erosion brought about by the slopes from the west to east regions.

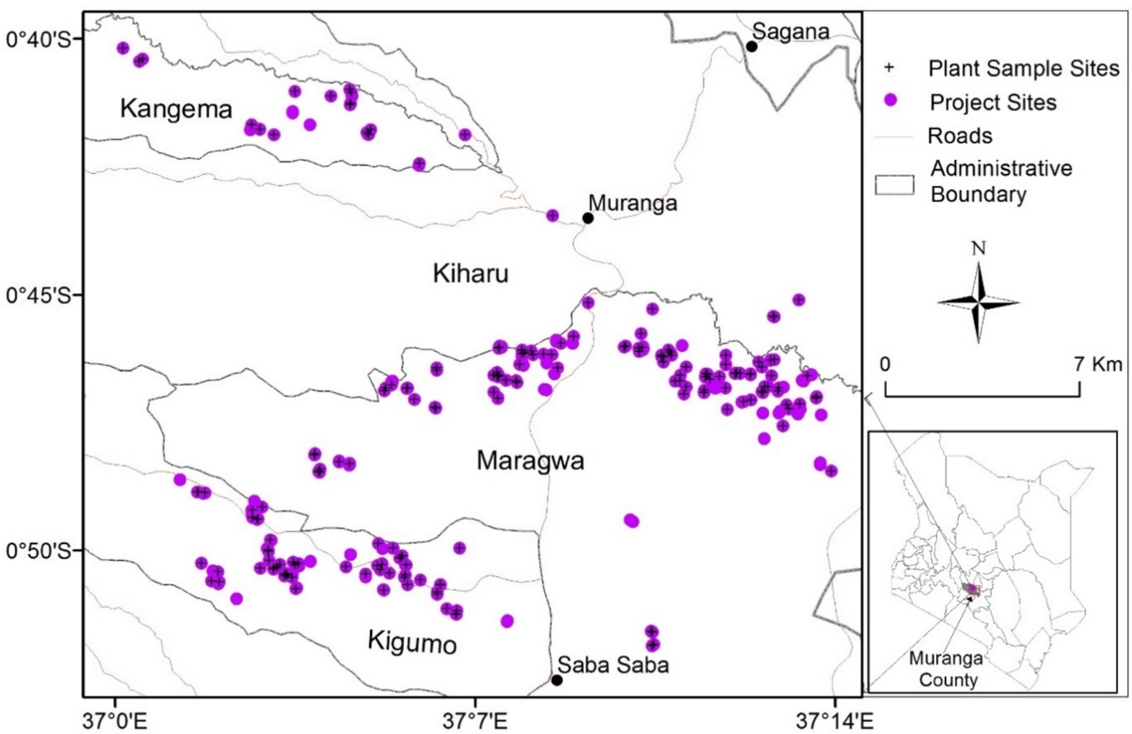


Figure 1: Location of the study area, Muranga Country, Kenya

The rainfall pattern in the County is a clearly separated bimodal with the first rains occurring between March and May and the second rains occurring between October and November. The average annual rainfall ranges from less than 800 mm in the south-east to about 2600 mm in the North-West. The western region including Kangema and higher parts of Kigumo is generally wet and humid because of the Aberdare ranges and Mt. Kenya. The eastern region including lower parts of Kigumo, receive less rain and crop production requires irrigation (County, 2014; Geertsma et al., 2011).

2.2. Data collection

2.2.1. Approach

The general approach and the main steps we followed to develop evidence-based Soils Agronomy for sustainable maize production is summarized in *Figure 2*. The sampling areas were preselected in Nginda and Kambiti wards in Maragwa subcounty and Kigumo and Kangema sub counties.

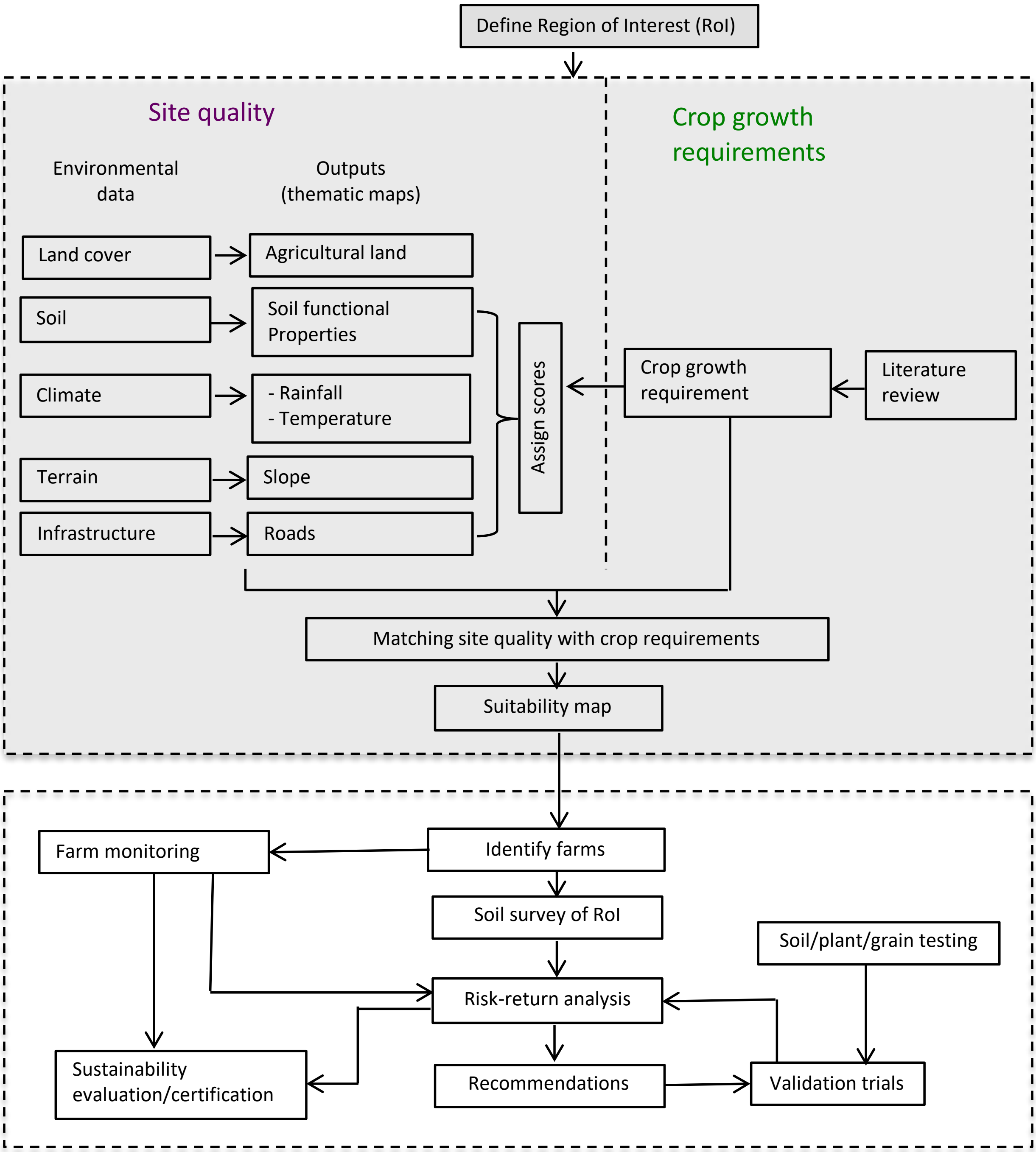


Figure 2: Flowchart showing the general approach to develop evidence-based Soils Agronomy for Sustainable Maize production in Kenya

In this project we covered the shaded part of the workflow. Lack of field level crop-response trial to assess the effectiveness of the input recommendation could lead to some uncertainties.

2.2.2. Soil sampling

We collected soil samples from 0 - 20 cm and 20-50 cm depth ranges using a soil auger. Composite samples from four points were collected for each sampling point (*Figure 3 a*). We collected 524 soil samples from 177 farmers' fields. The samples were dried, crushed and sieved to pass through the 2mm sieves. The sieved samples were sub sampled (10g) using coning and quartering and milled to less than 75 µm using Retsch RM 200 mill. The milled samples were analyzed using Inductively Couple Plasma – Optical Emission Spectroscopy (ICP-OES) after extraction with Mehlich 3 reagent. Mid-Infrared spectral analysis, with fine-tuning of the calibration using data from wet chemistry analysis obtained from the Crop Nutrition Laboratories (CNLS) for about 20% of the total samples was done.

