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Soil fertility Evaluation for the Potential Coffee Areas in Morogoro and Mvomero Districts, Eastern Tanzania

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Abstract Soil fertility evaluation for Arabica and Robusta coffee was conducted in Morogoro and Mvomero districts, representing the historical, yet insignificant, Eastern coffee area. Field characteristics were recorded and soil samples collected from 0-30, 30-60 and 60-90 cm depths in nine wards per district. Samples were analyzed for soil texture, pH-water, organic carbon, total nitrogen, available phosphorus, CEC, exchangeable bases and extractable Cu, Fe, Mn and Zn. Qualitative (simple limitation), quantitative evaluation of the supply potential of N, P and K, spatial and multivariate statistical analysis were used. Over 70% of survey sites were moderately fertile, implying that coffee production is viable. Mvomero was lower than Morogoro in both pH and OC; hence lower in total available NPK. Soil pH, OC, available P, Fe, Mg/K, TEB and K/TEB explained 32.05% of the total variability, with CEC, BS and ESP explaining 19.00%. Four ward clusters were identified, with clusters best expressed by micronutrients (Cu and Fe), followed by total N, Na, K/TEB, Zn, Mg and K. Soil fertility limitations were low pH, low Ca and K, low OC, low N and very low micronutrient levels. District councils should devise coffee development programmes, taking cognizance of the intervention strategies suggested in this work.

Keywords: *evaluation, potential coffee areas, soil fertility, Eastern Tanzania*

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1. Introduction

Coffee is one of Tanzania's primary agricultural export commodities. Its importance in the Tanzanian economy is well documented by [1,2,3,4] among others. Coffee production in Tanzania has been oscillating around an annual average of 50,000 metric tons, contributing only 0.6% of global coffee output. In order to boost coffee production to at least 100,000 metric tons in 2021, the Tanzania Coffee Board, together with other coffee stakeholders, is implementing a coffee industry development strategy 2011-2021 [5], one of the approaches being to expand coffee growing land by encouraging investments in potential but currently insignificant coffee areas. One such area is the Eastern coffee zone, particularly Morogoro Region.

The Eastern Zone has history with coffee. It is noted in [6] that Arabica coffee was imported by the French Catholic missionaries from the Reunion Islands, through Kilwa Port in 1883, and planted for the first time at Matombo village in Morogoro. In 1885, it was introduced at Kilema Parish, Kilimanjaro before moving further to Nyeri, Kenya in 1896. This historical fact underscores the importance of coffee in this zone, which, unfortunately, does not reflect itself in terms of production. According to [5], Morogoro and Mvomero districts are regarded as insignificant coffee areas but with potential for coffee expansion. Both Arabica and Robusta coffee are grown, in less-than-commercial scale. The hypothesis was that farmers are either not aware as to whether their soils have potential for coffee establishment at a commercial scale, or they are not motivated to improve productivity due to some intrinsic factors within their own system. The rationale for this study was therefore to fill the knowledge gap by providing up-to-date soil information for use by interested investors, and also to identify impediments for expansion of coffee cultivation.

2. Materials and Methods

2.1. Study Area

The study districts lie approximately between Latitudes 6.01° and 7.54° S and Longitudes 37.39° and 38.31° E. The altitude ranges from 132-528 meters above sea level (masl) for Morogoro and 393-1636 masl for Mvomero.

The two districts experience unimodal rainfall pattern with annual total of 892 mm (Morogoro) and 1063 mm (Mvomero). Mean temperatures are 24.3°C and 24.5°C respectively for Morogoro and Mvomero. Land use in these two districts consists of approximately 10-20%

under forest (on higher slopes of Mvomero) or woodland and up to 80% under agriculture: mainly coffee, banana and vegetables, irregularly mixed with maize, beans, cassava, pigeonpeas, sugarcane and scattered cocoa trees [7].

