

Pedological Characterization and Fertility Assessment of Mbimba Substation Soils Under Coffee Production in Mbozi District, Tanzania

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Abstract

Pedological characterization was carried out on soils of Mbimba Mbozi, Tanzania. A representative soil profile (TaCRI-P1) was identified, excavated and described using FAO (2006) Guidelines. Four disturbed soil samples and three undisturbed core samples were taken from the profile horizons for physico-chemical laboratory analysis. The pedon developed under udic moisture and thermic temperature regimes was very deep (> 150 cm), well drained and had dark brown to black topsoil colour over dark brown to dark reddish subsoil colour. Soil texture ranged from clay loam to clay. Soil pH was rated as very strong acid to medium (4.73 - 5.98) for all horizons. Organic carbon was low to medium; N was very low to low; CEC was medium to high and exchangeable bases ranged from low to high. Bulk densities were high (2.24 - 2.44 g/cc) for topsoil and low (0.33 - 0.91) for subsoil. Soil moisture retention properties indicated that surface horizon (0 - 5 cm) retained more water followed by intermediate (45 - 50 cm) horizon and the subsoil (95 - 100 cm) respectively. According to USDA Soil Taxonomy and World Reference Base for Soil Resources, the pedon at Mbimba was classified as Typic Palehumults and as Haplic Alisols, respectively. These taxa reflected properties that may guide on the use and management of soils. Before lime application, the upper two horizons of the pedon had total nitrogen level ranging between 0.04 - 0.17%, Phosphorus 2.91 - 4.59 mgkg⁻¹, Potassium 2.36 - 1%, Calcium 2.36 - 2.35 cmol(+)kg⁻¹ and Magnesium 0.71 - 1.93 cmol(+)kg⁻¹ which were low to medium. Thus, application of inorganic (N, P, K - rich), Ca+Mg and organic fertilizers is recommended to increase nutrient availability. Use of CaMg(CO₃)₂ as soil amendment should be taken into consideration to raise soil pH and enhance balanced nutrient availability for coffee growth.

Key Words: Soil Characterization, Soil Morphology, Physical Characteristics, Soil Chemical Properties, Soil Classification.

1. INTRODUCTION

Characterization of soil properties is fundamental to all soil studies [1]. Complete soil characterization for classification purposes requires that all horizons of a standard soil profile (to a depth of 180 cm) be analysed. Results from such an analysis provide information that can give a clear understanding of the origin of such soils, morphology, classification and spatial distribution of soils in an area [2]. Climatic and other ecological characteristics as well as socioeconomic factors are also important elements in land management [3]. Plant nutrients in soils originate from parent materials from which soils were formed through the weathering of rocks and minerals [4]. Soil variability is the result of natural processes and management practices [5]. Natural variability results from complex geological and pedological processes. Soil properties and related site characteristics are important for one to be able to advise both current and future potential land users on how to use the land in the best possible way [2]. Assessment of the potentials and limitations of soils for different land uses provides the basis for formulating appropriate management strategies which target specific management problems to improve crop production and soil and water conservation strategies [6,2]. According to Jenny cited by [7], soil forming factors namely climate, parent material, biota, relief and time influence the morphological, physical, chemical and biological characteristics of soils. Chemical weathering of silicate rocks plays

a major role in geochemical cycles, particularly in the cycle of CO₂. Carbon dioxide is removed from the atmosphere by rock weathering process and is converted to bicarbonate in streams and eventually in oceans. Soil characterization provides better understanding of soil genesis [1]. According to [8], for effective planning for different land uses, pedological characterization provides information related to potentials and constraints of the land. The intensification of agriculture on land requires a thorough knowledge of the soil as a resource and attributes of the land, its potential and constraints for appropriate soil and water management systems [2]. In addition, environmental characteristics (e.g. climate) and socio-economic factors are also important elements in pedological characterization to provide data and knowledge on soil properties related to the site characteristics (slope, soil color, vegetation) [8]. Also, the knowledge of site characterized soil's physical and chemical properties together with other ecological conditions will aid in determining the correct type and amounts of fertilizer to be applied for optimum crop nourishment and production [2]. To carry out specific soil characterization before crop establishment is important, as crop production is a function of soil properties. Soil characterization provides the basic information necessary to create functional soil classification schemes and to assess soil fertility in order to unravel some unique soil problems in an ecosystem [9].

2. MATERIALS AND METHODS

2.1 Description of study sites

The study was conducted in Mbozi District, Songwe Region Tanzania. The study area is located within latitudes 9°05'35.97"S and 9°05'13.10"S and longitudes 32°57'14.51"E and 32°57'22.32"E. The field trial was carried out at Mbimba substation located in Mlowo Ward, Mbimba Village, 2 km from the headquarters of Mbozi District and Songwe Region along Mbeya - Zambia highway. Figure 1 shows the location of the studied representative soil profile depicted on