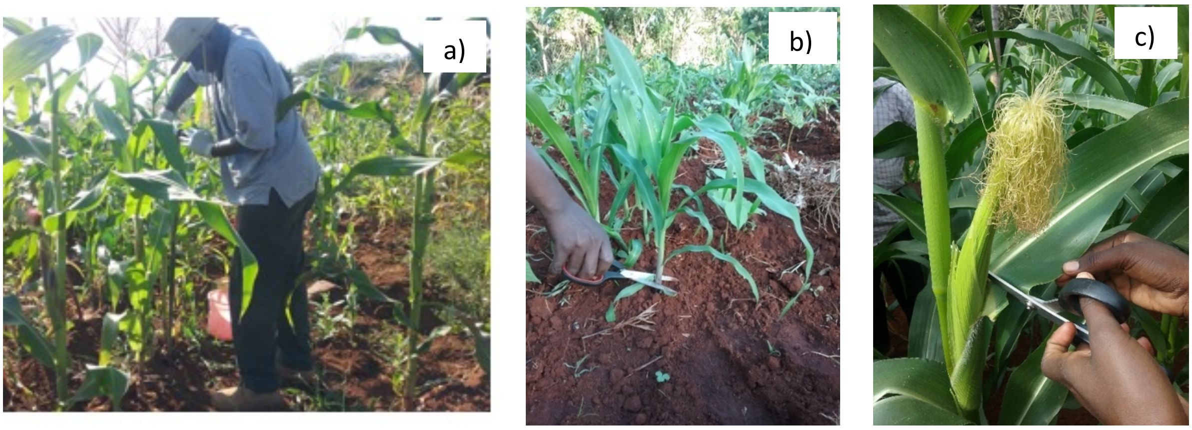


Figure 3: a) soil sample collection, b) V3 and c) V8 plant tissue sampling

2.2.3. Plant tissue sampling

Plant (ear leaf) tissue samples were taken from farms where the crop was approaching flowering and fruiting stage. The ear leaf was located (*Figure 3 c*) and plucked downwards (at roughly an adjacent angle of <30°) with moderate force. The collar leaf method of sampling was used because it was an important stage which corresponds to the period where maximum uptake of nutrients had already happened in plant tissues. Tissue samples were taken from about 13 to 15 maize plants below the ear node and from plants that were representative of the plot and were not damaged or having disease (Stewart, 2016). The ear leaf is the leaf adjacent to the uppermost developing ear. The leaves were cleaned with distilled water, dried using a piece of cloth, packed in labeled khaki bags and immediately sent to ICRAF laboratory in Nairobi in cooler boxes. On arrival the samples were immediately oven dried at 60 °C for 48 hours. The dried leaves were then milled and digested in Aqua Regia

solution and analyzed with ICP-OES. We collected 205 plant tissue samples form 143 farmers' fields.

To determine the P available for early plant route growth, whole plant at V3 vegetative growth is preferable. The collar leaf method for V8 sampling was used because it was an important stage which corresponds to the period where maximum uptake of maximum nutrients had already happened in plant tissues, and therefore is a good indicator of plant mineral nutrients (Stewart, 2016).

Plant tissue sampling at V3 stage

The V3 is a vegetative growth stage of maize when three leaves with visible collars can be counted. V3 plant tissue samples were collected from the 17 demonstration farms where soil sample were collected. In each individual plot where maize was planted, 10-15 tissue samples were collected in a random procedure, avoiding the guard rows. The whole plant was cut and harvested by cutting the stem at about 2 cm above ground level and whole plants harvested (*Figure 3 b*). The tissue samples were quickly dipped into a bucket containing distilled water to wash off any dust particles and possible contaminant on the leaves. They were rinsed with a spray of distilled water from a wash bottle. The plants were dried using a clean damp cloth and the samples placed into a clean labelled khaki paper sample bag.

Plant tissue sampling at V8 stage

From the same plots ear leaf tissue was collected randomly from 15 plants. Ear leaves are considered to have the best indicators in maize plant for determination of plant nutrients (Campbell and Plank 2000; Ramulu and Raj 2012). Ear leaves can be observed and identified during the growth period between tasseling and silking stage. Using a scissors, an ear leaf sample is collected by cutting at its collar leaving behind the leaf base that circles the stem. The collar leaf method of sampling was used because the collar leaf is an important part which corresponds to the growth stage where maximum uptake of maximum nutrients had already happened in plant tissues. Tissue samples were taken from about 10 to 15 maize plants below the ear node and from plants that were representative of the plot and were not damaged or having disease (*Figure 3 c*). The tissue samples were quickly dipped into a bucket containing distilled water to wash off any dust particles and possible contaminant on the leaves. They

were rinsed with a spray of distilled water from a wash bottle. The plants were dried using a clean damp cloth and the samples placed into a clean labelled khaki paper sample bag.

From the demonstration farms we collected 22 V3 early growth and 21 V8 tasseling tissue samples which were placed in well labeled sample bags and delivered to the ICRAF laboratories in Nairobi for preparation and analysis. We oven dried the tissue samples at between 30 to 40 °C until they were crispy dry. Thereafter, the tissue samples were milled to 0.5mm particle size. Infra-red measurement was done at ICRAF. Subsamples were obtained for macronutrients and micronutrients analysis. The wet chemistry tissue analysis was carried out at Crop Nutrition Laboratories, in Nairobi on 17 demonstration farm tissue samples and 10% of tissue samples from the rest of the farms as reference.

2.2.4. Laboratory analysis

Soils

Soil samples were air dried, crushed by rolling pins and sieved through a 2mm sieve. 10g subsamples were obtained by coning and quartering method and then milled to pass a 75-µm sieve using a Retsch RM 200 mill (Retsch, Düsseldorf, Germany) for Infra-Red analysis using a high-throughput Bruker Tensor 27 Fourier Transform MIR spectrometer attached to a High-Throughput Screening (HTS-XT). MIR diffuse reflectance spectra were recorded for all samples at a waveband range of 400 to 4000 cm^{-1} (Towett et al., 2015).

Twenty per cent of the samples were selected as reference samples and analyzed using Mehlich III wet chemistry method for micro and macro nutrient content (Shepherd & Walsh, 2007). The reference samples were used to calibrate and validate MIR spectra prediction. Nutrient extraction was carried out using ammonium fluoride (NH_4F) and ammonium nitrate (NH_4NO_3) followed by quantitative determination done by inductively coupled plasma atomic emission spectrometry (ICP-OES) (Njuguna et al., 2015).

Total and organic C and N contents were analyzed using the flash dynamic thermal combustion method using the Flash EA 1112 Elemental Analyzer (Thermo Fischer). Soil organic carbon (SOC) was obtained by acidifying soils to remove the inorganic carbon.

Sand, silt and clay contents were determined using a laser diffraction particle size analyzer (Horiba LDPSA Analyzer). The automated analyzer is a rapid low-cost technique using laser light on dispersed soil particles and then counts diffraction patterns.

Plant tissue

All 205 leaf tissue samples were washed under running tap water and rinsed with de-ionized water to remove superficial dusts and contaminants before drying them in an oven at 60 °C for 3 days. Milling of the plant materials was done in a Thomas-Wiley Laboratory Mill, Model 4 (Thomas Scientific, USA) to convert the sample into a homogeneous material suitable for laboratory analysis. This was done by drying to a constant weight in a Memmert UF750 forced-draft oven at 40 to 50°C and followed by milling to 0.5 mm particle size using a Thomas Scientific Wiley Mill to ensure good sample representative matrix.

Wet chemical analyses were done by Crop Nutrition Laboratory Services using Mehlich 3 which is a weak acid method for extraction for determination of macronutrients and micronutrients and analyzed using Inductively Coupled Plasma–Optical Emission Spectrometry (ICP–OES). Total Nitrogen was determined colorimetrically after Kjeldahl digestion. Plant samples were also analyzed using portable X-ray fluorescence analyzer (pXRF).

Maize grain yield

We collected maize grain yield data from the 16 demonstration farms. We used crop cut method where we harvested all grains from using 2 m x 2m plots.