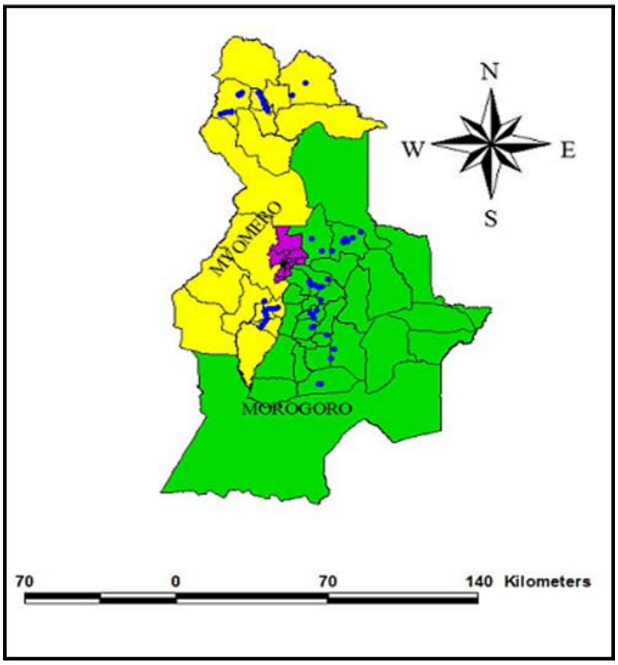

Figure 1. Study areas with survey sites in blue dots

2.2. Soil Survey

In September 2013, a total of nine wards were surveyed in each of the two districts of Mvomero and Morogoro Rural (See Figure 1 and Appendix 1). The survey sites were georeferenced by using a GPS, and the information was later geocoded and input into the GIS database. Soil characteristics investigated were depth, drainage, colour, texture, structure, consistence, porosity and root distribution. Presence of morphological features such as compaction and gravely layers were described and recorded. One representative profile per district was accorded a Class 1 description [8] and a two-tier classification according to World Reference Base for Soil Resources [9].

2.3. Soil Sampling and Analysis

Soil sampling was done by using hand augers at pre-defined depths 0-30, 30-60 and 60-90 cm in the survey sites. Where sampling was done in coffee fields, casual interview was administered to the owners to solicit their views as to the impediments to coffee development. A total of 184 soil samples (109 from Mvomero and 75 from Morogoro Rural) were collected and sent to Lyamungu Soil Fertility Laboratory. They went through the routine of registration, air-drying, grinding by means of a soil grinder, sieving through the conventional 2-mm sieve and properly packaged. They were analyzed according to procedures outlined by [10,11,12]. Soil pH was determined from a 1:2.5 soil water suspension using an electrode pH-meter. Cation exchange capacity (CEC) and cation levels were determined through extraction with NH_4OAc at pH 7 followed by distillation-titration for CEC and atomic absorption spectroscopy for the exchangeable bases. Organic carbon (OC) determination followed the Walkley and Black wet digestion method. Total nitrogen was determined through the semi-micro Kjeldahl method, while phosphorus was determined colorimetrically using Bray & Kurtz 1 method. The micronutrients Fe, Mn, Cu and Zn were determined by diethylene triamine penta-acetic acid (DTPA) extraction followed by atomic absorption spectroscopy.

2.4. Soil Fertility Evaluation

A qualitative approach in soil fertility evaluation for both Arabica and Robusta coffee, following the simple limitation method suggested by FAO [13,14] and adopted in [15] was used. The soil data were assessed against the requirements of the two coffee species (Appendix 2) as adapted from [16,17,18,19]. Separate parameters were scored and total scores assigned new ratings. Final scores ranged from 0 (very poor) to 4 (very fertile) with descriptions shown in Appendix 3. Parameters involved in the scoring were soil pH water, Ca, Mg, K, CEC, OC, Total N, available P, extractable Cu, Fe, Mn and Zn, and texture. The distribution of rating scores were exposed to descriptive statistics on Excel Spreadsheet and expressed as percentages of the number of samples analyzed. In the quantitative approach, only a few selected parameters were involved: pH and OC as fertility drivers, and N, P and K as primary macronutrients, as in [20]. Soil pH was used to establish the correction factors for available N, P and K (fN, fP and fK). Then relationships were empirically worked out between the correction factors, OC and the amount of total N, available P and exchangeable K to get the total available forms of each in kg ha^{-1}. The nutrient equivalent factors of 1, 0.175 and 0.875 were derived for coffee as suggested by [21] and used to make the amount of nutrients uniform, and therefore additive. Soil fertility was measured in terms of total soil available nutrients (TSA) in kE ha^{-1}.

2.5. Mapping of Soil Fertility Status

ArcView GIS Version 3.2 was used to build shapefile database from the original Excel spreadsheets. A base map boundary layer was digitized from the National Census Database Map of 2012. Attribute data generated during the field work and laboratory analysis were geocoded into GIS-compatible format and loaded into the attribute tables. The shapefiles were then exported to QGIS Version 3.2 for spatial interpolation of important fertility attributes. The inverse distance weighting (IDW) algorithm was used to interpolate pH, CEC, OC and TSA in kE ha^{-1}, with the resultant rasters clipped on basis of the boundary shapefiles.

2.6. Statistical Data Analysis

The raw data were exported to the Statistica V7 Software for further processing and multivariate analysis. The principal component analysis (PCA) was performed with 16 parameters, while cluster analysis was done with 18 wards and 20 parameters, where clustering was by

Euclidean distance, as in [22]. Data used in PCA were those of pH, CEC, OC, total N, available P, percent clay, extractable Cu, Fe, Mn, Zn, TEB, Ca/Mg, Mg/K, K/TEB, BS and ESP. In cluster analysis, individual bases Ca, Mg, K and Na were also involved.

