Soil Characterization and Soil Fertility Mapping of Main Research Station of Sirinka Agricultural Research Center

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Abstract

Soil characterization and soil fertility investigation are the basic criteria in selecting sites for research that represent the surrounding recommendation domain. Taking this into account, soil fertility investigation and characterization was done for the main research station of Sirinka Agricultural Research Center (SARC). Following 50 m by 50 m fixed grids, a total of 164 soil samples were collected at two depths, 0-20 cm and, 20-40 cm. Six soil mapping units were identified based on differences in soil color, surface soil texture, and slope. In each soil mapping unit, soil profiles were opened and soil profile description was made based on the Food and Agricultural Organization (FAO) guideline. The reference soil group and subgroup classification were finally made based on the FAO World Reference Base for Soil Resources (WRB) international soil classification system. The soil characterization results show that the soils in the research station are very deep (>150 cm) with surface and subsoil textures of clay and heavy clay, respectively. While the soil structure varied from weak medium granular in the surface to strong very coarse prismatic and weak medium prismatic in the subsoil and weak medium blocky and angular blocky at the bottom layers. The soil reaction (pH) of the research station is in the neutral to a slightly alkaline range (6.90-7.59). The organic matter content of the surface soil varies from 1.91 to 3.4%, the total N content from 0.022 to 0.17% and available phosphorus content from 5.0 to 17.0 mg kg^{-1} and are all rated in the low to medium levels. While the exchangeable cations of the surface and subsurface soils K (0.6-1.2), Ca (>20.0) and Mg (3.0-6.0) content in (cmol(+) kg^{-1}

Introduction

The basic purpose of soil fertility investigation is to provide information on the nutrient status of the soil, to predict the relative response to added nutrient and for the general planning of agricultural development (Tisdale *et al.*, 1993). Soil fertility refers to the inherent capacity of the soil to supply nutrients in adequate amounts and in suitable proportions for crop growth and crop yield. Soil fertility gives an idea of the status of soil with respect to its ability to supply elements essential for plant growth without a toxic concentration of any element.

Soil properties change in time and space continuously (Cichota *et al.*, 2006). According to Feng *et al.* (2008), heterogeneity can occur at large scale (region) or at a small scale (community), even in the same type of soil or in the same community. Spatial variability is a term indicating changes in the value of a given property over space (Ettema and Wardle, 2002). It can be assessed using classical descriptive statistics (i.e., mean, range, coefficient of variation) or geo-statistics. The amount and pattern of nutrient variability vary greatly between fields and are affected by soil type, topography, management, fertilization, and land use history. Therefore, knowledge of the spatial variability of soil properties is essential for site-specific soil management and evaluation of various agricultural land management practices.

Agricultural research stations are established based on their representation of a wider area in terms of soil characteristics (soil type and soil fertility), climatic and topographic features as most of the research outputs that are generated in the research stations are supposed to work for the wider target area they represent. So far, some of the research findings have proved to be more or less successful. However, there were also pitfalls in some areas due to a very generalized and approximation of recommendation. Amongst is the difficulty in dissemination and extrapolation of research findings outputs to other areas due to lack of sufficient soil information.

Sirinka Agricultural Research Center (SARC), which is located in Northeastern Ethiopia, is one of the research centers under Amhara Regional Agricultural Research Institute (ARARI). There are two research sub-centers (Kobo and Jari research sub-centers) and five research stations (Chefa, Jamma, Gimba, Geregera, and Estayish) under SARC situated in different agro-ecological areas in Eastern Amhara. So far, there were efforts to assess the farming system including biophysical resources of the research stations. However, there is lack of detail characteristics of soils of the research sites of SARC. This proposal was, therefore, initiated with the objectives of characterizing soils of SARC main research station and developing a detailed soil fertility map.

Materials and Methods

Description of the Study Area

The soil survey was conducted for the main research station of Sirinka Agricultural Research Center (SARC) at Sirinka in 2015. Sirinka Agricultural Research Center is located at an altitude of 1850 meters above mean sea level within the geographical coordinates of 11^0

and 39^0

mm and the mean maximum and minimum temperatures are 26 and 13^oC, respectively. The total area of SARC main research station including the office compound, residents and livestock barn is about 40 ha.