2.3. Plant nutritional status analysis

The leaves were analyzed for N, P, K, Mg, Ca, S, Fe, Cu, Zn, and Mn. We also used the Diagnosis and Recommendation Integrated System (DRIS) to evaluate plant nutritional status. DRIS indices were calculated using formula describe by Walworth & Sumner, (1987). DRIS norms for maize developed by Elwali & Gascho, (1984) were used due to lack of locally calibrated norms. The DRIS indices were then interpreted using methods proposed by Wadt (1996) which classified the nutrients according to probability of response to fertilizer application. For interpretation of the DRIS indices, method proposed by Wadt (1996)was used; Nutritional

Balance Index (NBI) which is sum of all absolute values of all nutrient indices was computed. Secondly Average Nutritional Balance Index (NBIa) of the 10 nutrients, NBI/12 was calculated. Three ranges; deficiency, adequate and high were established based on the relation between the sample nutrient index and Average Nutritional Balance Index.

Deficiency = (IA) < 0 and |IA| > NBIa

Adequate = |IA| ≤ NBIa

High = IA > 0 and IA > NBIa

2.4. Statistical analysis

All the statistical analysis was done in R statistical software package version 3.2.3 (R Development Dore Team, 2017).

3. RESULTS AND DISCUSSION

3.1. Macro and micro nutrients in soils and plant tissue

The soils results showed that they varied substantially in physio chemical properties (Table 1). The pH value dominantly ranges between 4.4-7.1 for the top soils while the pH values for the sub soil ranged between 4.5 and 7.1 which is suitable for maize cultivation.

Table 1: Summary of key nutrients contents in soils (0-20 cm), maize plant tissues, in Muranga Country

		N (%)	P (%)	K (%)	Ca (%)	Mg (%)	S (%)	Al (ppm)	Cu (ppm)	Fe (ppm)	Mn (ppm)	Zn (ppm)
Plants	Min	2.024	0.0535	0.489	0.1999	0.09685	0.0515	160.5	3.5	320	76	7
	Max	3.301	0.2585	2.503	1.0475	0.2567	0.1558	189.5	9	1788	507	58
	Mean	2.76	0.15	1.64	0.43	0.16	0.11	172.60	5.73	558.86	176.01	23.47
	SD	0.24	0.03	0.39	0.11	0.03	0.02	12.55	1.37	163.78	79.29	9.47
	Median	2.7555	0.143	1.677	0.4122	0.15595	0.1101	171.50	5.50	542.00	161.50	542.25
	N	176	176	176	176	175	175	5	31	176	176	176
Soils	Min	0.09	0.0001	0.005	0.0376	0.01329	0.0002	587.2	1.78	45.22	88.06	1.18
	Max	0.25	0.0039	0.125	0.8481	0.20685	0.0039	1554.49	8.36	159.12	616.81	30.01
	Mean	0.16	0.00	0.03	0.15	0.05	0.00	1111.39	5.02	78.35	278.89	4.89
	SD	0.03	0.00	0.02	0.09	0.03	0.00	137.95	1.33	18.75	89.51	3.31
	Median	0.16	0.0005	0.022	0.1258	0.04346	0.0011	1118.84	5.305	75.235	273.3	4.155
	N	176	176	176	176	176	176	176	176	176	176	176

P = Phosphorus by Mehlich 3 extraction; K = Exchangeable potassium concentration by Mehlich 3 extraction; B = Boron by Mehlich 3 extraction; Zn = Total Zinc; Mn = Manganese by Mehlich 3 extraction

Although it was expected to the top soil to have more soil organic carbon than the sub-soil, we found no significant difference (***Figure 4***). This could be due to remove of organic sources like crop residues from farm lands which makes the soils to have low soil organic carbon in the top soil.

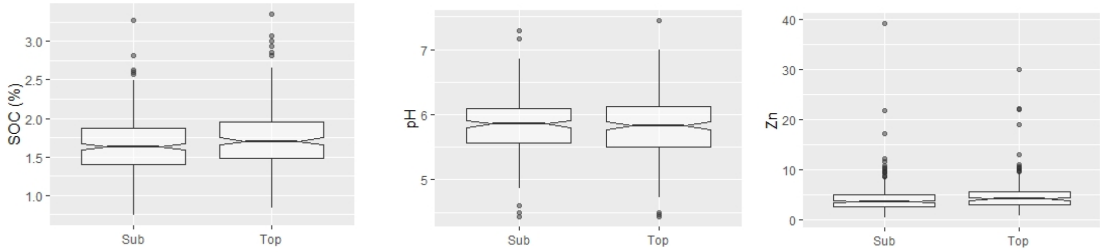


Figure 4: Top and sub soil parameters

Density plots as shown in

Figure 5 were developed for the three sub counties within Muranga county.

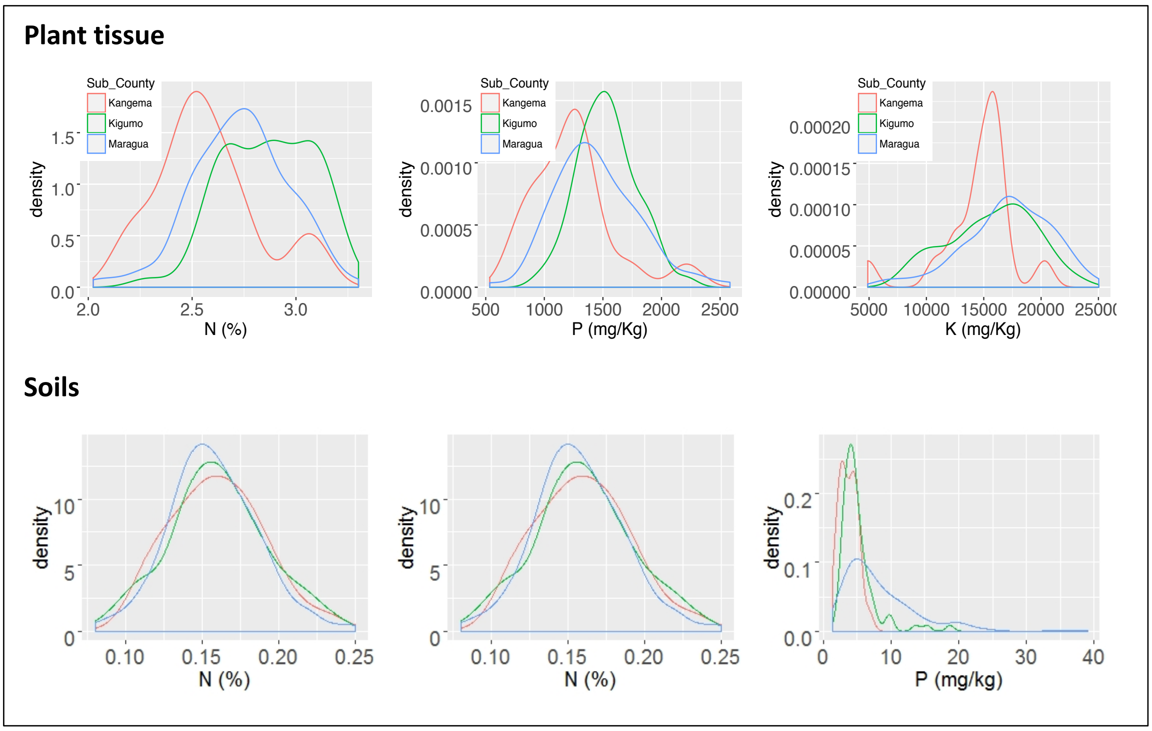


Figure 5: Density plots of selected plant tissue and soil properties in the three sub-counties

Principal components analysis of the plant tissue MIR spectral data showed two distinctive clusters. The first two components, respectively, accounted for 55% and 17% of the overall data variation (*Figure 6*).