3. Results and Discussion

3.1. Pedological Properties of the Study Area

A summary of the detailed description of soil profiles representative of the two districts is given in Table 1. The Mvomero profile, with an argic subsoil layer having CEC of 10 cmolc kg^{-1} and BS 32.8% was classified as a Haplic Acrisol (Cutanic, Profondic); while that of Morogoro, with a cambic horizon having same CEC value but a lower BS of 15.1% was classified as a Dystric Cambisol (Luvic, Ferric). Both are common soils for coffee in Tanzania, according to [23].

Table 1. Some attributes of representative soil profiles in the study areas

Site	Mvomero	Morogoro
Profile location	Peko Misegese (37°34'317" E/ 06°59'802" S; 777 m ASL.)	Mkambarani (37°48.823 E/ 06°46.302 S; 455 m ASL.).
Parent material	Colluvial and alluvial derived from metamorphic - gneissic rocks.	Colluvial and alluvial derived from metamorphic - gneissic rocks.
Soil properties	Ustic, hyperthermic, fairly deep, well drained B to RB, SCL to clay, with thin brown SCL topsoils.	Ustic, hyperthermic, very deep, well drained B, BB to O, SL throughout.
Diagnostic properties	Moderate to very strong coarse AB subsoil with clay cutans increasing with depth. gradual/diffuse and wavy boundary.	Medium and fine SAB, with no cutans in the subsoil. Gradual/diffuse, wavy boundary.
Analytical indicators	Low CEC (≤ 22 cmol(+) kg^{-1}) and BS of average 32.8%	Low CEC (≤ 22 cmol(+) kg^{-1}) and BS of average 15.1%
Soil name	Haplic Acrisol (Cutanic, Profondic).	Dystric Cambisol (Humic, Ferric)

Colours: B=brown, RB=reddish brown, BB=bright brown, O=orange. Texture: SCL=sandy clay loam; SL=sandy loam. Structure: AB=angular blocky, SAB=subangular blocky.

3.2. Qualitative Evaluation Results

A summary of qualitative evaluation results is given in Table 2 and Table 3 for Arabica and Robusta coffee respectively, with data expressed as percentages of the total number of survey sites per district. The extremes (categories 0 and 4) did not feature in the surveyed locations; neither for Arabica nor Robusta. The absence of Category 0 (low fertility) in the survey sites is encouraging in that none of the survey sites is totally unsuitable for coffee. On the other hand, the absence of Category 4 (high fertility) means that none of the sites is perfect; therefore some form of ISFM is needed for coffee to grow and produce optimally. Morogoro appears to be better suited for both Arabica and Robusta than Mvomero, with 10.35% and 17.25% of survey sites in the former falling under Category 3 (moderately high fertility) with none in the latter. Over 70% of the survey sites fell under Category 2 (moderate fertility), thus needing moderate ISFM efforts to produce coffee optimally. Soil fertility limitations are low pH, low nutrient cation level (particularly Ca and K), low OC and particularly low N levels. Also the micronutrients were in all cases far below their threshold levels.

Table 2. Percentage ratings for the two districts (Arabica coffee)

District	n	0	1	2	3	4
Mvomero	37	0	18.92	81.08	0	0
Morogoro	29	0	17.24	72.41	10.35	0

Table 3. Percentage ratings for the two districts (Robusta coffee)

District	n	0	1	2	3	4
Mvomero	37	0	5.41	94.59	0	0
Morogoro	29	0	10.34	72.41	17.25	0

3.3. Quantitative Evaluation Results

The total soil availabe nutrients ranged from 43.3-715.6 kE ha^{-1} (Morogoro) and 129.8-608.2 kE ha^{-1} (Mvomero). Extremes on both ends were noted in Morogoro where two sites in Kinole recorded 43.3 and 81.37 kE ha^{-1}, which showed to be related to low pH values of 4.26 and 4.33 respectively. At the other end is Mtombozi site in Matombo Division (where Arabica coffee was first planted in 1883) which showed to be most fertile with the natural capacity to supply N, P and K to plants at the level of 715.6 kE ha^{-1}. This could be associated with optimal pH of 5.8 and optimal K level of 0.82 cmolc kg^{-1}.