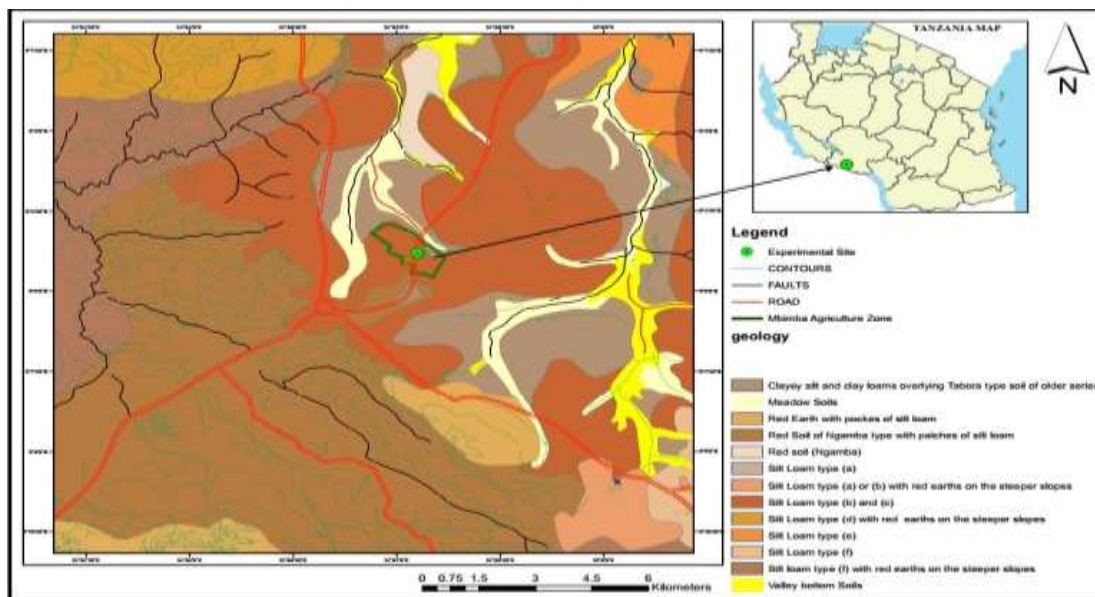


Figure 1. Location of the studied soil profile depicted on the generalized soil map of Mbimba, Mbozi District, Tanzania (Source: Tanzania Government Printer)

the generalized soil map of Mbimba, Mbozi District, Tanzania, which is based on textural differentiation. The average altitude of the study area is 1 400 m.a.s.l. The rain season starts between November and December and lasts until May. Mean annual soil temperature at a depth of 50 cm ranges between 20.9 and 22.5°C. Soil temperature trends appear to decrease from 2010 to 2017 may be due to increase in soil moisture as a function increase of rainfall. The study area experiences monomodal rainfall pattern with mean annual rainfall ranging between 1 000 and 1 500 mm (Fig. 2 and Fig. 3).

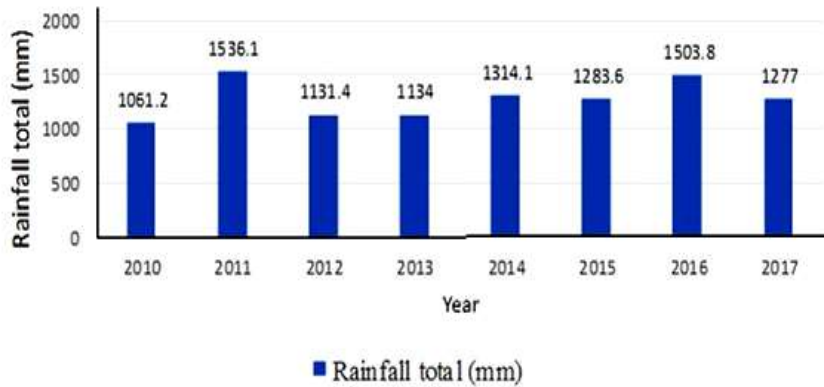


Figure 2. Mean annual rainfall in Mbozi District (2010 - 2017) Source: Mbimba Tanzania Meteorological Agency (TMA) Office

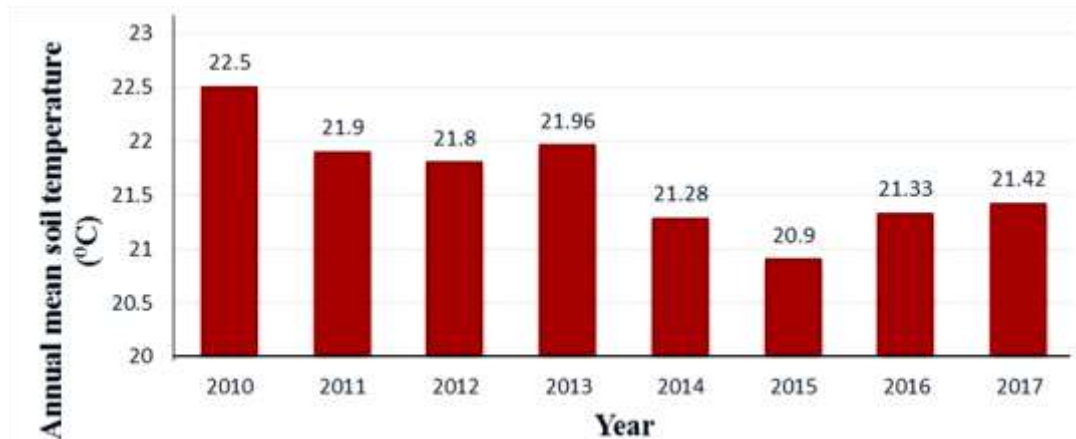


Figure 3. Annual soil temperature (20 cm depth) in Mbozi District, Tanzania (2010-2017) Source: Mbimba Agrometeorological Station

2.2 Field work

Reconnaissance survey in the study area was carried out based on transect walks, auger observations and soil descriptions to establish the soil settings at the study site on the basis of landforms and other physiographic attributes [10]. Data and information based on landform, soil morphological characteristics, elevation, slope gradient, vegetation and land use/crops were collected from different observation sites that represented the major landforms. The informations were collected and presented in field description forms designed according to the FAO Guidelines for Soil Description [10]. Based on the information gathered during the survey, a single profile for classification of the soil at the study area was established and excavated. Soil horizons were identified, demarcated, described and sampled according to FAO Guidelines for Soil Profile Description [10]. Geo-referencing of the representative profile was done using global positioning system (GPS) Model Garmin *etrex* 20. Disturbed soil samples were taken from respective genetic horizons of representative profile for laboratory determination of physical and chemical properties. Three undisturbed samples were also taken from the profile for the determination of bulk density and soil moisture characteristics.