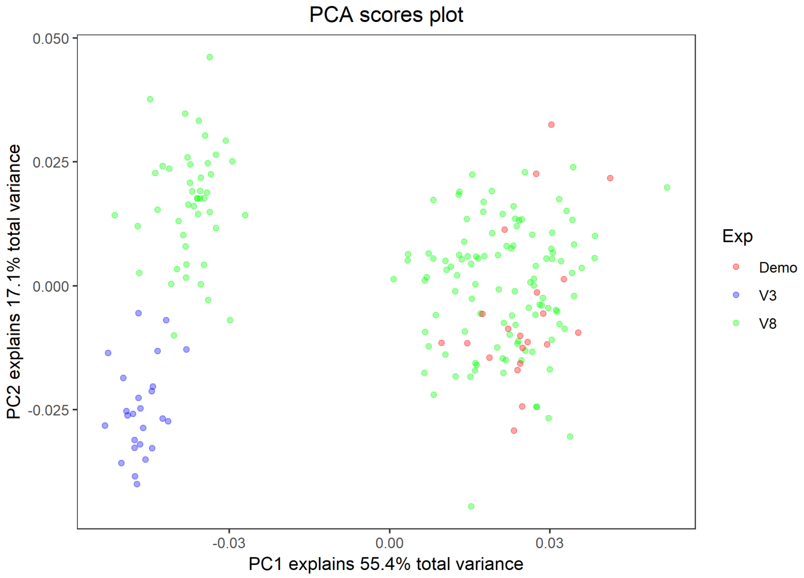


Figure 6: Cluster analysis of V3 and V8 plant tissue samples.

3.2. Soil plant nutrient relationships

We found significant correlation ($p < 0.05$) between the soil and plant P, K, and Mn Mg, Cu, contents (*Table 2*). However, there was no significant correlation between soil TN, Ca, Fe, and Zn.

Table 2: Correlation between nutrients in soil and plant maize plant tissue

		Soil								Plant tissue							
		N	P	K	Ca	Mg	Fe	Mn	Zn	N	P	K	Ca	Mg	Fe	Mn	Zn
Soil	N																
	P	**0.18**															
		(0.014)															
	K	**0.34**	**0.28**														
		(<0.001)	(<0.001)														
	Ca	0.08	**0.57**	**0.32**													
		(0.315)	(<0.001)	(<0.001)													
	Mg	-0.08	**0.29**	**0.16**	**0.86**												
		(0.316)	(<0.001)	(0.03)	(<0.001)												
	Fe	**0.15**	**0.48**	**-0.26**	**0.53**	**0.51**											
		(0.043)	(<0.001)	(<0.001)	(<0.001)	(<0.001)											
	Mn	0.11	**-0.26**	0.11	**-0.33**	**-0.44**	**-0.35**										
		(0.152)	(<0.001)	0.146	(<0.001)	(<0.001)	(<0.001)										
	Zn	**0.54**	-0.03	**0.30**	-0.01	-0.07	**0.19**	**0.23**									
		(<0.001)	(0.718)	(<0.001)	(0.876)	(0.328)	(0.011)	(0.002)									
Plant tissue	N	-0.08	-0.05	-0.05	-0.04	-0.11	-0.10	0.12	-0.15								
		(0.28)	(0.477)	(0.495)	(0.559)	(0.151)	(0.189)	(0.123)	(0.053)								
	P	0.02	**0.16**	0.03	**0.16**	0.13	**0.19**	-0.02	-0.04	**0.50**							
		(0.763)	(0.037)	(0.734)	(0.03)	(0.078)	(0.012)	(0.843)	(0.639)	(<0.001)							
	K	-0.04	0.03	**0.39**	0.01	-0.08	**-0.32**	0.06	-0.06	**0.33**	**0.24**						
		(0.556)	(0.703)	(<0.001)	(0.908)	(0.321)	(<0.001)	(0.4)	(0.423)	(<0.001)	(0.001)						
	Ca	0.09	**0.20**	-0.01	0.08	0.01	**0.25**	-0.02	0.09	-0.11	-0.14	**-0.50**					
		(0.217)	(0.007)	(0.894)	(0.267)	(0.91)	(0.001)	(0.787)	(0.234)	(0.138)	(-0.056)	(<0.001)					
	Mg	0.00	**0.21**	0.06	**0.27**	**0.25**	**0.22**	-0.09	-0.09	**0.23**	**0.35**	0.00	**0.32**				
		(0.987)	(0.005)	(0.395)	(<0.001)	(0.001)	(0.004)	(0.257)	(0.239)	(0.002)	(<0.001)	(0.981)	(<0.001)				
	Fe	-0.13	**-0.15**	**-0.16**	-0.09	-0.07	-0.05	-0.01	-0.11	0.15	0.14	0.06	-0.05	**0.18**			
		(0.09)	(0.044)	(0.040)	(0.249)	(0.382)	(0.508)	(0.941)	(0.131)	(0.053)	(0.057)	(0.427)	(0.535)	(0.019)			
	Mn	-0.13	-0.14	-0.02	**-0.34**	-0.40	**-0.34**	**0.21**	**-0.18**	**0.16**	0.05	**0.17**	0.03	0.06	**0.26**		
		(0.076)	(0.069)	(0.758)	(<0.001)	(<0.001)	(<0.001)	(0.005)	(0.019)	(0.039)	(0.518)	(0.028)	(0.682)	(0.436)	(<0.001)		
	Zn	0.03	-0.08	0.07	-0.07	-0.05	-0.03	0.08	0.03	**0.19**	0.11	0.08	-0.12	0.08	0.00	0.13	
		(0.657)	(0.266)	(0.357)	(0.329)	(0.548)	(0.670)	0.321	0.655	(0.011)	(0.134)	(0.283)	(0.119)	(0.283)	(0.951)	(0.096)	

***Note**: numbers on top are the correlation coefficient values (r) and numbers in brackets are their respective P values for soil the top 0-20 cm soil depth.* Blue fonts indicate significant at $p < 0.05$. the cells with grey background indicate the correlation values of similar nutrients in soils and plant tis

3.3. Plant nutrient status

Soil health constraints

Soil physiochemical results showed deficiencies in N, K, P, Mn Cu, Zn and B owing to several factors which include management practices. Fertilizers amendments containing these micro and macro nutrients can be used to replenish the low levels. The farms that had soils with pH < 5.5, will require liming or organic material like crop residue application. The soil results were compared to critical level as indicated in (Naidu, L, G, Challa, Hegde, & Krishnan, 2006) and AfSIS technical specifications based fertility capability classification scheme intended to identify basic soil production constraints (*Figure 7*).

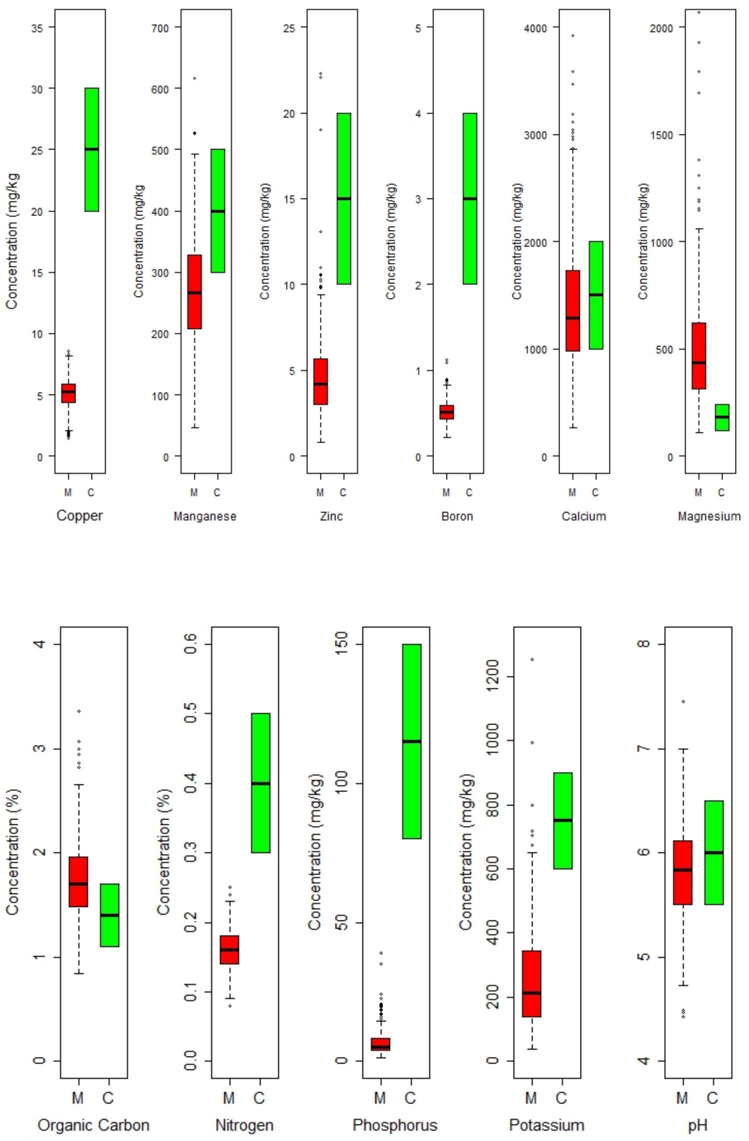


*Figure 7: Muranga site soil nutrient parameters (F) compared to moderately suitable levels (M) according to AfSIS,*Huu Nguyen et al., 2017) *and Naidu 2006.*