3.4. Spatial Presentation

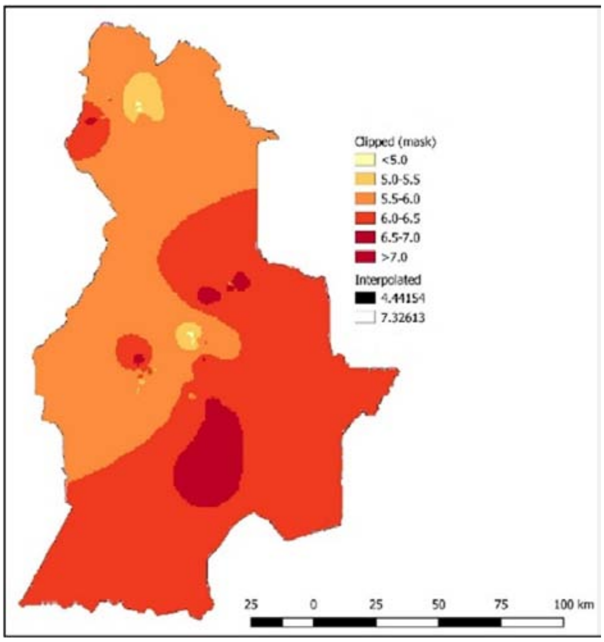

Figure 2a. Soil pH variation over the study areas

Figure 2 shows the spatial distribution of pH, CEC, OC and TSA in the study areas. The pH and OC (Figure 2a and 2c respectively) showed an almost equal pattern with cut-off points at pH 6.0 and OC 1.5%. Values below the cut-off points dominated in Mvomero while those above dominated in Morogoro. Both can have some relationship with altitude, whereby respective averages are 1073 and 369 masl. Approximately 75% of the area has CEC of 40 cmolc kg^{-1} and above, mainly to the south (Morogoro) and North East (Mvomero). As for the TSA, which is a quantitative measure of soil fertility [15], the whole of Morogoro, plus Mgeta and Mlali Divisions of Mvomero, have ≥ 300 kE ha^{-1}, while the northern part is less fertile (< 300 kE ha^{-1}). The implication is that Mvomero is slightly less fertile than Morogoro, thus needing a more intensive ISFM effort.