2.3 Laboratory methods

Undisturbed samples were used for determination of bulk density and moisture retention characteristics. Bulk density was determined by the core method [11]. Pressure plate membrane apparatus [12] was used to determined soil moisture retention characteristics. Disturbed soil samples were air-dried, ground and passed through a 2-mm sieve for physical and chemical soil properties. Particle size distribution was determined by hydrometer method [13] after dispersing soil with sodium hexametaphosphate and textural classes determined using the USDA textural triangle [14]. Soil pH was measured potentiometrically in water and 1M KCl at a ratio of 1:2:5 soil-water and soil-KCl suspensions [15]. Organic carbon was determined by the Walkley and Black wet oxidation method [16] and the organic carbon was converted to organic matter by multiplying by a factor of 1.724 [17]. Total nitrogen was determined by the micro-Kjeldahl digestion – distillation method [18]. Available P was extracted by the Bray and Kurtz 1 method [18]. Cation exchange capacity (CEC soil) was determined by the 1M ammonium acetate saturation method (pH 7.0) [19]. Cation exchange capacity of clay (CEC clay) was calculated using the formula outlined by Baize [19] as follows: $[\text{CEC clay} = \{(\text{CEC soil} - (\% \text{ OM} * 2)) / \% \text{ clay}\} * 100]$. Magnesium and Ca_2^+ in the

ammonium acetate filtrates were quantified by Atomic Absorption Spectrophotometer while Na^+ and K^+ were quantified by the flame photometer, respectively. Total exchangeable base (TEB) was calculated arithmetically as sum of the four exchangeable bases (Ca^{++} , Mg^{++} , Na^+ and K^+) for a given soil sample. Formulas used for the calculation of sodium adsorption ratio, exchangeable sodium percent and base saturation were as given by [20]. Soil extractable Cu, Zn, Fe and Mn were extracted by the DTPA method [21]. The electrical conductivity was determined in 1:2:5 soil:water suspensions, electrometrically (potentiometrically) using an electric conductivity meter [22]. Soil samples for total elemental analysis were prepared through sorting, grinding to powdery form and sieving the powder sample through a sieve of 75 micro millimeters. The powdery samples were exposed to XRF spectrometry for determination of minerals composition in the samples. Total elemental composition was determined by using PAN analytical XRF spectrometry [23].

2.4 Classification of soils

Using field and laboratory data, the soil at the study area was classified to family level of USDA Soil Taxonomy [24] and to tier-2 of FAO World Reference Base for Soil Resources [25].

2.5 Soil fertility evaluation

Soil fertility characterization was carried out for the purpose of establishing the fertility status of the soil at the study site before application of dolomitic lime. By using an auger, soil was sampled at the depth of 0 - 30 cm, gathered, mixed thoroughly to constitute composite sample for the fertility evaluation. The samples were taken to SUA soil laboratory for analysis. In the laboratory the soil sample was air dried, ground to break soil aggregates and sieved through 2 mm sieve for comprehensive laboratory analysis, for soil fertility evaluation. The parameters analysed for soil fertility evaluation were; particle size distribution which was determined by the hydrometer method [26], soil pH was determined electrometrically in 1:2:5 soil: 0.01M CaCl_2 suspensions [15], organic carbon by the wet oxidation method [27] and total nitrogen by the micro-Kjeldahl digestion – distillation method [28]. Available phosphorus was determined using filtrates extracted by Bray and Kurtz-1 method and determined by spectrophotometer at 884 nm wavelength following colour developed by molybdenum blue method [29]. Cation exchange capacity (CEC) was determined by the neutral buffered 1M ammonium acetate saturation method [30]. Calcium and Magnesium in the ammonium acetate filtrates were quantified by Atomic Absorption Spectrophotometer while K^+ and Na^+ were quantified by flame photometer. Plant available Cu, Zn, Fe and Mn were extracted by the DTPA method [21]. The electrical conductivity was determined in 1:2:5 soil:water suspensions, electrometrically (potentiometrically) using an electric conductivity meter [22]. The undisturbed soil samples were used to determine bulk density and the soil moisture characteristics. The bulk density was determined by the core method [11]. Soil moisture retention characteristics were determined using sand kaolin box for low suction values and pressure apparatus for higher suction values [12].

3. RESULTS AND DISCUSSION

3.1 Morphological characteristics of the studied soil profile

Some important morphological properties of the soil profile at Mbimba TaCRI substation are presented in Table 1. The soil was very deep (>150 cm), well drained, with gray to very dark gray colour. The soil structure of the topsoil was moderate, medium subangular blocky, while the consistence was very friable when moist, and sticky and plastic when wet. The three bottom horizons (28 - 190+ cm) were very clearly different from the topsoil (0 - 18 cm). The soil structures of these horizons were moderate to strong medium subangular blocky, while the consistence was very friable when moist, and very sticky and very plastic when wet. Roots were distributed throughout the profile but highly dense at in topsoil and decreasing with increasing depth. Soil horizon boundaries were quite distinct, ranging mostly from clear to abrupt with either smooth or wavy horizon topography. Few distinct clay cutans, and common distinct clay cutans were observed respectively in the third and fourth horizons affirming the processes of clay eluviation and illuviation as typical pedogenic processes in the studied soil.

