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Digital soil mapping for site-specific management of soils

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ABSTRACT

Classification of fields into management zones based on variability of soil fertility parameters is under use in precision agriculture. The study w as conducted in west Wollega zone of Ethiopia covering nearly 40 km^2 of agricultural land, with the aim to explain variability of soils in the field, classify soils into mapping units and produce a map of these soils at a scale of 1:10000 using geostatistics. In this paper, soil mapping units (SMUs) were interchangeably used with management zones. Ten SMUs were identified in the study site. The SMU mean pH value varied between 5.3 in the SMU6 and 6.4 in the SMU7. Variation in soil texture, pH, exchangeable acidity, exchangeable potassium (K), calcium (Ca), magnesium (Mg), sodium (Na), cation exchange capacity (CEC), organic carbon (OC), total nitrogen (TN), and plant available phosphorus (AvP), were observed within and among SMUs. Variability of soil parameters ranged from 1.06% (Na) in the SMU5 to 172.94% (AvP) in the SMU8. The OC and AvP content of all SMUs were found in the very low and low critical ranges. Intensive grid sampling had helped to produce digital soil maps and exposed the soil heterogeneity across the landscape. We suggest that classification of fields into management zones was a remedy to low crop production occurred from uniform applications of nutrients and chemical amendments to significantly varying soils.

1. Introduction

Soil properties vary spatially (for example within a field or within a larger region due to both intrinsic (soil forming factors) and extrinsic). Fields that has

...atial variability in soil properties could be better ...ng and classifying the field into soil mapping units ...es (Inman et al., 2005; Lagacherie et al., 2006; ... Cullum et al., 2017). The precise amount of lime ...ation for example may be determined for each part ...han treating the whole field uniformly in the lime ...ation process. The primary benefit of variable rate ... nutrient use efficiency.

...oils of Ethiopia are poor in OM contents due to low ...aterials applied to the soil and complete removal of the biomass from the field (Yihenew, 2002; Tesfaye and Sahlemedhin, 2009). Because of their low OM content, most of the soils in Ethiopian highlands have low total N content (Abayneh et al., 2006). The soils are also generally deficit in macronutrients such as P, K and, S (EthioSIS, 2014). According to Deressa et al. (2013), the K content of soils of Western Ethiopia is estimated to be below the optimum level for adequate crop production. The annual nutrient deficit in the country is estimated at 41 kg N, 6 kg P, and 26 kg K per ha (Stoorvogel and Smaling, 1993). Such nutrient depletion is due to lack of adequate fertilizer input, limited return of organic residues and manure, and high biomass removal from farm lands, high soil erosion rate, leaching loss, and fixation and extraction by

Crop production system of Ethiopia is not only affected by deficiency of soil nutrients but also the fertilizer management practices that did not consider the spatial variability of soils across the field (Tamene et al., 2017; Fanuel et al., 2018). A high degree of variability in crop response to nutrients and amendments is observed in major cereal growing areas in Ethiopia (Tamene et al., 2017). This is mainly associated with variability in soil characteristics within and between sites and application of uniform rate of nutrients over such variable fields. Fertilizers are commonly managed according to traditional farmers' practices and, thus, variable rate nutrient applications are rarely known

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in the area. A few nutrient recommendations made for wider areas of land such as districts or zones are based on plot level trials done at specific sites that cannot represent the whole area.

Depending on variability of soil forming and other environmental factors across landscape, soil acidity also varies spatially. Information on the spatial variability of soil pH across the landscape is required for many ecological and environmental models (Sulaeman et al., 2012). Digital soil pH mapping with variable rate application of lime is a current concern in precision soil acidity management (Goulding, 2016; Campbell and Torpy, 2017). Hence, conventional geo-referenced soil sampling helps to identify the variability of soil properties within fields.