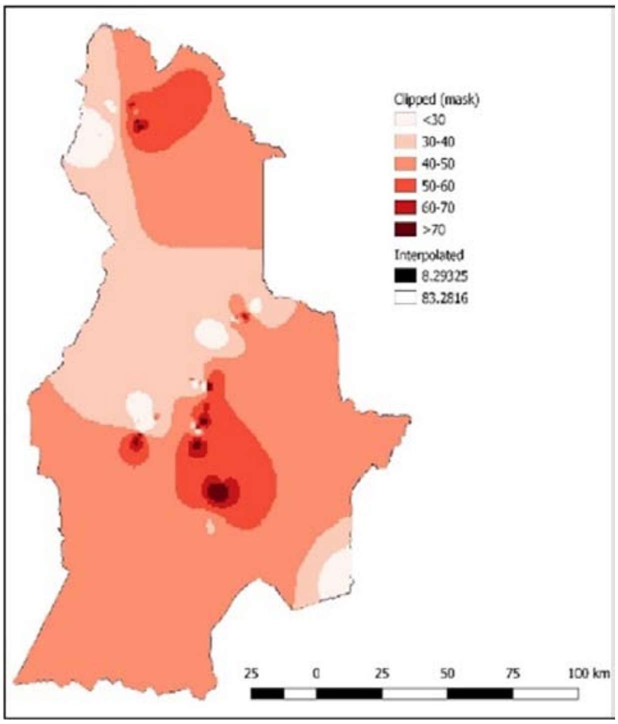

Figure 2b. Variation in CEC over the study area

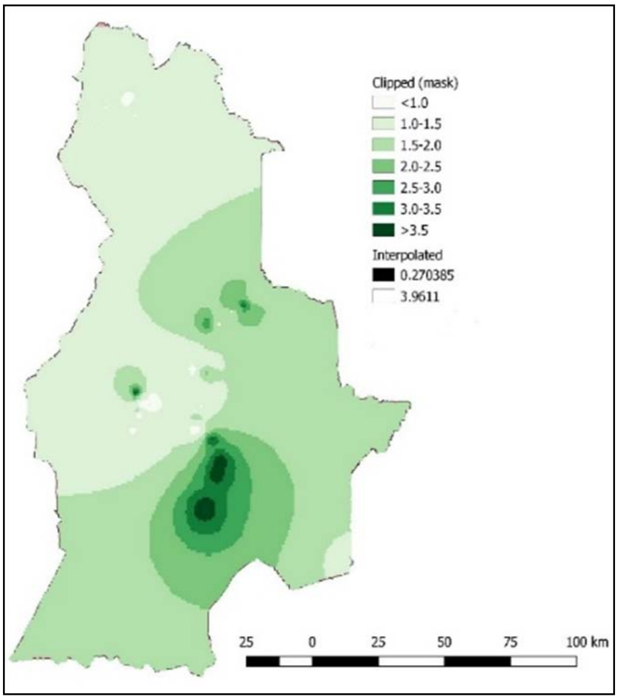

Figure 2c. Variation in OC over the study area

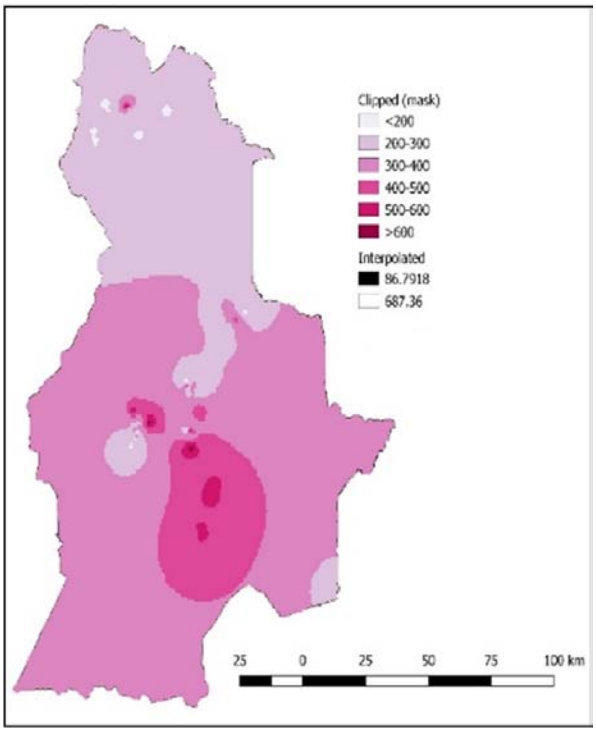

Figure 2d. Variation in NPK supply potential over the study area

3.5. Multivariate Statistical Results

There were five principal components that could explain 83.6% of the variability, with eigenvalues greater than 1.0. The first two, which account for slightly over 50% of the total variability were used in this analysis. The first principal component with eigenvalues of 5.13 explains 32.05% of the variability and shows strong influence of pH, OC, available P, Fe, Mg/K, TEB and K/TEB. The second principal component with eigenvalues 3.04 explains 19.00% of the total variability, with strong influence of CEC, BS and ESP. The other parameters (total N, % clay, Ca/Mg, Zn and Mn) showed a rather weak influence on the soil fertility of the study districts. The variable projection on the factor plane for the two principal components is given in Figure 3a.

In the cluster dendrogram (Figure 3b), four ward clusters are clearly seen. At 10 Euclidean distances (EDs), Mhonda and Nyandira, joined with Kanga, constituted Cluster 1. Cluster 2 comprises Maskati and Bunduki, joined with Kinda. All these are in Mvomero. Cluster 3 has Langali (Mvomero) and Mkambalani (Morogoro). At 20 EDs, the three clusters join variously with one another, and with Kisemu, Mtombozi, Kinole, Kibaoni, Mlali, Mkuyuni and Mikese to form a supercluster. We call this the Northern Supercluster. Cluster 4 is the Southern Supercluster, starting with Lundi and Mvoha between 10-20 EDs, joined variously with Bwakilachini at 20 EDs and the Northern Supercluster at about 52 EDs. The within-cluster variability is best described in terms of micronutrients Cu and Fe, followed by total N, Na, K/TEB, Zn, Mg and K , which dominated Objects 1-2 at < 1.0 EDs. pH was not as important here as in Barahona [22], as it only made a break at 12.76 EDs and dominating at higher EDs. The least contribution to the variability in soil fertility for the study wards was from CEC and available P, covering Objects 19-20 at > 120 EDs.