Table 1. Key morphological characteristics of the studied soil profile TaCRI-P1

Horizon	Depth (cm)	Texture	Moist Color ¹	Consistence ²	Structure ³	Other key pedogenic features ⁴	Horizon boundary ⁵
Ap	0 - 18	Clay	db(5YR3/2)	vfr, s&p	m,m,sbk	-	cs
Ah	18 - 28/35	Clay	bl(5YR2.5/1)	vfr, s&p	m-s,sbk	-	cw
Bt1	28/35 - 82/99	Clay	drb(5YR3/4)	vfr, vs&vp	m-s,sbk	fdcc	cw
Bt2	82/99 - 190+	Clay	db(7.5YR3/4)	sha, fr, s&p	m-s,m,sbk	cdcc	-

¹Soil color: db=dark brown, bl=black, drb=dark reddish brown

²Consistence: fr=friable, vfr= very friable, s&p=sticky and plastic, vs &vp= very sticky and very plastic, sha = slightly hard

³Structure: m,m,sbk=moderate medium subangular blocky, m-s,sbk=moderate to strongsubangular blocky

⁴Other pedogenic features: fdcc=few distinct clay cutans, cdcc=common distinct clay cutans

⁵Horizon boundary: cs=clear smooth, cw=clear wavy

3.2 Soil physical characteristics

Soil physical properties of the horizon soil samples are presented in Table 2.

3.2.1 Soil particle size distribution and silt/clay ratios

Tables 2.2 indicate soil particle size distribution and silt/clay ratios. Particle size distribution of the four horizons Ap, Ah, Bt1 and Bt2 all show clay texture dominance and clay content increased down the profile. The results are similar to those indicated by [31] for soils of Busia County, Western Kenya. This supports the fact that the soils has developed largely under similar soil forming factors and have attained comparable degree of pedogenesis [32]. Silt/clay ratios of the subsoil are lower compared to those of the upper two horizons indicating higher degree of weathering in the subsoil. On the basis of textural class, soils of Mbimba substation indicate good water and nutrient holding capacity that is important for coffee growing. Similarly, [33] indicated that clayey texture is associated with high water retention capacity and high nutrient retention. In Bangladesh and Western Kenya, some researchers observed consistent clay increase with depth as an indication of clay migration [34]. Texture is the most stable physical property which influences other soil properties like soil structure, consistence, soil moisture regime and infiltration rate, runoff rate, erodibility, workability, permeability, root penetrability and fertility of the soil [20]. Textural data of the studied pedons are presented in Table 2.

Table 2. Selected physical properties of the studied pedon TaCRI-P1 in Mbimba Substation, Mbozi, Tanzania

Horizon	Depth (cm)	Sand	Clay	Silt	Textural class	Silt/clay ratio	BD Mg m ⁻³	Porosity (%)	PR (MPa)	#PAW (mm)
		%								
Ap	0 - 18	30.2	47.1	22.6	C	0.48	0.97	63.4	1.01	14.4
Ah	18 - 28/35	30.2	48.1	21.6	C	0.45	nd	nd	0.79	nd
Bt1	28/35 - 82/99	22.2	60.1	17.6	C	0.29	1.15	56.6	0.84	30.72
Bt2	82/99 - 190+	26.2	54.1	19.6	C	0.36	0.95	64.2	2.21	54.60

C = clay #PAW = Plant available water nd = not determined PR = Penetration resistance

Note:

1. Porosity=(1-(Bulk density/Particle density) x 100) assuming particle density 2.65g/cm³
2. PAW(mm)=10 [Moisture at Field Capacity (FC) in m³/m³ - Moisture at Permanent Wilting Point (PWP) in m³/m³ x horizon depth in cm]
3. PR (kg/cm²) based on penetrometer model: DIK-5551 Japanese (Daiki Rika Kogyo Co. LTD. = (100 x penetrometer reading(r)/0.7952(40- r)² where r is in mm
4. PR (MPa)=PR(kg/cm²) x 0.0981

3.2.2 Bulk density and porosity

Bulk density (BD) is an important parameter for the description of soil quality and ecosystem function. The upper two horizons of Mbozi soils have BD value of 0.97g cm⁻³ while subsoil BD values of Mbimba ranged from 0.95 - 1.15 gcm⁻³. Critical levels of BD for clays are 1.0 to 1.60 gcm⁻³ and for sands is 1.20 to 1.80 gcm⁻³ with potential root restriction occurring at ≥ 1.40 gcm⁻³ for clay; and ≥1.60 gcm⁻³ for sands [35]. [37] indicated that BD critical range for clay soils is from 1.46 to 1.63 gcm⁻³ and potential root restriction occurs at values ≥ 1.4 g cm⁻³ for clays. Similarly, [36] pointed out that BD of 1.46 to 1.63 gcm⁻³ for silts and clays, may impose many stresses such as mechanical resistance, poor aeration and changes in hydrological system in soil. Mbimba soils have low BD values according to [20] who stipulated that cultivated soils have bulk density ranging from 0.9 to 1.4 gcm⁻³ which would favour the growth of coffee plants. The Mbimba soil bulk density values are similar to those reported by [31] for soils of Western Kenya. Low bulk density values may be attributed to presence of organic matter and/or the presence of allophane which contribute to formation of porous soil structure [37,38]. Bulk density affects infiltration, rooting depth, available water capacity, soil porosity, plant nutrient availability and soil microbial activity which influence key soil processes and productivity [39]. Low bulk density facilitates water infiltration, high soil microbial activity and easy plant root penetration for nutrients and water extraction. [40] indicated that, top soils that are loose facilitate root growth and easy tillage. The relatively higher bulk density in the mid horizon of studied soil profile may be due to lower organic carbon and organic matter content [41]. According to [42], as quoted by [20], bulk density of 1.46 to 1.63 for silts and clays may cause hindrance to root penetration. [11] pointed out that, bulk density is influenced by the amounts of organic matter in the soil. The bulk density determines the magnitude of particle to particle contacts and how they influence the total porosity and available soil moisture [20]. Total porosity (% vol/vol) of the

studied soils shows that topsoil has porosity of 63.4 while subsoil has porosity ranging between 56.6 to 64.2%. [20] pointed out that, total porosity of soils usually lies between 30 and 70% and may be used as a very general indication of degree of compaction in the same way as bulk density is used. The Ap horizon had higher porosity value than Bt1 horizon (Table 2). This may be due to higher organic matter in Ap horizon than in Bt1 horizon.