The soil fertility parameters for continuous field are predicted from point observations. Once a variogram model is fit to the sample data or measurements made at point locations, estimates of un-sampled data or sites can be determined using the kriging interpolation (Rabi, 2003; Cressie and Wikle, 2011). Predictions of soil classes and properties in the digital mapping are based on relationships among soil types and easy-to measure factors and processes of soil formation. It is used to create spatial soil information. Birhanu et al. (2016) indicated that Ethiopia is striving to build soil data at 1:10,000 resolutions so as to strengthen the Ethiopian Soil Information System (EthioSIS). The EthioSIS is a soil fertility mapping project underway in Ethiopia and the first of its kind in Africa aimed at building a national soil digital library. Therefore, the present study was conducted with aim to identify soil mapping units, evaluate their fertility status, and produce a digital map of these soils.

2. Materials and methods

2.1. Study area

The study was conducted in Babo Gambel district of west Wellega zone, Oromia, Ethiopia. Its elevation ranges between 1338 and 1462 m above sea level. The mean annual rainfall is 2300 mm while the mean annual temperature is 21 °C (NMA, 2017). The study area exhibits varying landforms (plain, depressions and plateaus). The dominant land use type is grassland followed by cultivation of annual crops such as maize (*Zea mays*), sesame (*Sesamum indicum*), and sorghum (*Sorghum bicolor*). The land along the river courses are covered with riverine forest. The study site covers a total area of 4082 ha.

2.2. Soil survey, sampling, and analysis

The study comprises a series of tasks that were performed during pre-fieldwork, fieldwork, and post-fieldwork stages. During the pre-fieldwork stage, preparation of base maps was undertaken for planning of soil and land survey activities. Base maps of landform and land use/land cover were created using ARC GIS 10.3 software by overlaying a 30 m resolution LANDSAT ETM + and Google earth imagery. The slope of the study site was classified from 30 m resolution digital elevation model (DEM) derived from ASTER using Global Mapper 30.2 software. The base maps produced for slope, landform, and land use/land cover were used to delineate the study boundary. The location and number of auger observation points that helped field survey activities were estimated based on 300 × 300 m grid size and distributed on the base map with finer resolution of 1:10,000. To delineate soil units for the study site, grid survey technique was employed.

During the fieldwork stage, all field soil investigations were done following preliminary reconnaissance survey of the study site. Using the grid survey (300 m × 300 m), about 400 auger observation points were physically located in the field using predetermined GPS coordinates. The landscape variables such as UTM coordinates, elevation, landform, slope steepness, land use type, vegetation type, and parent materials were characterized according to FAO (2006) guideline. Besides, soil attributes such as soil depth and texture were described at every auger observation sites to 1.2 m depth unless restricted by rock or water table. Combining soil and landscape information such as slope, soil depth, and soil texture obtained from auger observation points, the entire study site was classified into 10 major soil mapping units (SMUs). This was done by overlaying the maps of slope, soil depth, and texture to develop soil units that have similar characteristics. When we delineate SMUs based on criterions such as slope, soil depth and texture, we found only 10 SMUs which might be because the variability of these parameters across landscape was not very high in the study area. Hereafter, soil samples were collected at 20 cm depth to evaluate fertility status of the soils. About 8 subsamples were collected within 150 m radius of each grid point to form a composite sample. Then, a total of 400 composite samples were collected from all SMUs.

Post-fieldwork activities were focused on soil analysis in the laboratory, geospatial analysis, mapping and nutrient recommendations. Soil samples brought to the laboratory were air dried, and crushed to pass through 2 mm sieve size according to the procedure outlined by Van Reeuwijk (1993). Consequently, particle size distribution was determined by the Bouyocous hydrometer method (Bouyocous, 1962). Soil pH was measured potentiometrically in 1:1.25 soil water suspensions (Black, 1965). Exchangeable acidity was determined by titration with NaOH (Hesse, 1971). Soil OC was determined by Walkley–Black oxidation method (Walkley and Black, 1934). The TN and AvP were determined using Mehlich-III soil test extraction procedure (Mehlich, 1984). The CEC was determined using ammonium acetate extract (Page et al., 1982). Exchangeable Ca^{2+} and Mg^{2+} were measured from the original ammonium acetate leachate on atomic absorption spectrophotometer; whereas exchangeable K^{+} and Na^{+} determined by flame photometry (Chapman, 1965).