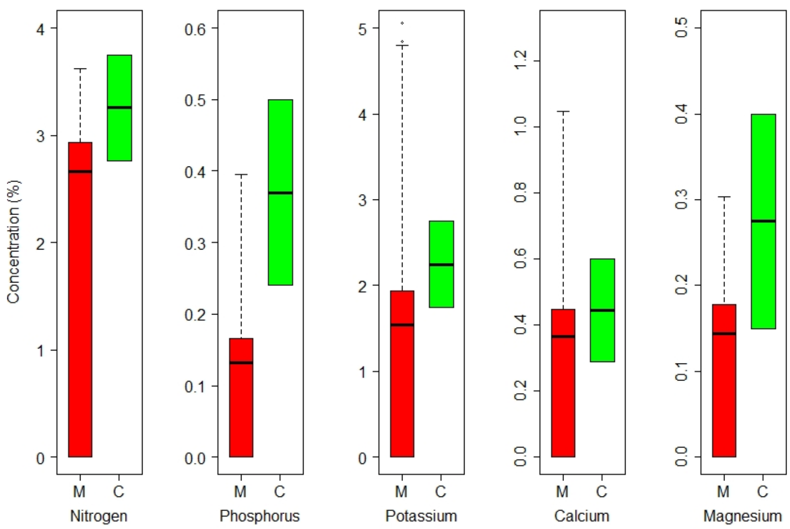
Nutrient status in plant tissue

Based on the interpretive ranges for plant nutrients in corn leaf tissue at silking to tasseling as used by the Soil & Plant Analysis Lab, W-Madison (Schulte & Kelling, 2017). We found NPK as the major plant nutrient constraints (*Table 3*).

Table 3: Correlation between nutrients in soil and plant maize plant tissue

Nutrient	Unit	Deficient	Low	Sufficient	High	Excessive	Total
N	%	0	51	49	0		100
P	%	70	30	1	0		100
K	%	15	44	41	0		100
Ca	%	0	6	88	6	1	100
Mg	%	2	40	58	0		100
Zn	ppm	6	27	67	0	0	100
Mn	ppm	0	0	0	100		100
Fe	ppm	0	0	0	4	96	100
Cu	ppm		0	100	0	0	100

Based on tissue mean values, all the six micronutrients investigated had at least sufficient nutrient concentrations (*Figure 8*). However, Fe concentration was excess (>350 mg/kg) in 96% and high in 4% of the tissue samples analyzed. This finding was not in agreement with NAAIAP 2014 document which identified Fe as the third most limiting nutrient after P and N in Muranga County. Zinc values ranged between 7 mg/kg and 58 mg/kg (*Table 1*).



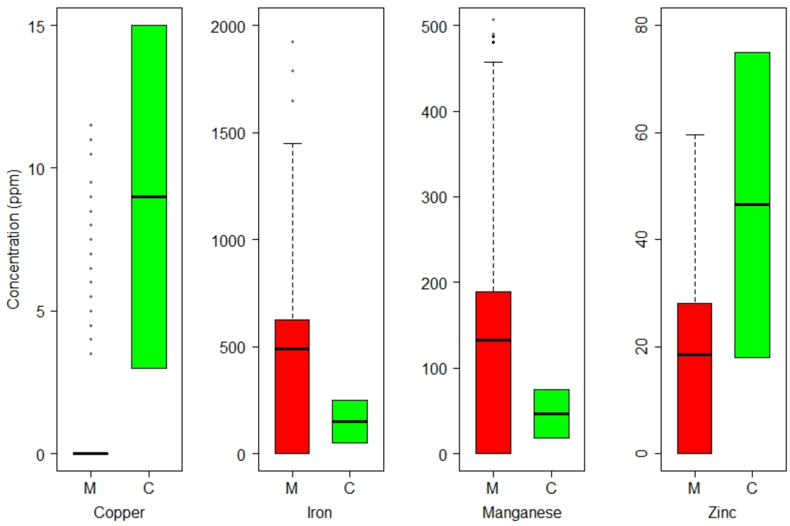
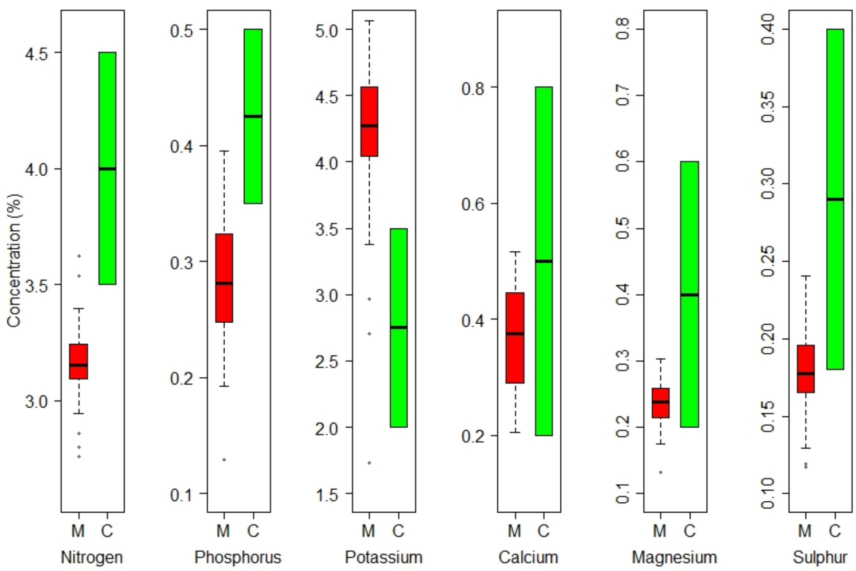


Figure 8: Macro and micro nutrient concentration in maize leaf tissue at silking to tasseling stage (V8) (M) compared to literature sufficiency ranges (C).

Nitrogen and Phosphorus were critically low at the early growth stage (V3) development stage (*Figure 9*).



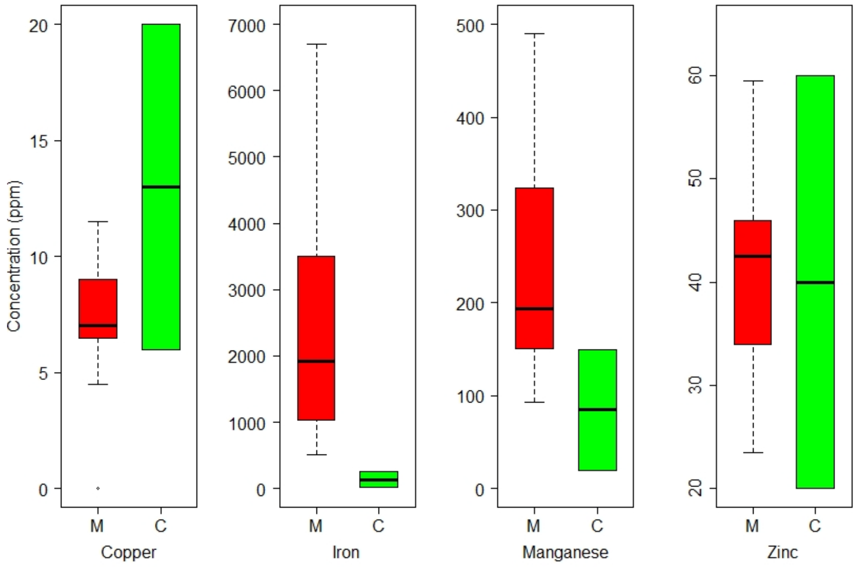


Figure 9: Macro and secondary nutrient concentration in maize leaf tissue at V3 stage (M) compared to literature sufficiency ranges (C).