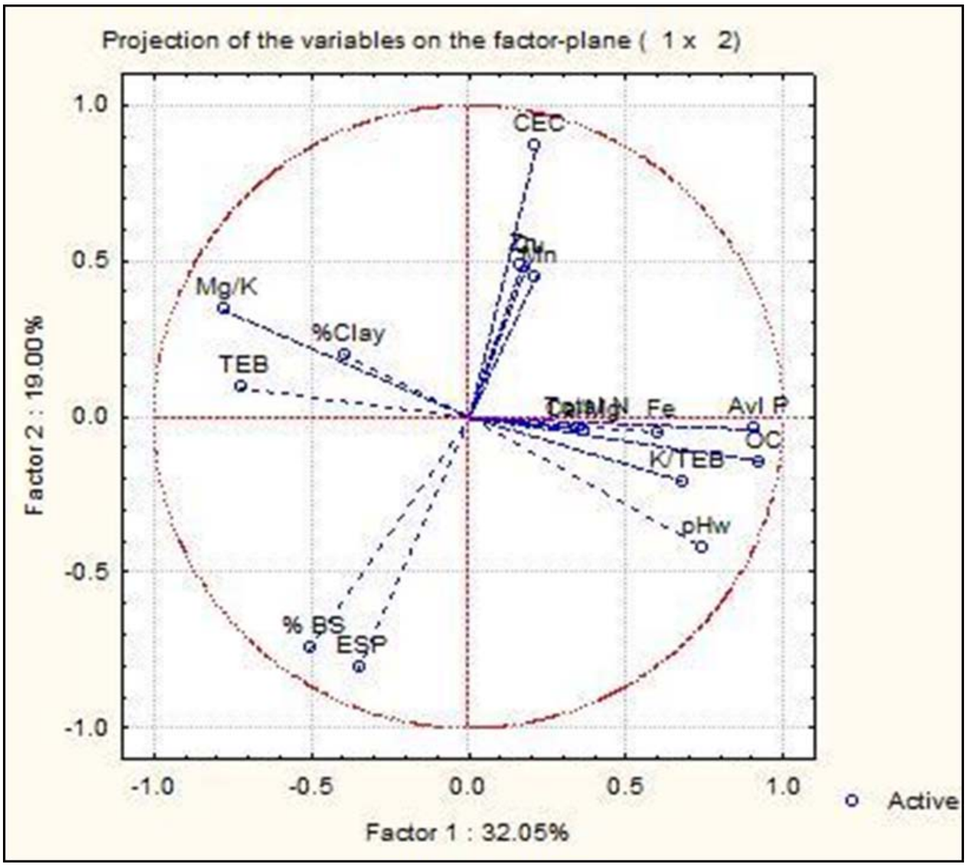

Figure 3a. PCA results for soil fertility parameters

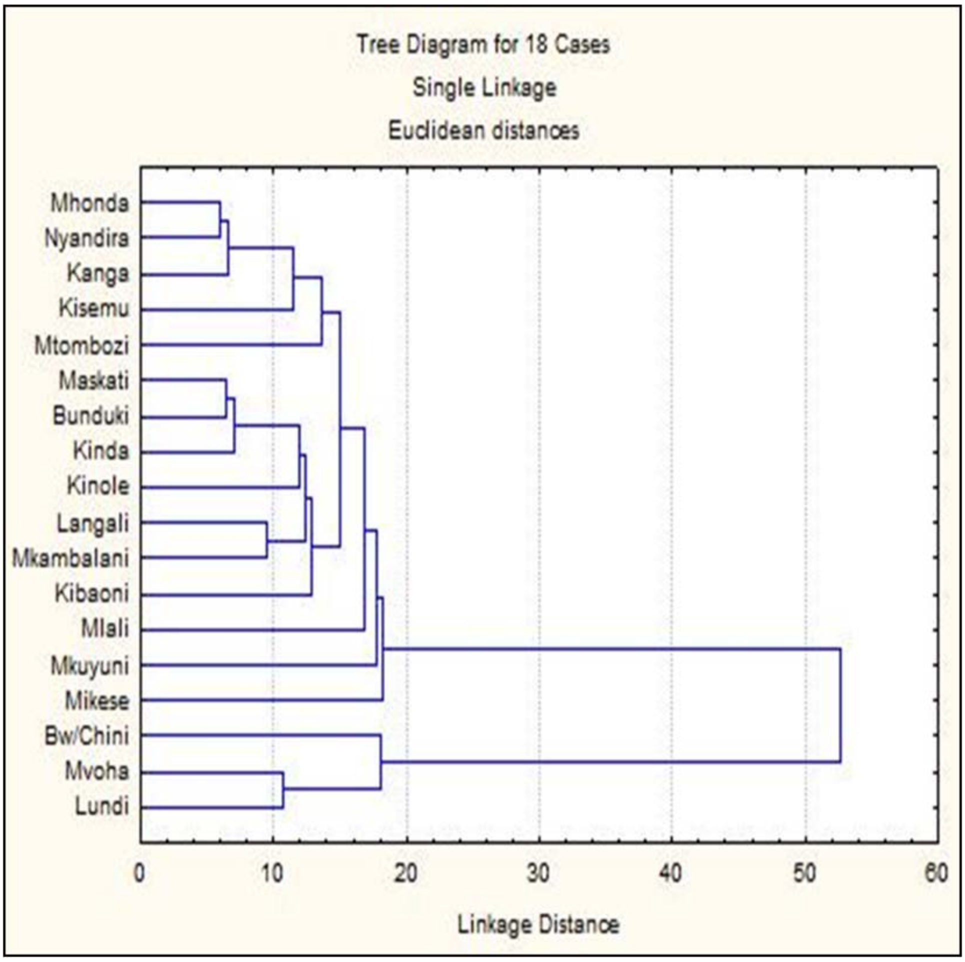

Figure 3b. Cluster analysis results for wards

3.6. General Discussion

Soil fertility evaluation of an area or region is one of the basic decision making tools for sustainable soil nutrient management [24,25]. It can be carried out at a general scale as in [26,27] or with reference to specific crops as in wheat [28], vegetables [25], coffee [15,22]. It may also be related to specific farming systems as in dryland farming [29]. Impliedly therefore, the complexity of approaches and the level of details involved differ from one situation to another. Some researchers go straight to soil sampling and analysis as suggested by [26] while others like [24,29] are more detailed, including some exploratory information such as profile description. This work belongs to the latter category, just like in [15] who worked on soils of Hai and Lushoto Districts, Northern Tanzania. In terms of the methodologies used, this particular work is a blend of [15] for pedological description, qualitative, quantitative and spatial analysis, and [22] for multivariate statistics.

According to [23], cited in [30], the Tanzanian soils that grow coffee belong to seven reference groups which include the Acrisols and Cambisols described in this work. It was noted that soils in the two districts are neither totally unsuitable for coffee, nor are they perfect; therefore some form of ISFM is needed for coffee to grow and produce optimally. Having over 70% of the survey sites under moderate fertility category is an encouraging indication for coffee production. The qualitative, quantitative and spatial analysis all agree that Mvomero is slightly less fertile than Morogoro, thus needing a more intensive ISFM effort.

Multivariate statistics, as described by [31], are those statistics in which there are more than two variables simultaneously analyzed. Many different approaches are available depending on the type of data; however, the two methods used in this work have shown much success in dealing with soil fertility data. PCA uses an orthogonal transformation to convert a set of possibly correlated variables into a set of values of linearly uncorreleted variables called principal components [32]. It is well described, step by step, by [33], who also states the importance of the so-called eigenvalues (the variance explained by each principal component). The first principal component in this work was strongly influenced by direct indicators of soil fertility which can easily be manipulated through tailored ISFM. Cluster analysis [34] is a technique that finds groups of similar items within a data set. Hierarchical agglomerative cluster analysis defined ward clusters (cases) and explained the within-cluster differences (variables). Clusters with geographical affiliation were noted, with clustering best described in terms of micronutrients Cu and Fe, followed by six other parameters. These results support the view from qualitative, quantitative and spatial analysis, that coffee production is a viable venture in the two districts.