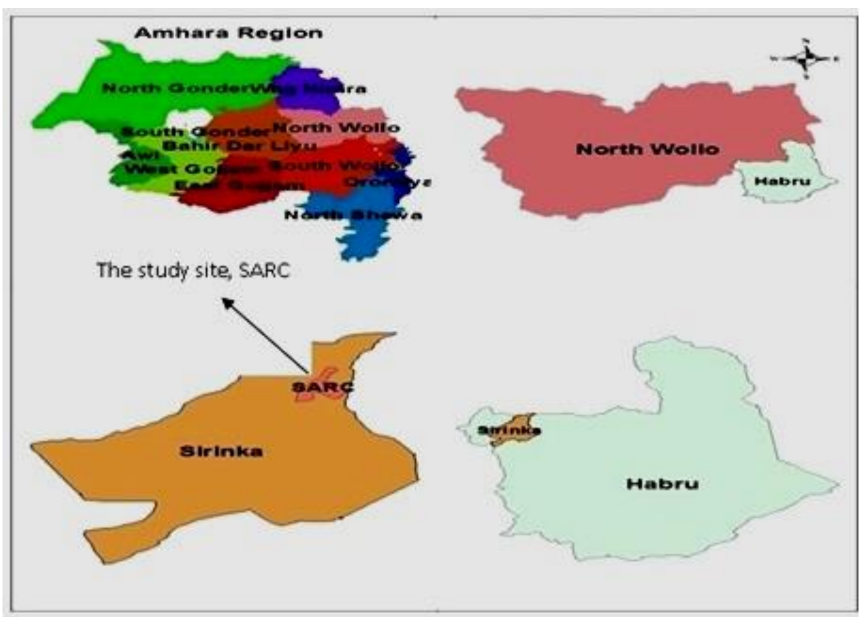


Figure 1. Location map of Sirinka Agricultural Research Center (SARC)

Geology of the Study Area

The geology of Eastern Amhara is covered by Cenozoic volcanic rocks with some sedimentary rocks (Damene *et al.*, 2012). The Cenozoic volcanic rocks have developed from tertiary flood basalt sequences with intercalation of felsic lava and pyroclastic rocks up to 3 km thick. The Cenozoic volcanic rocks and the associated sedimentary rocks are further subdivided into various formations. The major formations are Ashangi, Tarmaber-Megezez, Alajae, Aiba basalts and Amba-Aradom formations covering 49, 18, 14, 12 and 3%, respectively (Teffera *et al.*, 1996).

According to Mohr (1963), the soils of Wollo area have been developed almost exclusively on trap series volcanoes. The soils on the landforms, which include wide parallel valleys, side slopes and volcanic plateaux, are generally stony phase eutric and dystric Vertisols or vertic Cambisols. In the intensively cultivated, even on minimum slopes, these highly erodible soils can become quite shallow. On the steeper landforms, eutric Cambisols predominate, with lithic phases and Leptosols occurring on the steepest slopes.

Survey Methods

Office and field work procedure

Different digital mapping tools like Google Earth images were used to classify different soil mapping units within the study site. A preliminary field assessment was conducted to map the overall layouts, landforms, and attributes of the study site prior to the field soil investigation. During site mapping, altitude and geographical points of block boundaries and important landmarks were recorded with handheld GPS. Soil mapping units were identified and delineated based on slope, soil color, land use history, and surface soil texture. Soil profiles were opened in each mapping units to describe the morphological, physical and chemical characteristics of the soil profile based on the FAO guideline (Shand, 2007). Soil samples were collected from each genetic soil horizons.

All the soil samples collected were analyzed for soil pH (H_2O), texture, organic carbon (OC), total N, available P, Cation Exchange Capacity (CEC), exchangeable bases (Ca, Mg, K and Na). Finally, the reference soil group and subgroup classification were made based on the soil classification system of FAO World Reference Base (WRB) for Soil Resources (Food and Organization, 2014; Wrb, 2015). For the soil fertility assessment and mapping, surface soil samples were collected at two depths (0-20 and 20-40 cm) with auger following 50 x 50 m grid points. The sampling points were geo-referenced with GPS and hence a total of 164 geo-referenced auger observations at two soil depths (0-20 and 20-40 cm) were made.

The shapefile of the study area (SARC main research station) was prepared by importing the study area image from Google earth into ArcGIS/ArcMap v 10.0 software: the study area image was created from Google earth following the add polygon procedure and saved in KML format. The KML format image was converted to layer on ArcMap through the conversion tools procedure and was exported and converted into shapefile. The laboratory analysis values of the nutrients input in Microsoft Excel was added into ArcMap and exported into shapefile. The spatial distribution and soil map of pH and N, P, K, Ca, Mg concentration and the organic matter content (OM) were finally prepared separately for each parameter by Inverse Distance Weighted (IDW) interpolation method by overlying the soil sampling points over the shapefile of the study area created.

The soil map and legend

Soil mapping units were classified based on major soil/land characteristics such as soil color, surface texture, slope, and soil depth. Slope level in the research site ranges from 0-6%. Six soil mapping units were identified based on the above-mentioned criteria (Table 1). Each mapping units are indicated with four codes/elements such as slope class, soil depth, soil texture, and soil color, respectively (Table 2).