3.2.3 Penetration resistance

Table 2 presents the penetration resistance values of the studied pedon. Topsoil penetration resistance values of the studied pedons ranged from 0.79-1.01MPa while those of subsoils ranged from 0.84-2.21MPa. This indicates low soil compaction in topsoil which may be attributed by presence of organic matter. According to [43, 31], penetration resistance of <2.94 MPa, implies less possibility of soil compaction in the profile horizon and hence this is not likely to impair plant growth and development.

3.2.4 Soil moisture retention characteristics

Soil water retention curves of the studied profile are presented in Figure 4, showing amounts of water retained by the soil at various suction pressures for three sections of the studied soil profile i.e. surface horizon (0 - 5 cm), intermediate horizon (45 - 50 cm) and subsurface horizon (95 - 100 cm). Surface horizon retained less water than other horizons under all suction pressures. The trend of moisture retained at various suction pressures was as follows: surface soil < intermediate < subsurface soil. This is in line with the fact that clay content increased with depth (Table 2). Similar trend was observed for other soils in Tanzania [44]. When clay content increases, ability of soil to retain water increases at any particular matric potential and the more gradual is the slope of the curves [11, 45]. Moreover, the results correspond to those of [20, 45] depicting that clay soils, generally show slow and regular decrease in water content with increased suction pressure. According to [46], soil particle size distribution, organic matter and soil type influence the variation of available moisture content in the soil. Plant available water (PAW) in the studied soil profile appears to increase with increasing depth (Table 2). This is attributed to increase of clay content down the profile.

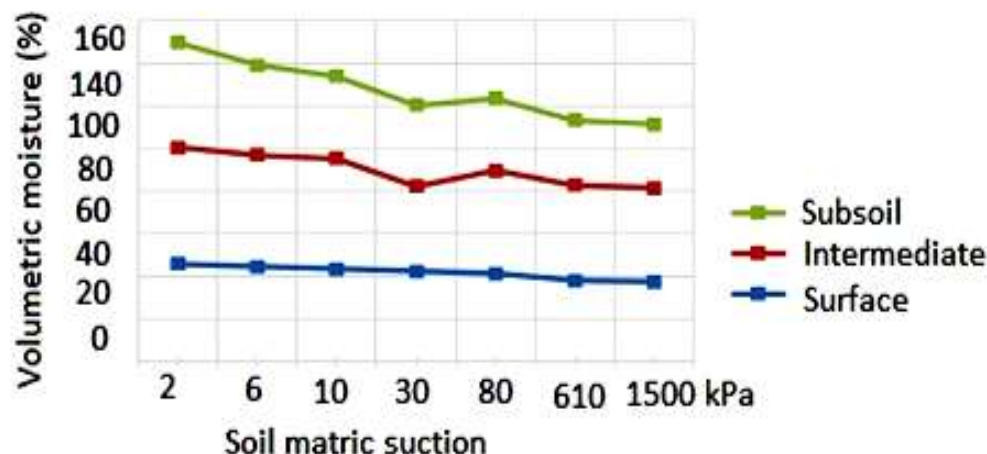


Figure 3. Soil moisture characteristics curve of the studied soil in Mbozi District, Tanzania

3.3 Chemical properties

3.3.1 Soil reaction (pH)

Soil pH is an important chemical property because of its influence on nutrient availability [47]. According to [48], coffee plants thrive well in soils of pH 5.6 to 6.6. Furthermore, [19] pointed out that most plants thrive well in soils with pH 6.5 - 7.5. From this point of view, the studied soils with pH (water) values ranging from 5.8 to about 6.0 (Table 3) may present some limitations to crop production. According to [49], low pH may adversely affect availability of various plant nutrients such as phosphorus and basic cations like Ca and Mg. According to [50], the pH values observed in the studied soil profile have been rated as medium acid. Such values are likely going to trigger nutrient imbalances, toxicity and nutrient unavailability. Low pH in horizons could be attributed to the relatively high leaching of Na, Ca, and Mg ions which is due to high rainfall and nutrient mining/uptake by plants. According to [51] low soil pH values have potential to cause toxicity problems and deficiency of some essential plant nutrients as well as affect soil microbial activities due to high concentration of H^+ and Al^{3+} . Soil pH <5.5 could also cause dissolution of aluminum and iron minerals which precipitates with phosphorus effectively causing its fixation.

3.3.2 Available phosphorus

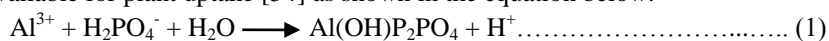
The results in Table 3 indicate that available phosphorus decreased down the pedon. According to [52], phosphorus is highly affected by pH. Phosphorus availability decreases as soils become acidic. In the Table 3, P concentration ranges between 0.11 and

4.59 mgkg⁻¹. The upper two layers of the pedon have phosphorus content ranging between 2.91 and 4.59 mgkg⁻¹. According to [20], available P (Bray-Kurtz 1) at <7 mgkg⁻¹ is considered as low phosphorus. Furthermore, concentration of P < 3 and 3 - 6.5 ppm is considered as acutely deficient and deficient respectively.