DRIS indices

Nutrient index values lower than the negative value of Average Nutritional Balance Index (NBIa) were classified as deficient whilst those higher than NBIa were classified as excess. Index values which fell between ± NBIa were regarded as sufficient with more negative ones seen as been prone to deficiency. P, S, and Fe were the three most important nutrients that increasing their concentration could lead to improved crop yield (*Figure 10*).

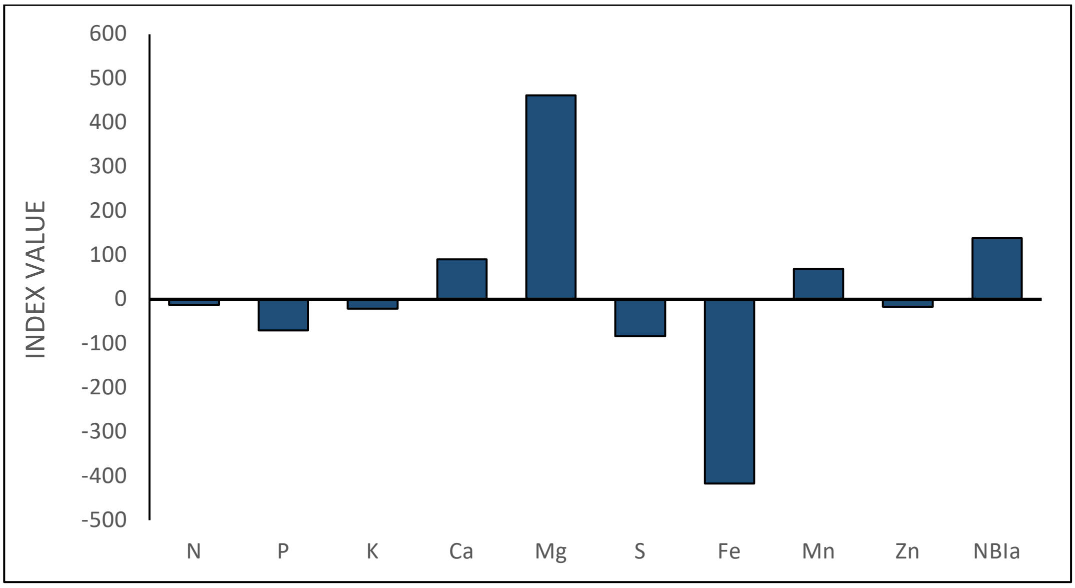


Figure 10: Nutrient index values for maize tissue at tasseling stage

Based on nutrient index values (Figure 10) S and P were the most limiting nutrients. Nitrogen index value was just above negative value of NBIa which indicates that it is the third most limiting nutrient. Potassium, Cu and Zn were the other elements with negative index values but were higher than NBIa. Calcium, Mg, Mn and Fe also had index values higher than NBIa. Based on the indices and interpretation according to Wadt (1996) there is positive and high probability of response to S, P and N fertilizer applications. There was agreement in interpretation of the results based on DRIS and the sufficiency range methods with both methods indicating S, P and N as deficient.

3.4. Maize yield

We found a mean maize grain of 2.5 t/ha from. We found a wide ranging (0.6 – 6.1 t/ha) maize yield (Figure 11). This indicates the study area has the potential to increase at least for those who gained grain yield lower than the mean/median values with some and improved production systems.

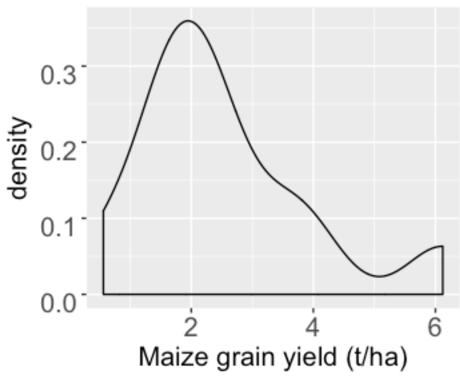


Figure 11: Distribution of maize grain yield for 17 demonstration plots

3.5. Manure nutrient content

Manure is a good source of plant nutrients N, P, and K. In addition, manure returns organic matter and other nutrients such as Ca, Mg, and S to the soil to improve soil quality. The distribution of manure nutrient content are indicated in *Figure 12*.

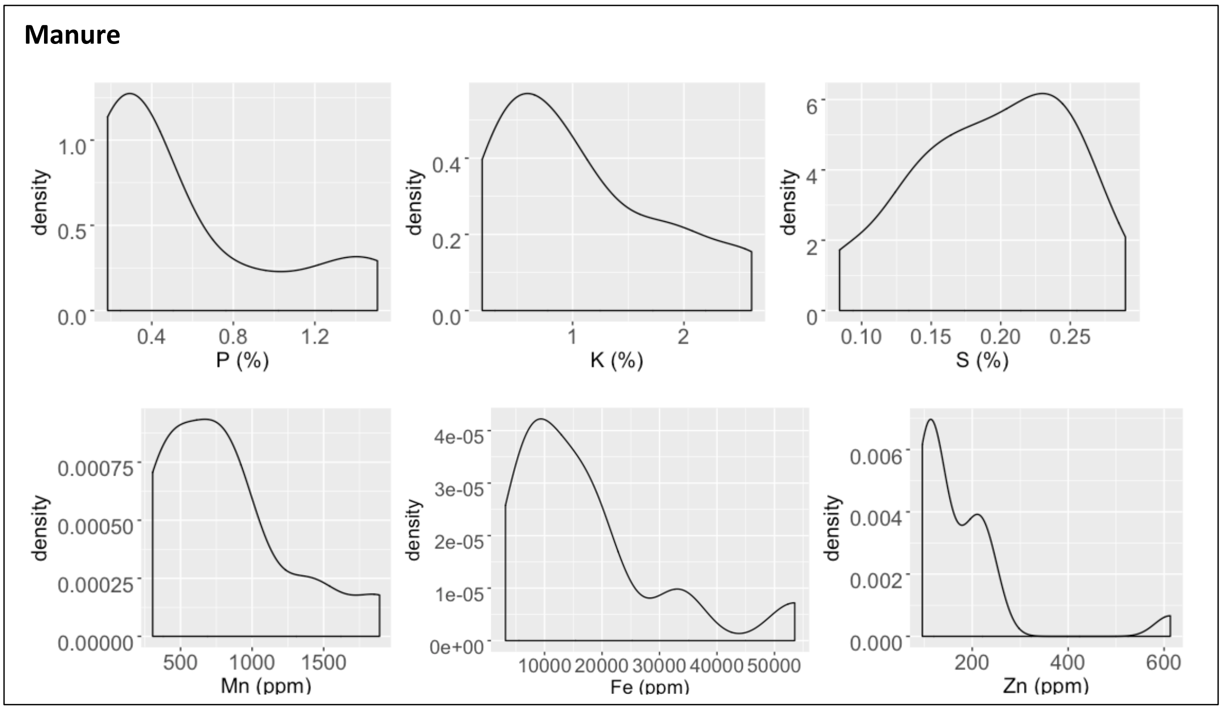


Figure 12: Distribution of manure nutrient for 17 manure samples collected from demonstration farms.

3.6. Interventions to improve soil health constraints

Farm management

Any strategy to maintain or enhance crop growth should consider the three basic factors: soil, climate, and management. Soil nutrient amendments can be approached through integrated agronomic soil fertility management and sustainable biophysical land management and socio economic measures (Tamene, Mponela, Ndengu, & Kihara, 2016). The great extent to which the skills and practical knowledge of a farmer can augment yields is well known. Several variables need to be considered in the agronomic factors. These include but not limited to the soil conservation practices based on the farm topography, liming, seed quality, seed spacing during planting, the plant density in the farms, the weeding practices being used and the seed quality. Socio economic factors such as input risks, labour and sensitization programs to the farmers about maize crop production should also be factored in.

Manure

About 78% of the top soils have soil organic carbon value of less than 2%. More than 85% of the farmers apply dry and fresh manure which could help to improve the soil organic carbon stocks. The organic fraction of manure plays an important role in increasing soil organic matter, improving soil structure and water infiltration. Many of the nutrients in the manure, however, are tied up in the organic fraction and must go through a decomposition process to be converted to the inorganic forms available for plant uptake. The relative nutrient concentration of cattle manure is quite low compared to commercial fertilizers. The low concentration of nutrients in cattle manure requires large application rates to supply an equivalent amount of nutrients.