Table 1. Mapping unit identification codes

Slope		Soil Depth		Surface texture		Soil color	
Class (%)	Code	Cm	Code	Type	Code	Color	Code
1-4	1	>200	a	Clay	2	Very dark	Vd
4-6	2	150-200	b	Clay loam	3	Black/dark	B
		100-150	c	Silt clay	4	Gray	G
				Heavy clay	1	Brown	Br
						Reddish Brown	Rb

Table 2. Soil mapping units identified in SARC main research site at Sirinka

Mapping Units	Pedon No.	Slope (%)	Soil Depth (cm)	Texture (0-30 cm)	Area (ha)
1a2b	P1	1-4 (4)	> 200	Clay	2.69
1b2vd	P2	1-4	150-200	Clay	5.32
1a3b	P3	1-4	>200	Clay loam	6.13
2b4rb	P4	4-6	150-200	Silt clay	0.71
2c1b	P5	4-6	100-150	Heavy clay	6.47
2b1g	P6	4-6	150-200	Heavy clay	0.80

Laboratory Analysis

Soil texture was determined by the modified Bouyoucos hydrometer method (Bouycous, 1962) using sodium hexametaphosphate as a dispersing agent. Soil textural class names were assigned based on the relative contents of the percent sand, silt, and clay separates using the soil textural triangle of the USDA. While soil pH was measured potentiometrically using a pH meter with a combined glass electrode in a 1:2.5 soil-water suspension (van Reeuwijk, 1992). Organic carbon (OC) was determined by wet digestion method, and following the assumptions that OM is composed of 58% carbon, the conversion factor, 1.724 was used to convert the OC into OM (Walkley and Black, 1934). Determination of total N of the soil was carried out through Kjeldahl digestion, distillation and titration procedures of the wet digestion method (Black *et al.*, 1965). (Olsen, 1952).

Exchangeable bases were extracted with 1M buffered ammonium acetate extractant; K and Na were then measured using flame photometer and Ca and Mg were measured using atomic absorption spectrophotometer (Chapman, 1965). While CEC was determined by 1M buffered ammonium acetate extraction method followed by displacing the ammonium saturated soil with sodium acetate and distilling off the displaced ammonium in a Kjeldahl distillation apparatus while receiving the distillate in boric acid and then titrating with sulfuric acid (Chapman, 1965). As it is mentioned in Annex, the soil nutrient level classifications and ratings were made based on (Cottenie, 1980; Tekalign *et al.*, 1991; Jones Jr, 2002; Jahn *et al.*, 2006; Hazelton and Murphy, 2016).

Results and Discussion

Soil Mapping Units

Based on the aforementioned criteria in the materials and methods section, six soil mapping units, as shown in Figure 2 below, were identified.

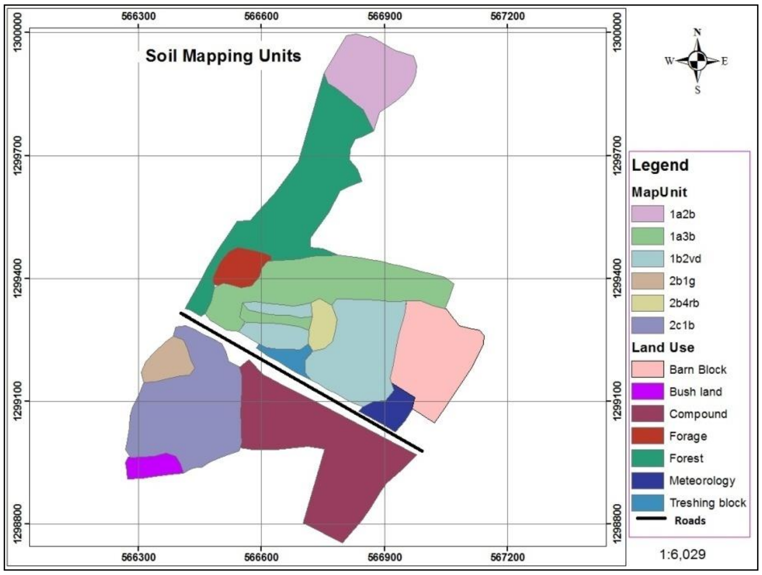


Figure 2. Soil mapping units and the different land uses at SARC

Morphological and Physico-chemical Characteristics of the Soil Mapping Units

The morphological and physico-chemical characteristics of the soil mapping units are discussed in the sections below.

Mapping unit 1: 1a2b

This soil unit refers to the soil behind the forestry arboretum to the north most direction with a regional slope of 4%. Soils of this unit are well drained, very deep (>200 cm) and black 10YR2/1 moist color in the surface and reddish brown (5YR5/3) and grayish (10YR5/1) moist color in the bottom layers. The texture of this soil is dominated by clay (>55%) with weak medium granular structure on the surface layers and strong very coarse prismatic and strong very coarse angular blocky structure in the subsoil and bottom layers, respectively. These soils have a hard consistency when dry and slightly sticky and plastic when wet.