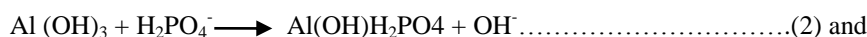
Table 3. Soil reaction and selected macronutrients

Horizon	Depth (cm)	pH 1:2:5		OC	OM	TN	C/N	Avail P mg/kg Bray and Kurtz 1
		H ₂ O	KCl					
Ap	0 - 18	5.82	4.86	2.44	4.21	0.17	14	4.59
Ah	18 - 28/35	5.79	4.84	2.04	3.51	0.15	14	2.91
Bt1	28/35 - 82/99	5.96	4.99	0.91	1.57	0.07	13	0.43
Bt2	82/99 - 190+	5.98	5.03	0.33	0.57	0.04	8	0.11

According to [53], an available P level of 15 mg/kg is generally considered as the critical level below which P deficiency symptoms are likely to occur in many crops. Trends of available P in the studied soil decreases with increasing profile depth. The possible cause can be due to decrease in organic matter content with depth because soil organic matter plays a key role in P availability due to its ability to coat aluminium and iron oxides, which reduces P sorption [54]. Similarly, low soil pH observed may provoke the reaction of P iron (Fe) and aluminium (Al) thereby producing insoluble Fe and Al phosphates that are not readily available for plant uptake [54] as shown in the equation below:



The presence of chemically active oxides/hydroxide can also fix P as follows:



3.3.4 Organic carbon, organ matter, total nitrogen and carbon/nitrogen ratio

The two-subsoil horizons have very low to low organic carbon content ranging from 0.33 - 0.91. According to [55], organic carbon less than 0.6 is considered as very low and 0.60 - 1.25 as low. The OM content in the studied pedon ranged from low to medium (0.6 - 4.2%) and decreased down the profile (Table 3). OM level in the soil is strongly correlated with the soil's CEC, and is a source of many plant nutrients, particularly nitrogen [38]. Soil organic matter enhances soil water retention because of its hydrophilic nature and its positive influence on soil structure [56]. Total nitrogen level as shown in Table 3 ranges between 0.04 and 0.17%. Total nitrogen levels of less than 0.2% and organic carbon values below 0.6% are considered low for agricultural activities [20]. According to [2], low N content in the soil can be supplemented by N fertilizer application for optimal plant growth. The low soil pH also may be the cause for low nitrogen content as low pH affects microbial activity in the soil and the consequence is low organic matter breakdown [20]. C/N ratios in the studied soil ranged from 8 - 14 and there was a general trend of narrowing of the ratios with increasing depth. According to [57], the C/N ratios in the upper 100 cm were rated to be of moderate to good quality whereas those in the deeper subsoil were rated to be of poor quality, although [57] indicated that, C:N ratio of 10:1 indicates good quality organic material, they cautioned that C:N ratio might not be a good indicator of soil fertility, and thus encouraged use of individual C and N values instead.

3.3.5 Exchangeable Ca, Mg, Na, K and CEC

The results on exchangeable cations of the studied soil profile are given in Table 4. Exchangeable cations were rated as very low to high for Calcium, while Magnesium was rated as medium and Potassium rated as medium to very high. Exchangeable cations levels were variable within the studied pedon with a general tendency for Mg and K to increase down the profile. [9] made similar observations and pointed out that exchangeable cations increase down the profile for highly leached soils. Amount of exchangeable sodium in Mbimba soils varied from 0.03 to 0.19 cmol(+)kg⁻¹ (Table 4). According to [48], sodium concentration levels <0.1 and 0.10 - 0.30 cmol(+)kg⁻¹ are considered as very low and low respectively. Thus, the upper horizon (Ap) had very low sodium while the (Ah) horizon had low sodium concentration which increases down the profile indicating leaching of Na. According to [48], soils with ESP <3 is considered as non-sodic and soils with ESP 6 - 10 considered as slightly sodic. Thus, the soils of Mbimba Mbozi are considered as not salt-affected. Potassium level ranged between 0.05 and 1 indicating low potassium concentration while the optimal concentration for optimal arabica growth is 1.21 - 2.0 mgkg⁻¹ [20]. Furthermore, in all horizons, concentration of cations increased down the profile which may be due to leaching of these cations. Levels of exchangeable cations have direct implications on the cation exchange capacity (CEC), soil pH and finally plant nutrient imbalances, unavailability and nutrient induced deficiencies. For example, Mg acts as a phosphorus carrier in plants and therefore, P uptake is influenced by exchangeable Mg [8]. Cation Exchange Capacity (CEC) in the studied soil profile was rated as medium to high (24 - 27 cmol(+)kg). High CEC is due to clay content in the pedon [58]. The [10] quotes values of 8 - 10 cmol(+)kg⁻¹ of soil as indicative

for minimum value in the top 30 cm of the soil for satisfactory crop production, provided other factors remain favourable. According to [10], any value $<4 \text{ cmol(+)kg}^{-1}$ soil (measured at the pH of the soil) indicates a degree of infertility normally not suitable for crop production. In the Table 4, percent base saturation (BS) varied from 19.62 to 30.54 cmolkg^{-1} and decreased with depth. According to [20], BS% <20 is considered as low, between 20 and 60% medium and $> 60\%$ high. Generally, the soil of Mbimba Mbozi was rated to be of low fertility. [20] pointed out that, availability of nutrients for uptake by plants depends not only upon absolute levels of nutrients but also on the nutrient ratios. Ca/Mg ratios in the studied soil profile ranged between 0.04 and 3.3 for all horizons while Ca/Mg ratios of 2 to 4 are considered as favourable for most crop plants to grow [59, 8]. The upper two horizons (Ap and Ah) had Ca/Mg ratio between 2.6 - 3.3 implying optimal conditions.