2.3. Geo-statistical analysis and soil mapping

Geo-statistical analysis was performed using the ordinary kriging interpolation technique within the spatial analyst extension module in ArcGIS 10.3 software package to determine the spatial variability of soil properties. The basic equation for interpolation by kriging at an un-sampled location S_0 was given by:

$$\hat{Z}(S_O) = \sum_{i=1}^{n} \lambda_i Z(S_i) \tag{1}$$

where $Z(S_i)$ is the measured value at the i^{th} location, λ_i is an unknown weight for the measured value at the i^{th} location, S_0 is the prediction location and n is the number of measured values. Hereafter, the final soil map was produced where predictions were made for a discretization grid. The conceptual model used in this study was a discrete model of spatial variation (Bregt, 1992), which assumes that the landscape can be divided into distinct polygons of 'natural' soil bodies.

2.4. Critical levels of soil parameters and lime recommendation approach

Critical values of soil parameters adopted by Bruce and Rayment (1982) for soil pH, Landon (2014) for OC, Karltun et al. (2013) for TN and AvP, and Metson (1961) for CEC and Ca:Mg ratio were used to judge the fertility status of soils. The threshold values of soil nutrients were used as baselines for general nutrient or fertilizer advisory work. The logic of acid saturation method which depends on permissible acid saturation (PAS) interim of major crops grown in Ethiopia recommended by Farina and Chanon (1991) was used to estimate lime requirement of soils. But, we adopted PAS of 10% for Ethiopian soils and used Taye (2008) modified lime requirement factor which was equal to 1160 kg lime ha^{-1} $cmolc^{-1}$ to estimate lime requirement rate for the SMUs as follows:

$$LR = 1160\ (EA - (ECEC * PAS)) \tag{2}$$

where LR is recommended lime rate (kg/ha), EA is exchangeable acidity ($cmol_c\ kg^{-1}$), ECEC is effective cation exchange capacity ($cmol_c\ kg^{-1}$),