The pH of the surface soil is 7.53 (slightly alkaline) and increases to 7.80 and 8.14 (moderately alkaline) in the sub horizons. The organic matter (OM) content is in the medium to low ranges varying from 2.32 in the surface horizons to 0.99 in the sub soils. But, the second layer lying at the depth of 20-115 cm had an OM content of 3.6% falling in the medium range, which might be presumably due to the movement of surface soil OM to the subsoil through cracks created during the dry season. The total N is in the medium range, 0.169% in the surface soil and decreases to very low, 0.04% in the sub soils. The available P content is in the low to medium ranges (4-10 mg kg^{-1}) and shows an increasing trend along with depth. Ranging from 1.0 to 1.2, 20 to 36, 6.4 to 6.7 cmol(+) kg^{-1} of soil, respectively, the exchangeable K, Ca and Mg fall in the high to very high ranges both in the surface and subsoil layers. The K:Mg concentration in the surface soil varies from 0.19 to 0.15, well below the ideal K:Mg concentration (0.5), indicating a possible antagonistic effect of Mg on K uptake (Hannan, 2011). While the Ca:Mg ratio (3.2-5.5) of the soil layers shows an optimum nutrient balance according to Havlin *et al.* (2016). Being very high based on the rating made by Landon (2014), the CEC ranges from 60.2 in the surface layers to 53.7 cmol(+) kg^{-1} soil in the subsoil layers.

Mapping unit 2: 1b2vd

The soil depth in this mapping unit is greater than 150 cm with deep black 10YR2/1 moist color on the surface and it varies from black 10YR2/1 in the subsoil to reddish brown 5YR5/3 in the bottom. The soil texture varies from clay (>50%) in the surface and subsoils to sandy loam in the bottom layer, while, the soil structure is weak medium granular with moderately sticky and moderately plastic consistency in the surface layer, strong very coarse prismatic with lots of slickenside faces in the subsoil and platy structure in the bottom layers.

The pH of the soil increases downward along with depth ranging from 7.18 (neutral) in the surface soil to 7.45 and 7.82 (moderately alkaline) in the subsoil and bottom layers, respectively. The OM and total N content of the soil which vary from 2.73 and 0.02, respectively in the surface to 1.26 and 0.06, respectively in the subsoil layers fall in the low to medium ranges, while, the available P lies within low ranges (6.7-8.0 mg kg^{-1}) in the surface and subsoil layers. The exchangeable K, Ca and Mg which vary from 1.0 to 1.13, 11.8 to 24.7, 6.9 to 7.2 cmol(+) kg^{-1} of soil, respectively, fall in the high ranges.

The K:Mg concentration in the surface soil was found to vary from 0.16 to 0.15, which is below the optimum K:Mg concentration (0.5), indicating a possible competing effect of Mg on K uptake (Hannan, 2011). The Ca:Mg ratio of 3.4 in the surface soil layer shows a balanced nutrient stock. However, the Ca:Mg ratio (1.7-2.1) in the subsoil layers indicates a tendency of low Ca supply for deep-rooted plants due to possible ion competition from Mg (Havlin *et al.*, 2016). The CEC of the soil varies from 58.0 to 60.0 cmol(+) kg^{-1} and based on the ratings by Landon (2014), it is found to be in the very high range.

Mapping unit 3: 1a3b

Covering the largest portion of the research station, the soil in this mapping unit is very deep (>2m) with a texture varying from clay (>55%) in the surface soil to heavy clay (65%) in the subsoils. The moist soil color varies from dark grayish 10YR4/1 in the surface soil to black 10YR2/1. The surface soil has a weak medium granular structure with moderate stickiness and plasticity, while, the second and third layers of the subsoil have moderate medium angular blocky and strong medium prismatic structure with high stickiness and plasticity, respectively. There are abundant slickenside faces on the surface of the prismatic soil aggregates in the third layer of the subsoil.

Varying from 7.4 to 7.7 (slightly alkaline), the soil pH increases along with depth. While the organic matter content being 1.6% in the surface and 2.06% in the subsoil is in the low range. The total N content of the soil which ranges from 0.109% in the surface soil to 0.067% in the bottom layers is in the medium range, while, the available P content of the soil varies from high (17.0 mg kg^{-1}) in the surface to low (4.0 - 6.0 mg kg^{-1}) in the sub soils. The exchangeable K, Ca and Mg vary from 1.05 to 1.19, 10.7 to 19.9, 6.6 to 7.0 cmol(+) kg^{-1} soil, respectively, are in the high ranges. The K:Mg ratio (0.18 to 0.15) in the surface soil is below the optimum K:Mg nutrient balance (0.5) signifying a possible antagonistic effect of Mg on K uptake. According to Havlin *et al.* (2016), the Ca:Mg ratio of 3.0 of the surface soil layers indicates an optimum nutrient balance between Ca and Mg. However, in the subsoil layers, there is a possibility of low Ca supply for deep-rooted plants due to a competition effect from Mg as the Ca:Mg ratio in the subsoil ranges from 1.6 to 2.7. In both the surface and subsoil layers, the CEC which varies from 55.0 to 60.0 cmole(+) kg^{-1} soil is very high based on the ratings by Landon (2014).