One may ask, why then is coffee not as important a crop as it should be, given its historical background? According to [7], bio-physical constraints to coffee production in the Eastern coffee zone are diseases (mainly CBD and CLR), pests, declining soil fertility, soil erosion and poor husbandry practices. Many of these bio-physical constraints are surmountable, with the advent of new disease resistant varieties, packaging and promotion of GAPs (including IPM and ISFM). This work provides information on the soil fertility status of the two districts and suggests intervention approaches to reverse the declining soil fertility, borrowing from [35,36,37]. Other approaches as used by the SECAP project in Lushoto, Tanga [38] can be called upon in the steeper slopes like parts of Mvomero to conserve soil from erosion. According to farmers interviewed during the survey, unreliable coffee market is the single biggest socio-economic constraint and a disincentive to coffee expansion. The farmers depend on individual private buyers who buy their produce at a throw-away price and make super profits. The low return to farmers implies inadequate capital and, given high price of inputs, most of the coffee fields are old and neglected.

The northern part of Mvomero, particularly the wards in the neighbourhood of Mhonda, Kanga and Maskati, has limited potential for coffee expansion due to the rolling to steep terrain of the Nguu Mountains on one hand, and on the other hand the swampy lowlands currently used for paddy or serving as outgrower farms to Mtibwa Sugar Estate. The other areas (including Mgeta and Mlali Divisions) have great potential for coffee expansion. Parts of Ulanga and Kilosa districts were also suggested by [7] to have potential for coffee introduction or expansion.

4. Conclusion and Recommendations

Soil fertility was evaluated for Arabica and Robusta coffee in two districts of Morogoro and Mvomero, Eastern Tanzania so as to provide information that will contribute to transforming this area from a minor to a major coffee area. The four distinct approaches used (qualitative, quantitative, spatial and statistical) agree that coffee production is a viable venture in the two districts, contrary to our assumption that the government has virtually given up due to so many bio-physical impediments. Soil fertility is moderate in over 70% of the survey sites with low pH, low nutrient cation level (particularly Ca and K), low OC, low N levels and very low micronutrient levels being the limiting parameters. As for the TSA, the whole of Morogoro, plus Mgeta and Mlali Divisions of Mvomero, have ≥ 300 kE ha^{-1}, while the northern part is less fertile (< 300 kE ha^{-1}). Another general agreement is that Mvomero is slightly less fertile than Morogoro, thus needing a more intensive ISFM strategy.