We found soil carbon significantly correlated with macro and micro-nutrients thus increasing the soil carbon level through sustainable land management practices like application of manure and agroforestry interventions is important to improve crop response to fertilizers. Water availability could be constraint to crop production in the study area where agriculture was rain-fed. A study in Nigeria and Zambia reported that intercropping cereals with legume trees and supplementation with inorganic fertilizer can increase rain use efficiency and yield stability in rain-fed agricultural systems (Sileshi, Akinnifesi, Ajayi, & Muys, 2011).

Maize requires a well- drained sandy loam to silt loam soils. High clay content (> 60%) was also identified as an inherent soil constraint for most fields which cannot be modified by management. Low soil organic carbon level is an indication of land degradation levels as below 2% is considered as a critical threshold. Soils reporting values below 2% SOC concentration are threatened with poor structure, and ability of soil functions, erosion and hence poor fertility (Oldfield, Bradford, & Wood, 2019; Shapiro et al., 2008). SOC can be increased by encouraging farmers to enhance plant residues and root inputs into soils, increase the quantity of organic matter inputs such as manure and compost to the soil (from on/off farm). To conserve and regenerate productive soils, there is need to build and maintain soil organic matter (SOM). Increased organic matter can form complexes with Al (high aluminum presence and thus decreasing its toxicity. Other management interventions will include limiting tillage operations to the minimum needed for adequate seed bed preparation and weed control and crop rotation using high reside crops.

Improving land health using Agroforestry interventions

The impact of human activities on natural systems has been intensifying rapidly in the past several decades, leading to disruption and transformation of most natural systems. Reducing soil and nutrient loss by water erosion using agroforestry interventions help to improve and maintain the health of farms. It has also several other benefits including reducing sediment load to reservoirs, biomass for energy, and improving biodiversity.

Agroforestry for soil conservation, treated in its wider sense to include both control of erosion and maintenance of fertility (Young, 1989). Erosion reduction in agroforestry systems is mainly attributed to its role to i) increase the ground cover by vegetation and ii) enhance physical, chemical and biological soil characteristics, thereby increasing soil fertility, controlling erosion and improving water availability. These roles help reduce surface run-off which is the main cause of soil erosion and reservoir sedimentation. A study in Ethiopia by Nyssen et al. (2010) found that catchment management has resulted in a higher infiltration rate and a reduction of direct runoff volume by 81% which has had a positive influence on the catchment water balance. Besides their positive effect on hydrology, increased infiltration and lower runoff lead to lower soil loss rates and a higher sediment deposition rate within the catchment (Nyssen et al., 2009).

Mulching, if adopted, would be very helpful in reducing evaporation and enhancing soil fertility at the same time. Mulching has many benefits such as; protecting the soil against erosion, conserving moisture, maintaining the soil temperature and prevents weed growth. The most effective mulch is the organic mulch because it enhances the soil fertility after decomposition. It also enhances the soil structure and encourages the development of soil organisms.

Fertilizer application

The purpose of the soil in this project was to develop a prediction of fertilizer requirements necessary to resolve the deficiency identified during the diagnosis by the soil test. Fertilizer recommendations for most crops in Kenya are very general. The availability of a limited number of fertilizer products, primarily DAP and CAN, hampers optimization of nutrient application rates (Bindraban et al., 2018). Farmers use blanket fertilizer recommendations

developed mainly using farm trial and error or taking experiences from other countries. This often leads to an imbalance in nutrients and soil degradation where the nutrients are under-applied. On the other hand, over-application of fertilizer results in lower profit for the farmers and causes soil health problems like soil acidification.

Fertilizer response and nutrient use efficiency by maize crop are spatially viable. A meta-analysis by Ichami et al. (2019) reported that there is good maize yield response for N fertilization in Kenya, reported a median N fertilizer response of 1.8 for maize in Kenya. Responsive soils were common in Kenya (86%) (Ichami et al., 2019) indicating the possibility of to reduce the current yield gap with appropriate interventions. A socio-economic study in the study area by ETC Consulting Ltd, (2019) reported that the mean maize yield reported by farmers is about 1.4 tonnes/ha.

The current fertilizer recommendations are based on soil test only without testing their performance in the field and this may have uncertainties. The recommendations could not be also transferred to the other places where the climate, soil type and plant variety are different. From a diagnostic point of view, we identified cases of extreme nutrient deficiency to identify the most serious problem cases. Defining a realistic target yield is needed before giving fertilizer recommendations. Fertilizer recommendation for these areas should directed towards blending that has balanced fertilizer which incorporates both soil macro and micro nutrients.

Macro nutrients

Our results showed that the soils in the study area were short of both macro (N, P, K) and micro (B, Zn, Mn, Cu) nutrients which makes them marginally suitable for maize production. Kihara and Njoroge (2013), for example, reported that omission of P and N result in a 50% and 43% reduction in yield, respectively, relative to a full NPK treatment. Poor soil health is one of the constraints leading to low (average 1.7 tones/ha) maize yield observed in Kenya. Integrated soil health improvement interventions are required to narrow down such yield gap. Soil nutrient amendments can be approached through integrated agronomic soil fertility management and sustainable biophysical land management and socio-economic measures. The great extent to which the skills and practical knowledge of a farmer can augment yields

is well known. A main factor is the exact timing of the fieldwork including ploughing and seedbed preparation at the right soil moisture condition, fertilizer applications, seeding, weeding, etc.

About 76% of the soils have pH values which are marginally to highly suitable while the remaining 24% are slightly acidic that requires lime application. Future management should consider maintaining the current pH level of most soils. CAN fertilizer, which contains about 8% calcium and 26% nitrogen, is preferred to use for such acidic soils. DAP (18:46:0) and CAN (26:0:0) were the most widely applied fertilizers as basal and top-dressing applications, respectively. Only less than 15% of the farmers apply NPK (17:17:17). This current fertilizer application rate does not address the potassium which critically deficient in the study area. It is therefore advisable to increase the application rate of NPK (17:17:17) to address macro nutrient gaps observed in the study area. It is critical to address all the micro-nutrients deficiency.

It is important to identify non-responsive soils before fertilizer recommendations. According to Ichami et al. (2019), soil pH, exchangeable K, P-Olsen, total C, silt and average rainfall during a growing season were the significant predictors of variation in fertilizer response in Kenya. Non- responsiveness of poor soils is often related to low soil organic matter content (Tittonell & Giller, 2013), causing soil physical constraints (low water-holding capacity), low micronutrient availability (Kihara, Sileshi, & Nziguheba, 2017) and low microbial activity. Only less than 10% of the soils in the study area fall under the non-responsive soil categories (Ichami et al., 2019) which is soil carbon level of less than 1.1%.

Micro nutrients

About 47% of the soils have extremely low Boron content making the fields unsuitable for maize production. The obvious fertility gaps occur due to the absence of micronutrients in the available fertilizer. Yield can be increased by use of fortified NPK, CAN, inorganic fertilizes or by blending fertilizers to incorporate S, Zn, Cu, Fe, Mn, B, and Mo nutrients which are required for plant growth at different stages.

NPK or Mavuno fertilizer are recommended for planting periods while CAN or Urea can be used for topdressing when the crop reaches at knee height. TSP fertilizers can be used in place of DAP whose continuous use leads to soil acidity.

Most of the farmers were using inorganic fertilizers. These fertilizers were addressing issues of N, P, K and Ca. From this, most of the required nutrients are lacking especially from the existing fertilizers. These nutrients include Sulphur, zinc, copper, iron, manganese, boron, molybdenum and aluminum. Other gaps that contribute to low yield are the insufficient soil information and fertilizer use knowledge. Several finds reported the positive relationships between ecosystem and human health. Crops grown in Zinc deficient soils could have Zinc deficiencies (Gibson, 2012) Such dietary Zn deficiency can have a range of health impacts including increased risk of child mortality due to diarrhoeal disease and stunting (Salgueiro et al., 2002). The use of Zn-containing fertilizers to increase dietary Zn supply is one of several strategies to address dietary Zn deficiency. Joy et al. (2015) recommended Zinc-enriched fertilizers as a potential public health intervention in Africa.