Mapping unit 4: 2b4rb

Soils of this unit are very deep (>175 cm) with the moist color varying from reddish brown 5YR5/3 in the surface layers to dark grayish 10YR4/1 in the sub soils. The texture varies from silt clay in the surface layers to silt loam in the subsoil and bottom layers, while, the soil structure varies from weak medium granular with slight stickiness and plasticity in the topsoil to moderate medium angular blocky with moderate stickiness and plasticity in the sub soils. There are many medium-sized black spots and distinct mottles of Fe and Mn and many $CaCO_3$ concretions. The pH level was observed to be slightly alkaline with an increasing trend from 7.4 to 7.8 across soil depth. The CEC, varying from 56 to 58 cmol(+) kg^{-1} soil, is in the very high range.

Mapping unit 5: 2c1b

The soil is deep (>170 cm) with deep black 10YR2/1 moist color on the surface and gray 7.5Y5/1 moist color in the sub soils. The texture varies from heavy clay on the topsoil layer to silt clay in the subsoil layers. Whilst, the soil structure varies from strong medium prismatic in the top layer with a consistency of highly sticky and highly plastic to strong medium angular blocky structure with a consistency of slightly sticky and slightly plastic in the subsoil. The CEC varying from 57.0 to 60.0 cmol(+) kg^{-1} soil is in all the soil layers is in the very high range.

Mapping unit 6: 2b1g

The soil is very deep (>170 cm) with moist soil color of dark brown 7.5YR4/3 on the surface, grayish 7.5Y5/1 in the middle layers and black 7.5YR1.7/1 at the bottom. The soil texture varies from clay loam in the surface layers to sandy loam and silty clay in the sub-surface and bottom layers, respectively. Whereas, the soil structure varies from weak medium granular with highly sticky and highly plastic consistency on the surface to weak medium prismatic structure with slight stickiness and plasticity in the middle and bottom layers. The CEC varies from 44.0 to 56.0 cmol(+) kg^{-1} soil and based on the ratings by Landon, 1991, it is in the very high range.

Soil Classification

Based on the IUSS Working Group WRB (2014) soil classification system, two reference soil groups, Eutric Vertisols, and Haplic Cambisols were able to be identified. Eutric Vertisols covers 93.1% of the total area (all except soil mapping unit 4; 2b4rb), while, 6.9% of the area (mapping unit 4-2b4rb) is classified as Haplic Cambisols.

Overall Soil Physico-chemical Properties

Soil depth

Almost all of the soil in the research station is very deep (>150 cm) capable of supporting annual and perennial plant growth.

Soil texture

The majority of the surface and sub-soil layers of SARC main research station vary from clay to heavy clay.

Soil structure

Weak medium granular soil structure dominates the surface soils. While the subsoil layers have strong medium prismatic soil structure with abundant slickenside and with some strong medium angular block and blocky structures at the bottom layers.

Soil reaction/Soil pH

The soil pH of most of the area in the research station is in the neutral to a slightly alkaline range (6.9-7.8).

Organic matter

The organic matter content of the surface soil ranges from 1.59 to 2.73% (Figure 3), which falls in the low range based on the critical ratings made by Tekalign *et al.* (1991).

Total nitrogen

The total N content of the surface soil ranges from 0.022 to 0.169% (Figure 4), which, based on the critical ratings made by Tekalign *et al.* (1991), is in the low to medium range.

Available phosphorus

The available phosphorus content of the surface soil ranges from 4.0 to 15.8 mg kg^{-1}, which is in the low to a medium level based on the ratings made by Cottenie (1980). And, it decreases downward in the sub-soils.

CEC and exchangeable bases (K, Ca, Mg and Na)

The CEC of most of the surface soil and subsoil layers ranges from 45 to 60 meq/100 g soil which is in the very high range. Similarly, the exchangeable bases such as K, Ca (Figure 5) and

Mg (Figure 6) content of the surface and sub-soils are also within high to very high ranges based on the ratings made by Jahn *et al.* (2006).

Cationic Balance

The K:Mg concentration of most of the surface soil is below the ideal K:Mg concentration (0.5) which indicates a possible antagonistic effect of Mg on K uptake. While the Ca:Mg ratio of the surface soil layers shows a balanced nutrient balance (3-6). However, the Ca:Mg ratio in the subsoil layers is below 3, which indicates a possible disruption in the Ca supply and uptake by deep-rooted plants due to ion competition effect from Mg.