On the other hand, extrinsic factors like altitude and rainfall have profound influence on the choice of coffee species to grow. The coffee area in Morogoro is in lower altitude (max 600 masl) than the one in Mvomero (max 1650 masl), with rainfall following the same trend (892 mm in Morogoro and 1063 mm in Mvomero). It follows that Arabica coffee is dominant in Mvomero while Robusta is mainly grown in Morogoro, and we would suggest the same for investors who wish to open up new land for respective coffee species.

For the Eastern Coffee Zone to transform from a minor to a major producer, concerted efforts are needed. This paper therefore recommends the following:

- District councils should devise strategies for coffee development, including the intensification in the existing coffee land and expansion in new areas.
- A more detailed soil survey should be undertaken to cover a wider area (including Ulanga and Kilosa Districts not covered in this work)
- Farmers and investors wishing to open up new coffee farms should have in place an intensive soil fertility management programme, priority areas including liming, manuring, composting, green manuring, recycling of crop residues, application of Minjingu Rock Phosphate (MRP), maintenance of cationic nutrient balance and supplementation of micronutrients.
- There is a need to study the coffee marketing systems operating in the study areas and come up with ways of improvement.
- The Tanzania Coffee Board (TCB) should consider establishing an office in Morogoro, in order to coordinate the coffee development strategies and to streamline the coffee marketing system.

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Appendix 1. Divisions and wards surveyed

District	Division	Ward
Mvomero	Turiani	Mhonda
		Kanga
	Mvomero	Maskati
		Kinda
	Mgeta	Bunduki
		Langali
		Nyandira
Morogoro	Mlali	Kibaoni
		Mlali
	Mkuyuni	Kinole
		Mkuyuni
	Matombo	Kisemu
		Mtombozi
		Lundi
	Bwakila	Bwakila Chini
	Mvoha	Mvoha
	Mikese	Mkambalani
		Mikese

Appendix 2. Qualifying criteria for fertility ratings

Characteristic	0	1	2	3	4
Texture	S, LS	SL, C	SCL, SiL	SC, L	SiCL, CL
pH	<5.2, >7.8	5.2-5.4, 7.4-7.8	5.4-5.6, 6.6-7.4	5.6-5.8, 6.2-6.6	5.8-6.2
Total N	<0.08	0.08-0.10	0.10-0.12	0.12-0.14	>0.14
OC	<0.8	0.8-1.2	1.2-1.8	1.8-2.4	>2.4
Avail. P	<5	5-10	10-20	20-40	>40
CEC	**<10.0**	**10.0-16.0**	**16.0-32.0**	**32-50**	**>50**
ESP	**>12**	**8-12**	**4-8**	**2-4**	**0-2**
Exch. Ca	**<1.0**	**1.0-2.0**	**2.0-4.0**	**4.0-10.0**	**>10.0**
Exch. Mg	<0.1	0.1-0.2	0.2-0.5	0.5-1.0	>1.0
Exch. K	<0.05	0.05-0.1	**0.1-0.2**	**0.2-0.5**	>0.5
Cu	<1.0	1.0-1.5	**1.5-2.0**	**2.0-3.0**	>3.0
Fe	<10	10-20	**20-30**	**30-40**	>40
Mn	<10	10-50	**50-100**	**100-150**	>150
Zn	<2	2-4	**4-6**	**6-8**	>8
Robusta					
pH	<4.5, >7.0	4.5-5.0, 6.5-7.0	**5.0-5.3, 6.0-6.5**	**5.3-5.5, 5.8-6.0**	5.5-5.8
OC	0.8	0.8-1.0	**1.0-1.2**	**1.2-1.5**	>1.5

Appendix 3. Description of final fertility scores

Total score ranges	New score assigned	Soil fertility description	Implication to coffee
<10	0	Low	There are more than 3 limitations to coffee productivity and the coffee business is uneconomical
10-20	1	Moderately low	There are 3 limitations to coffee productivity. Intensive ISFM effort can make coffee business economical
20-30	2	Moderate	There are 2 limitations to coffee productivity. Moderate ISFM effort will make coffee business economical
30-40	3	Moderately high	There is 1 limitation to coffee productivity. Slight ISFM effort will make coffee business economical
>40	4	High	Soil is ideal for coffee productivity. Effort needed only to sustain the current soil fertility.