Table 4. Exchangeable bases and nutrient ratios in the studied soil profile TaCRI-P1

Site	Horizon	Exchangeable bases $\text{cmol(+)}/\text{kg}$						BS%	Ca/Mg
		Ca	Mg	K	Na	CEC	TEB		
Mbimba TaCRI	Ap	4.59	1.41	1.3	0.03	24	7.33	30.54	3.3
	Ah	4.02	1.57	0.05	0.05	25	7.21	28.84	2.6
	Bt1	1.95	1.63	1.86	0.1	27	5.54	20.51	1.2
	Bt2	0.07	1.91	3.13	0.19	27	5.3	19.62	0.04

CEC=Cation exchange capacity, TEB =Total exchangeable bases, BS=Base saturation.

3.3.6 Micronutrient concentration in the studied soil

Table 5 presents results on the analysed micronutrients Cu, Mn, Fe and Zn. The results indicate the concentrations of the micronutrients as follows: Cu ($0.04 - 6.80 \text{ mgkg}^{-1}$), Zn ($1.07 - 5.93 \text{ mgkg}^{-1}$), Mn ($21.08 - 193.03 \text{ mgkg}^{-1}$) and Fe ($68.22 - 101.28 \text{ mgkg}^{-1}$). According to [57], concentration of micronutrients of Cu ($2 - 250 \text{ mgkg}^{-1}$), Zn ($1 - 900 \text{ mgkg}^{-1}$), Mn ($20 - 10000 \text{ mgkg}^{-1}$) and Fe ($50 - 150 \text{ mgkg}^{-1}$) are considered as optimal ranges. Thus, the results imply Cu to be deficient while Mn, Fe, and Zn are sufficient. The levels of micronutrients decreased with depth (Table 5). Similarly, [20] pointed out that availability of micronutrients decreases with increase in soil pH. Results in Table 3 indicate that the pH of surface horizon of the study area is very acidic and the pH decrease slightly as you move down the profile. [44] pointed out that, Cu and Mn are more available at pH of 5 to 6.5 and decrease when pH is below 5 or above 6.5.

Table 5. Micronutrient contents of the studied soil profile TaCRI-P1 in Mbimba Mbozi, Tanzania

Horizon	Depth (cm)	Micronutrient content mgkg^{-1}			
		Cu	Zn	Mn	Fe
Ah	10 - 18	6.80	5.93	193.03	101.28
Ap	18 - 28/35	2.63	3.13	82.85	97.82
Bt1	28/35 - 82/99	0.26	1.40	45.28	72.45
Bt2	82/99 - 190+	0.04	1.07	21.08	68.22

3.3.7 Total elemental composition of the studied soil Mbimba Mbozi, Tanzania

Results on total elemental composition of the studied soil are given in Table 6a. Silica (SiO_2) is the most abundant oxide ranging from 38.70 - 45.90%. The high values of SiO_2 indicate the existence of amorphous silica [8]. Concentration of Al_2O_3 (20.01 - 23.08%) and Fe_2O_3 (19.60 - 32.20%) are available in abundance compared to other oxides. The possible reason is the high presence of gibbsite and hematite in the soil [60]. Trends of other oxides i.e TiO_2 and RuO_2 indicate that their abundance increases down the profile while MnO and K_2O decrease down the profile. According to [60], soils in Mbeya have high concentration of TiO_2 similar to what is shown in the Table 5. According to [61], terrestrial plants and their associated microbiota, directly affect silicate mineral weathering in several ways: by generation of chelating ligands, by modifying pH through production of CO_2 or organic acids, and by altering the physical properties of a soil.

Concentration of potentially toxic elements in the studied soil profile are indicated in Table 6a. Concentration of Pb ($41 - 49 \text{ mg kg}^{-1}$), Cr ($186 - 199 \text{ mg kg}^{-1}$) and Zn ($96 - 155 \text{ mg kg}^{-1}$) found in the studied soil were found within the normal levels that are commonly reported in many soils around the world. According to [62], Zn concentration of 300 mg kg^{-1} , Ni concentration of 75 mg kg^{-1} and Cu concentration of 140 mgkg^{-1} are considered as maximum limit in the agriculture soils while [63] considered Pb concentration of 300 mg kg^{-1} as maximum limit and [64] 600 mg kg^{-1} is maximum limit for Cr in agriculture soils (Table 6b). The soil profile also had Cu concentration of 298 mg kg^{-1} and Ni concentration of 86 mg kg^{-1} which are above the maximum limit in

agriculture soil. The high concentration of these elements may have been contributed by application of pesticides and fungicides in the coffee farm.

The results on total elemental composition of Mbimba Mbozi soil as determined by total XRF are shown in Table 6a. Observed data shows that K_2O , MnO and Bi do not show significant variations in their concentration across the profile which implies there were no losses or gains through leaching or anthropogenic activities. Concentrations of S , Cu , Zn , CaO and SiO_2 apparently decreased down the soil profile. Higher concentrations of these elements in top soils may be contributed by application of fertilizers, fungicides or pesticides. Similarly, the upper three layers of the profile showed higher concentration of P_2O_5 and RuO than the subsoil. Concentration of Fe_2O_3 and TiO_2 increased down the profile which is likely due to leaching of some iron oxides and titanium oxides. The concentrations of Al_2O_3 , ZrO_2 , Sr , W , Ni , Pb and V showed inconsistent distribution within the profile.