Soil Maps

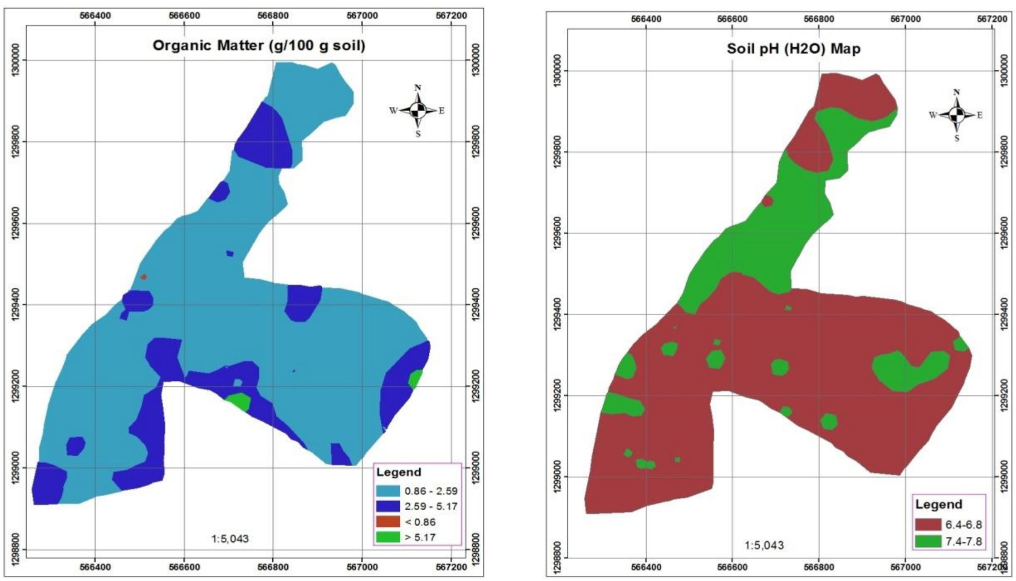


Figure 3. Soil map of organic matter (< 0.86 - Very low; 0.86-2.59 - Low; 2.59-5.17 - Medium; >5.17 - Very high) and soil pH (H_2O) (6.4-6.8 - Slightily acidic to neutral; 7.4-7.8 - Slightily alkaline)

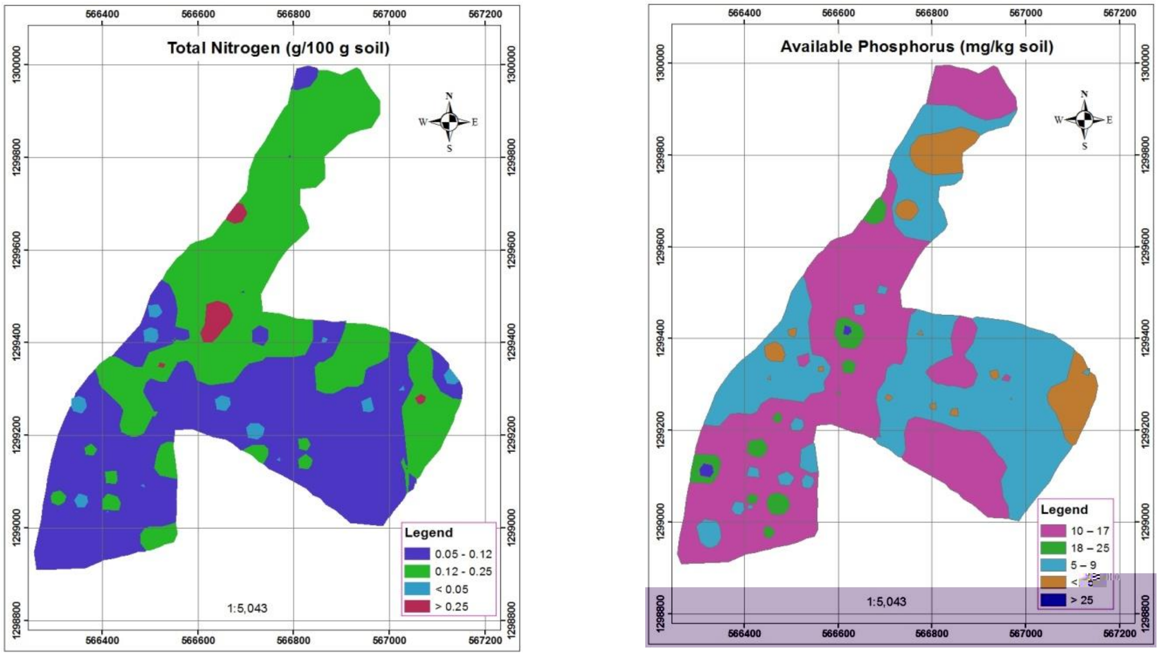


Figure 4. Soil map of total N (< 0.05 - Low; 0.05-0.12 - Medium; 0.12-0.25   High; > 0.25 - Very high) and available P (> 25 - Very high; 18-25 - High; 10-17 - Medium; 5-9 - Low; < 5 - Very low)