The most important management interventions are therefore to replenish the soil nitrogen phosphorus and potassium content and micronutrients such as boron, zinc and copper. Preserve, manage and build up soil organic matter content through recycling of crop residue and use of farmyard and compost manure. In these agroforestry technology fits very well. Fertilizer containing N, P an K which are fortified with micronutrients e.g. boron and zinc should be applied to supplement what is available in the soil. Micronutrient blended fertilizers e.g., Mavuno from Athi River Mining are some sources for increasing micronutrient contents.

According to Bindraban et al. (2018), there are several fertilizer distribution companies and retail outlets, mainly for NPK fertilizers in Kenya. In addition, there are five blending fertilizer companies: Export Trading Group (ETG), Toyota Tshusho, MEA Ltd, Minjingu, and Athi River Mining (ARM). These companies blend fertilizer based on soil tests and requests made mainly through large-scale farming operations. The main micronutrient additions to the NPK products are S, Zn, Cu, Ca, Mg, and Mn.

However, further research on crop response to the recommended interventions is critical to reduce any uncertainties and learning for adaptive management.

Limitations of the study

- All management interventions recommended were not validated using crop-fertilizer-response trials which is critical to learn from performance of interventions adapt management. Therefore, we gave broad recommendations on fertilizer types and amount using current soil nutrient values and widely used fertilizers used in the study area. We did not consider cost of inputs, target yield, capital available and price of crops into account. The use of fertilizers in maize production is often economic where improved varieties are used.
- All soils in the study region have micro-nutrient deficiencies. We did not find experience of addressing micro-nutrient deficiencies in the study area. This limits this report to give realistic recommendations to addresses micro-nutrient deficiencies. This will be further investigated.
- There was lack information on information on crops' soil requirement in Africa. We used Maize as an example crop to evaluate the soil nutrient health gap. The broad fertilizer recommendations we gave could also be applicable for other crops.
- We recommend organizing a stakeholder meeting which involves national and County level researchers to get their feedbacks on the recommendations. Such platform/ workshop to co-design a robust and optimum input recommendations.
- The yield and manure data were collected from only 17 demonstration farms that the results may not represent the entire study area.

4. CONCLUSION

The use of soil and agronomic survey was important to understand the cause of the current yield gap and target interventions to increase crop production. . Affordable innovations for land health assessment and other methods for data and information mining to address spatial soil constraints and yield potentials are important. In this project, we have demonstrated the use of soil and plant health evaluation using rapid and low- cost spectral technique to gain insight on management practices could improve crop production in small holding farmers in Muranga County.

Our results showed that the soils in the study area were short of both macro (N, P, K) and micro (B, Zn, Mn, Cu) nutrients which makes them marginally suitable for maize production. About 76% of the soils have pH values which are marginally to highly suitable while the remaining 24% are slightly acidic that requires lime application. Future management should consider maintaining the current pH level of most soils. CAN fertilizer, which contains about 8% calcium and 26% nitrogen, is preferred to use for such acidic soils. DAP (18:46:0) and CAN (26:0:0) were the most widely applied fertilizers as basal and top-dressing applications, respectively. Only less than 15% of the farmers apply NPK (17:17:17). This current fertilizer application does not address potassium which critically deficient in study area. It is advisable to increase the application NPK (17:17:17) to address macro nutrient gaps observed in the study area. It is critical to address all the micro-nutrients deficiency. About 47% of the soils have extremely low Boron content making the fields unsuitable for maize production. About 78% of the top soils have soil organic carbon value of less than 2%.

We found soil carbon significantly correlated with macro and micro-nutrients thus increasing the soil carbon level thought sustainable land management practices like application of manure and agroforestry interventions is important to improve crop response to fertilizers. Maize requires a well- drained sandy loam to silt loam soils. High clay content (> 60%) was also identified as an inherent soil constraint for most fields which cannot be modified by management.

We found a mean maize grain yield of about 2.5 t/ha. The variation in yield was wide (0.6- 6.1 t/ha). This indicates the study area has the potential to increase yield at least for those with those farmers producing lower than the mean/median values with appropriate inputs and improved production system.

We further recommend:

1) To study soil nutrient budget in the maize production system over a longer period of time. We also recommend implementing of on-farm crop response studies to screen the various soil nutrient enhancement options to match local contexts and determine the attainable maize grain response to and potential of profitability agro-inputs.

2) We also observed information gaps in maize nutrient requirements, critical limits and suitability grading. Similarly, literature on the critical nutrient values or sufficiency ranges for maize leaves/tissue are also lacking in Africa that future researches should consider addressing these gaps.
3) To minimize production losses and moving farmers towards more sustainable production should be a priority management intervention. When implementing technologies to reduce yield gaps, implementers should make due consideration for the technology's labour requirements, the farmers' financial ability and the farmers' management practices. Therefore, it is important develop the capacity of farmers on proper farm management practices particularly on conservational tillage practices and on weeding.

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Annex 1: Interpretive ranges for plant nutrients in corn leaf tissue at silking to tasseling as used by the Soil & Plant Analysis Lab, W-Madison

Nutrient	Unit	Deficient	Low	Sufficient	High	Excessive
N	%	<1.75	1.76-2.76	2.76-3.75	> 3.75	
P	%	<0.16	0.16-0.24	0.25-0.50	>0.50	
K	%	<1.25	1.25-1.74	1.75-2.75	>2.75	
Ca	%	<0.10	0.10-0.29	0.30-0.0.6	0.61-0.9	>0.9
Mg	%	<0.1	0.1-0.15	0.16-0.4	>0.4	
		<0.1	0.1-0.15	0.16-0.5	>0.5	
Zn	ppm	<12	12.0-18.0	19-75	76-150	>150
B	ppm	<2	2.0-5.0	5.1-40	41-55	>55
Mn	ppm	<12	12.0-18.0	19-75	>75	
Fe	ppm	<10	10.0-49.0	50-250	251-350	>350
Cu	ppm		<3	3.0-15	16-30	>30

Source: Schulte and Kelling (2017). Interpretive ranges for plant nutrients in corn leaf tissue at silking to tasseling as used by the Soil & Plant Analysis Lab, W-Madison

Annex 2: Soil suitability criteria used for maize suitability and nutrient status evaluation. The values in red are % of top (0-20 cm) soils under the different suitability ranges

Property	Unit	Highly Suitable	Moderately Suitable	Marginally Suitable	Not Suitable	Source
pH		6.5 - 7.3	5.5-6.5 7.3-8.4	<5.5 >8.4	-	AfSIS*
		4%	72%	24%	0%	
CEC		> = 20	15 - 20	10-15	< 10	Naidu 2006**
		19%	36%	39%	6%	
Organic Carbon	%	>= 1.7	1.1 - 1.7	0.5 - 1.1	< 0.5	Naidu 2006
		51%	45%	4%	0%	
Slope	%	<= 3	3-5	5-8	> 8	Naidu 2006
		34%	29%	24%	13%	
Clay	%	27 - 60	15 - 27 60 - 70	8-15 70 - 85	< 8 > 85	Naidu 2006
		3%	2%	25%	70%	
Total Nitrogen	%	> 0.5	0.3-0.5	0-1-0.3	< 0.1	AfSIS
		0%	0%	99%	1%	
Available P	mg/kg	> 150	80-150	15-80	< 15	AfSIS
		0%	0%	6%	94%	
Potassium	mg/kg	> 900	600-900	90-600	< 90	AfSIS
		1%	4%	85%	10%	
Calcium	%	> 80	70-80	30-70	< 30	AfSIS
		176%	0%	0%	0%	
Magnesium		>25	18-25	8-18	< 8	
		100%	0	0	0	
Manganese	mg/kg	> 500	300-500	60-300	< 60	AfSIS
		2%	39%	59%	0%	
Copper	mg/kg	> 30	20-30	0.5-20	< 0.5	AfSIS
		0%	0%	100%	0%	
Zinc	mg/kg	> 20	10-20	1-10	<1	AfSIS
		2%	2%	96%	0%	
Boron	mg/kg	> 4	2-4	0.5-2	< 0.5	AfSIS
		0%	0%	60%	40%	

* Africa Soil Information Service

** Naidu et al. 2006. Manual Soil-site suitability criteria for major crops, National Bureau of Soil Survey and Land Use Planning (ICAR), I