Table 6a. Total chemical composition of the studied soil pedon TaCRI-P1 at Mbimba Mbozi District, Tanzania¹

Depth (cm)	Al ₂ O ₃	SiO ₂	P ₂ O ₅	K ₂ O	CaO	TiO ₂	MnO	F ₂ O ₃	ZrO ₂	RuO ₂	Sr	W	Zn	Cu	Ni	S	Bi	Pb	Cr	V
					%								mgkg ⁻¹							
0 - 18	22.02	45.9	0.87	3.46	1.1	2.88	1.07	19.6	0.97	0.8	34	207	155	298	56	1079	100	44	187	158
18 - 28/35	22.05	45.2	0.87	3.53	1.15	2.88	1.08	20.2	1.01	0.9	35	192	125	126	72	900	99	41	199	133
28/35 - 82/99	20.01	38.7	0.99	3.49	0.91	3.19	1.18	26.4	1.53	1.3	30	171	111	98	86	831	101	49	186	157
82/99 - 190+	23.08	43.3	0	3.29	0.68	3.04	1.05	23.1	1.15	0	26	208	96	81	56	627	103	38	192	144

Table 6a¹ Note: Recovery of reference standard during analysis of soil

Element Spike	Al ₂ O ₃	SiO ₂	P ₂ O ₅	K ₂ O	CaO	TiO ₂	MnO	Fe ₂ O ₃	ZrO ₂	RuO ₂
	%									
Actual value	21.03	45.92	0.87	3.26	1.15	2.86	0.97	19.6	80.99	0.89
Measured value	20	40.88	0.75	3.20	1.14	2.48	0.97	19.01	79.00	0.80
Recovery %	95	89	86	98	99	87	100	97	98	90

Spike=In house reference sample. Most recoveries are close to actual value which is an indication that the analytical procedures were accurate and thus, validated the data presented in this study. For that case the analytical data obtained were presented without any adjustment

Table 6b: Concentration of potential toxic elements and their maximum limit

Element	Maximum limit in agriculture soils	References
Zn	300 mg kg ⁻¹	Commission of the European Communities (1986)
Pb	300 mg kg ⁻¹	Li <i>et al.</i> (2006)
Cr	600 mg kg ⁻¹	Pasquini (2006)
Ni	75 mg kg ⁻¹	Commission of the European Communities (1986)
Cu	140 mg kg ⁻¹	Commission of the European Communities (1986)

3.3.8 Classification of the studied soil at Mbimba, Mbozi, Tanzania

Tables 7 and 8 present the results on the classification of the representative soil profile of the study area using respectively the USDA Soil Taxonomy (to family level) and World Reference Base (WRB) for Soil Resources schemes (to tier 2). Diagnostic horizons and other features were identified in both systems and were then used to classify the soils using the taxonomic keys of the systems. According to USDA Soil Taxonomy *umbric epipedon* and *argillic subsurface horizon* were the diagnostic horizons of the soil. These horizons translated respectively into *umbric horizon* and *argic horizon* in the WRB system. The soil classified as *Gently undulating, very deep, clayey, medium acid, udic, isohyperthermic, Typic Palehumults* in the USDA Soil Taxonomy and as *Haplic Alisols (Clayic, Cutanic, Hyperdystric, Humic, Profondic)* in the WRB for Soil Resources.

Table 7: Summary of diagnostic features of the studied pedon TaCRI-P1 at Mbimba Substation, Mbozi, and classification according to USDA Soil Taxonomy (Soil Survey Staff, 2014)

Diagnostic horizon(s)	Other diagnostic features	Order	Suborder	Greatgroup	Subgroup	Family
Umbric epipedon; argillic horizon	Gently undulating (slope 5%), very deep, clayey, medium acid, udic SMR, isohyperthermic STR, presence of clay cutans	Ultisols	Humults	Palehumults	Typic Palehumults	<i>Gently undulating, very deep, clayey, medium acid, udic, isohyperthermic, Typic Palehumults</i>

Table 8: Summary of diagnostic horizons and features of the studied soils and classification according to World Reference Base for Soil Resources [IUSS Working Group WRB (2015)]

Diagnostic horizon(s)	Other diagnostic features/materials	Reference Soil Group (Tier 1)	Principal Qualifiers	Supplementary qualifiers	Tier 2 Soil name
Umbric horizon; Argic horizon	Gently undulating (slope 5%), very deep, clayey, presence of clay cutans (cutanic), high organic matter content	Alisols	Haplic	Clayic, Cutanic, Hyperdystric, Humic, Profondic	<i>Haplic Alisols (Clayic, Cutanic, Hyperdystric, Humic, Profondic)</i>

4. CONCLUSIONS

- The representative soil of the study area under coffee production in Mbimba, Mbozi District was classified as Ultisol (USDA Soil Taxonomy) and Lixisol (WRB).
- The soil is highly weathered, typically very deep, fine textured with moderate to strong subangular blocky structure.
- Generally, the soil has good physical properties.
- The pH of the soil is acidic due to the high rainfall of the study area
- The soil's essential nutrients N, P K, Ca and Mg are deficient ranging from very low to low.
- Micronutrient levels of Cu are low particularly in the subsoil, whereas Zn, Mn and Fe levels are adequate.

5. RECOMMENDATIONS

- Nitrogen, Phosphorus, Potassium, Calcium and Magnesium that were found to be deficient in the studied area need to be supplemented in form of fertilizers so as to improve arabica coffee growth and productivity in Mbimba Mbozi.
- Soils of Mbimba Mbozi need application of lime in order to raise soil pH from medium acid to better levels that will favor arabica coffee growth.

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