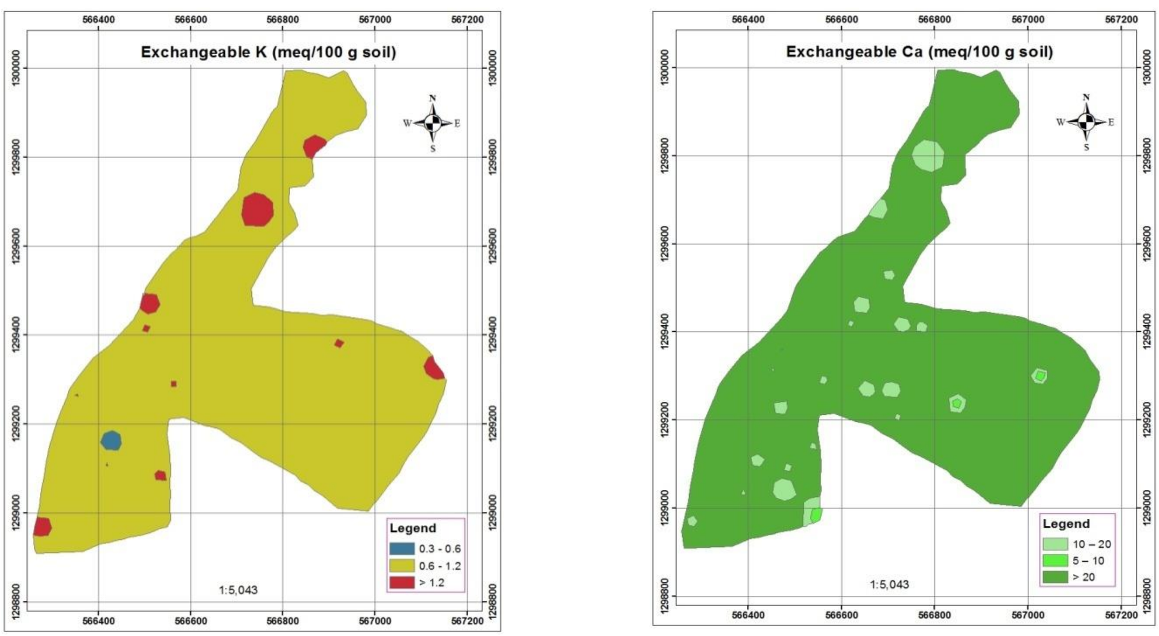
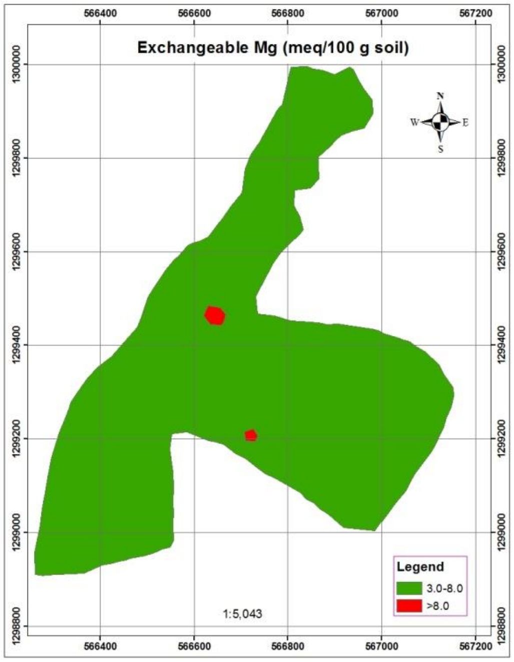


Figure 5. Soil map of exchangeable K (0.3-0.6   Medium; 0.6-1.2 - High; > 1.2 - Very high) and Ca (5-10 - Medium; 10-20 - High; > 20 - Very high)



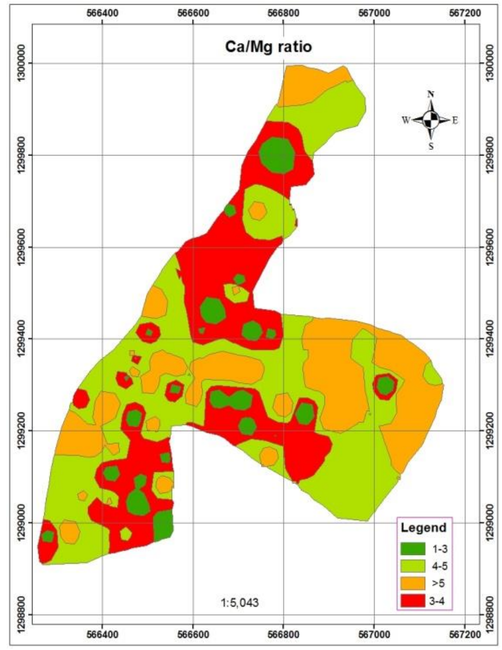


Figure 6. Soil map of exchangeable Mg (3-8 - High; > 8 - Very high) and Ca:Mg ratio

Conclusions and Recommendations

The soil characterization study result of SARC main research station shows that the research station is potentially productive and deep soil capable of supporting annual and perennial crop production. The soil is dominated by clay texture with a moderate medium granular structure in the surface layer and heavy clay texture with a strong medium prismatic structure in the subsoil layers. While the cation exchange capacity of the surface and sub-surface soil is in the very high range dominated by Ca, Mg and K, which are in the high and very high ranges. However, the K:Mg concentration ratios, particularly in the surface soils, indicated an imbalance in the relative concentration of K as compared to Mg which may result in an antagonistic effect of Mg on K uptake which may, in turn, lead to K deficiency. On the other hand, the Ca:Mg ratio shows an optimum nutrient stock in the surface soil and imbalance in the subsoil which may lead to a Ca deficient condition especially for deep-rooted plants. Therefore, nutrient response studies and K fertilization should be considered for balanced plant nutrition in the research station.