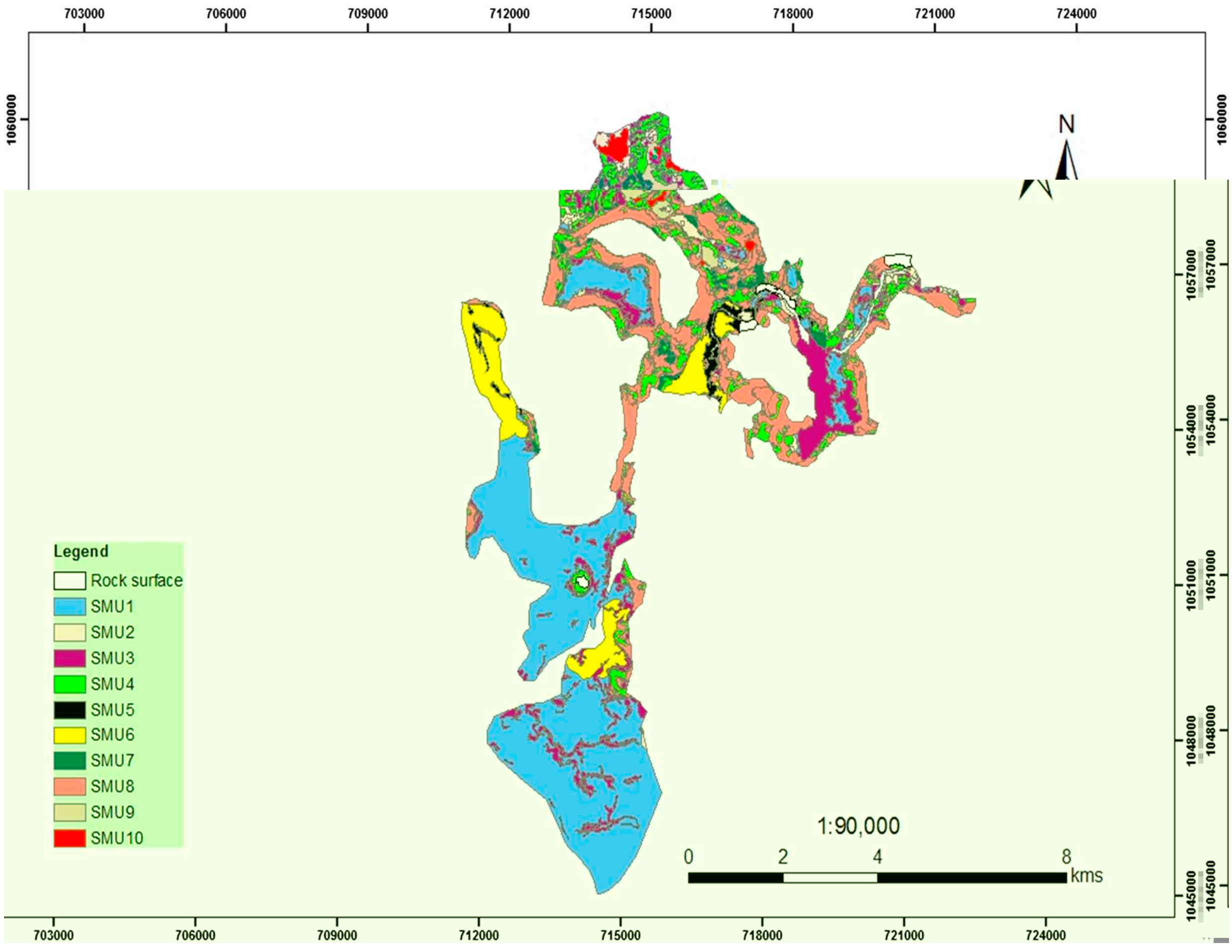


Fig. 1. Soil mapping units of the study area.

and PAS is permissible acid saturation specific for type of crop (%).

2.5. Statistical data analysis

Descriptive statistics and principal component analysis were carried out using XLSTAT 2017 software. Pearson correlation coe□cient among soil fertility parameters was estimated from soil samples data at significance level of 0.05. The mean values of soil parameters in each SMU were compared with their 'critical values' or threshold levels. Within SMU coe□cient of variation was estimated from soil samples data in the target SMU.

3. Results and discussion

3.1. Soil mapping units

Ten soil mapping units (SMUs) were identified in the site as presented in Fig. 1. Soil mapping units were classified based slope, soil depth and texture (USDA soil textural classes). The SMU1 occurred on gentle slopes (1–2%) dominated by very deep (> 150 cm) clay soils. The SMU2 were developed at plain landforms of grassland soils enriched with clay and clay loam. The SMU3 were prevalent along the plain landforms having uniform slopes of 1–2%. These soils showed wide and deep crack at the surface during dry season. Soils that genetically form cracks could be Vertisols as suggested by Coulombe et al. (1996) and Deckers et al. (2001). While SMU4 was formed at foot to mid-slope position of plateaus in cultivated land comprising a wide range of slope gradient (1–15%), SMU5 were developed at lower slope positions of depressions comprising 2% slope. Soils of the SMU6 were identified along flood plains of riverine forests with depression landforms enclosing 1–2% slope. Because of seasonal deposition of finer soil materials, they showed loamy soils deeper than 200 cm. Both SMU7 and SMU8 were widespread at mid-slope position of plateau terraces in the cultivated land containing scattered trees and dominated by clay and clay loam soils deeper than 150 cm. Though SMU7 was observed on uniformly rolling slope of 3%, the later was identified on concave part of slope comprising 5–10% slope gradient. The SMU9 was scarcely distributed at lower sections of plain and plateau landforms. Soils of this land unit showed wide gravely and stony surfaces with silty loam texture. Exceptionally, their depth was < 25 cm. Finally, SMU10 was identified at foot slope position of plateaus in the cultivated land having 2–3% slope.

3.2. Soil nutrients and their correlation

After classification of the study site into soil mapping units, the main activity performed was soil fertility evaluation for the top plow layer of the mapping units. The mapping units varied in terms of their fertility status (Table 1). The mean pH value ranged from 5.3 in the SMU6 to 6.4 in the SMU7 (Table 1). The weak acidity of SMU7 might be attributed to low exchangeable acidity (0.79 cmol (+)/kg). The soils of SUM1, SMU6 and SMU9 were strongly acidic based on Bruce and Rayment (1982) soil pH classification system (Fig. 2). All the SMUs contain very low to low estimated OC based on the ratings suggested by Landon (2014). This might be due to residue burning and continuous grazing and trampling over the soil surface by livestock. The mean value of exchangeable K was ranged from 0.04 cmol (+)/kg (very low) in the SMU9 to 0.64 cmol (+)/kg (moderate) in the SMU7 based on

Table 1
The (mean values, coefficient of variation) of selected soil fertility parameters for the upper plow layer.