The soil fertility assessment of the surface (0-40 cm) soil samples collected in 50 m x 50 m grids revealed that there is spatial variability of soil nutrients within the research station. The surface soil is dominated by clay texture with neutral to slightly alkaline soil reaction. The organic matter and total N content in the surface soil are low. Thus, the organic matter and N content of the soil should be restored by applying different organic amendments and practicing integrated soil fertility management. The available P level varied from low to medium indicating the importance of P fertilization. Based on the soil profile studies, two soil types, eutric Vertisol, and haplic Cambisol, were identified. The dominant soil type is eutric Vertisol with haplic Cambisol covering only 6.9% of the area.

References

Black, C., Evans, D., White, J., Ensm
I. American Society of Agronomy. *Inc. Publisher, Madison, Winconsin, USA.*

Bouycous, G. (1962). Hydrometer method improved for making particle size analysis of soil. *Agron J* 54: 406-465.

Chapman, H. (1965). Cation-exchange capacity 1. *Methods of soil analysis. Part 2. Chemical and microbiological properties* (methodsofsoilanb): 891-901.

Cichota, R., Hurtado, A. L. B. & Van Lier, Q. d. J. (2006). Spatio-temporal variability of soil water tension in a tropical soil in Brazil. *Geoderma* 133(3-4): 231-243.

Cottenie, A. (1980). *Soil and plant testing as a basis of fertilizer recommendations.*

Damene, S., Tamene, L. & Vlek, P. L. (2012). Performance of farmland terraces in maintaining soil fertility: a case of Lake Maybar watershed in Wello, Northern Highlands of Ethiopia. *Journal of Life Sciences* 6(11): 1251.

Ettema, C. H. & Wardle, D. A. (2002). Spatial soil ecology. *Trends in ecology & evolution* 17(4): 177-183.

Feng, D., Zongsuo, L., Xuexuan, X., Xingchang, Z. & Lun, S. (2008). Spatial heterogeneity of soil nutrients and aboveground biomass in abandoned old-fields of Loess Hilly region in Northern Shaanxi, China. *Acta Ecologica Sinica* 28(1): 13-22.

FAO (Food and Agriculture Organization), 1984. Ethiopian Geomorphology and Soils (1:1,000,000). Assistance to Land Use Planning, Addis Ababa, Ethiopia.

Food & Organization, A. (2014).World reference base for soil resources 2014: international soil classification system for naming soils and creating legends for soil maps. FAO Rome, Italy.

Hannan, J. M. (2011). Potassium-magnesium antagonism in high magnesium vineyard soils.

Havlin, J. L., Tisdale, S. L., Nelson, W. L. & Beaton, J. D. (2016). *Soil fertility and fertilizers.* Pearson Education India.

Hazelton, P. & Murphy, B. (2016). *Interpreting soil test results: What do all the numbers mean?* : CSIRO publishing.

Jahn, R., Blume, H., Asio, V., Spaargaren, O. & Schad, P. (2006). *Guidelines for soil description.* FAO.

Jones Jr, J. B. (2002). *Agronomic handbook: Management of crops, soils and their fertility.* CRC press.

Landon, J. R. (2014). *Booker tropical soil manual: a handbook for soil survey and agricultural land evaluation in the tropics and subtropics.* Routledge.

Mohr, P. (1963).The Geology of Ethiopia Addis Ababa. Haile Selassie University Press.

Olsen, S. B. (1952). Measurement of surface phosphate on hydroxylapatite and phosphate rock with radiophosphorus. *The Journal of Physical Chemistry* 56(5): 630-632.

Shand, C. (2007). Plant Nutrition for Food Security. A Guide for Integrated Nutrient Management. By RN Roy, A. Finck, GJ Blair and HLS Tandon. Rome: Food and Agriculture Organization of the United Nations (2006), pp. 348, US $70.00. ISBN 92-5-105490-8. *Experimental agriculture* 43(1): 132-132.

Teffera, M., Chernet, T. & Haro, W. (1996). Geological map of Ethiopia (1: 2, 000, 000). *Ethiopian Institute of Geological Survey, Addis Ababa, Ethiopia*.

Tekalign, T., Haque, I. & Aduayi, E. (1991). Soil, plant, water, fertilizer, animal manure and compost analysis. *Working document* (13).

Tisdale, S., Nelson, W., Beaton, J. & Havlin, J. (1993). Soil and fertilizer phosphorus. *Soil fertility and fertilizers. New York: Macmmillan*: 176-229.

van Reeuwijk, L. (1992). Procedures for soil analysis. ISRIC, Wageningen, the Netherlands. *Procedures for soil analysis. 3rd ed. ISRIC, Wageningen, the Netherlands.*: -.

Walkley, A. & Black, I. A. (1934). An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil science* 37(1): 29-38.

Wrb, I. W. G. (2015).World reference base for soil resources 2014, update 2015: International soil classification system for naming soils and creating legends for soil maps. 192: Fao Rome.