Soil mapping units	pH	Mean (cmol (+)/kg), CV (%)						Mean (%), CV (%)		
		Na	K	Ca	Mg	CEC	EA	OC (%)	TN (%)	AvP (%)
SMU1	5.4, 7	0.36, 90	0.13, 50	12.95, 16	2.97, 11	25.98, 28	2.03, 102	2.74, 27	0.27, 3	4.55, 123
SMU2	5.7, 3	0.23, 27	0.21, 135	8.37, 48	1.83, 52	19.14, 45	3.15, 56	2.81, 19	0.32, 9	5.33, 62
SMU3	5.7, 8	0.49, 67	0.29, 72	13.76, 39	2.96, 18	37.08, 30	4.51, 45	3.82, 37	0.41, 34	7.59, 28
SMU4	5.6, 7	0.32, 47	0.62, 13	12.42, 29	4.71, 34	29.96, 15	1.86, 170	2.65, 12	0.27, 19	1.61, 109
SMU5	6.4, 3	0.56, 1	0.05, 26	9.90, 11	2.17, 4	21.98, 23	1.14, 5	1.31, 12	0.13, 23	5.70, 21
SMU6	5.3, 4	0.12, 52	0.06, 60	12.13, 59	2.53, 38	31.15, 35	3.43, 42	2.19, 14	0.26, 51	3.77, 22
SMU7	6.4, 2	0.67, 1	0.64, 75	15.74, 7	3.06, 4	35.56, 19	0.79, 31	2.74, 36	0.20, 33	5.64, 3
SMU8	5.7, 5	0.18, 25	0.32, 113	12.40, 40	4.18, 37	28.36, 23	1.97, 122	2.57, 22	0.28, 27	0.48, 173
SMU9	5.5, 9	0.13, 5	0.04, 15	9.45, 43	4.03, 45	24.29, 51	2.38, 113	2.38, 3	0.30, 24	1.50, 141
SMU10	6.0, 2	0.18, 26	0.54, 104	14.53, 2	4.29, 10	31.26, 11	0.80, 85	2.78, 4	0.29, 5	2.00, 113

pH: power of hydrogen; Na: exchangeable sodium; K: exchangeable potassium; Ca: exchangeable calcium; Mg: exchangeable magnesium; CEC: cation exchange capacity; EA: exchangeable acidity; OC: organic carbon; TN: total nitrogen; AvP: available phosphorus.

Metson (1961) classification. Decrease in OC had possibly caused for K deficiency in most SMUs. Based on similar author's ratings, exchangeable Ca was varied between 8.37 cmol (+)/kg (moderate) and 15.74 cmol (+)/kg (high) in the SMU2 and SMU7, respectively. According to Karltun et al. (2013) ratings, mean TN was found to be 0.13% (low) and 0.41% (high) in the SMU5 and SMU3, respectively, and other SMUs contain optimum TN. Total N was high in the SMU3 which might be due to relatively better OC content of the land unit. Moreover, all the SMUs contained very low AvP (0–15%) on the basis of Karltun et al. (2013) ratings. This might be attributed to fixation of P in acid soils. Besides, the availability of P in most soils of Ethiopia continuously decline by the impacts of abundant crop harvest, land management practices and soil erosion (Dawit et al., 2002; Birhanu et al., 2016; Bereket et al., 2018). Variation in AvP content of the SMUs could be due to differences in strength of acidity, organic matter content, rocks, and amount of residual p-fertilizers found in the soils. The moderate to high CEC in soils of the study site might be ascribed to dominance of clay soils as OC content was generally low.

Pearson correlation matrix presented in Table 2 shows that OC was positively and significantly correlated with TN ($r^2 = 0.86$) and CEC ($r^2 = 0.54$) at $p < 0.05$. Besides, exchangeable Ca was significantly and positively correlated with pH ($r^2 = 0.41$), Mg ($r^2 = 0.60$), CEC ($r^2 = 0.83$) and TN ($r^2 = 0.33$) but negatively correlated with EA ($r^2 = -0.47$) at $p < 0.05$.

3.3. Variability of soil fertility parameters

Soil fertility parameters showed relatively considerable variation in the field (Table 1). Soil parameters variability was observed within and among SMUs. Within soil mapping unit's coefficient of variation was used to estimate the degree of soil variability within specific land unit. Within SMU variability was relatively low to moderate for pH, Na, Ca, Mg, CEC, OC and TN in all soil units. This indicates that classification of the study site into land units had reduced the spatial variation of pH, Na, Ca, Mg, CEC, OC and TN within SMUs. Exceptionally, within SMU variability was high for K, EA, and AvP only in a few soil units. For instance, AvP was highly variable (CV = 123%) within SMU1 while EA was highly variable (CV = 170%) within SMU4. The higher within SMU variation of AvP and EA in some SMUs might be due to the factors that were not considered during delineation of land units such as management practices, soil erosion, and so on.

Among SMUs' coefficient of variation measures the degree of each soil parameter's variation among different land units. Compared to other SMUs, pH was relatively less variable in SMU10 (CV = 2%) but more variable in SMU9 (CV = 9%) as presented in Table 1. Variability of exchangeable K in the field was highest in the SMU2 (CV = 135%) and lowest in the SMU9 (CV = 15%). The CEC was less variable in SMU10 (CV = 11%) but more variable in SMU9 (CV = 50.59%). Generally, those soil parameters having (CV ≤ 15%) showed low variability, whereas those with (15 < CV ≤ 35%) showed moderate variability compared to their mean according to the guidelines provided by Warrick (1998) for the variability of soil properties. Similarly, soil properties having CV > 35% showed high variability compared to their mean.

3.4. Site-specific management of soils

In the absence of free exchangeable Al, the optimum pH for many plant species is 5.5 to 6.8 (Amacher et al., 2007). Considering this range, soils of SMU1, SMU6 and SMU9 were currently not suitable for most crops. But this does not mean that all soils having pH range between 5.5 and 6.8 are completely suitable for all crops. For instance, barley (*Hordium vilgare L*) better adapts to pH range between little above 6 and little below 8 while maize prefers pH value between little above 5 and 7 (Hazelton and Murphy, 2007). Strongly acidic soils were usually managed using lime. The productivity of slightly acid SMUs might also be improved from application of chemical amendments but still they could be cultivated only by growing of relatively more acid tolerant crop varieties. Using crop tolerance level of 10% for annual crops as recommended for Ethiopian soils, Taye (2008) modified lime requirement equation provided lime rate presented in Fig. 3. Crop tolerance level indicates the permissible acid saturation that can be tolerated by crops. Crops that have high crop tolerance level reduce lime requirement (Farina and Chanon, 1991; Anderson et al., 2013; van der Berg, 2017). The estimated lime requirement rate ranged from zero for the SMU5, SMU7, and SMU10 to 3.2 t/ha for the SMU3. The highest estimated lime requirement rate for SMU3 could be due to high exchangeable acidity of the land unit. At moment, all farmers in SMU3 could apply 3.2 tons of lime/ha). However, owing to temporal variation of soil properties, the lime rate recommended this year may not work in other times. The level of soil acidity may fluctuate with time depending on the management practices and environmental factors. But it should be known that farmers in SMU3 are generally in a risk zone for low pH and they are advised to test the soil by collecting reference samples and lime according to the test result in the future. Agricultural offices and extension agents are also advised to allocate more amount of lime for farmers residing in the SMU3.

The mean values of AvP were very low in all the SMUs. Except SMU5, all SMUs contain moderate to high TN. Nearly 60% of the sampled sites contain very low to low K. Therefore, the major limiting factors in soils of the study area were soil acidity and deficiencies of AvP and K, though N is also not sufficient. Here, blended and compound fertilizers are recommended for such soils having broad spectrum of nutrient deficiencies. However, variation in levels of soil nutrients in the various SMUs presented in Fig. 2 indicates the need for variable rate fertilizer recommendations. Most SMUs have moderate to high levels of

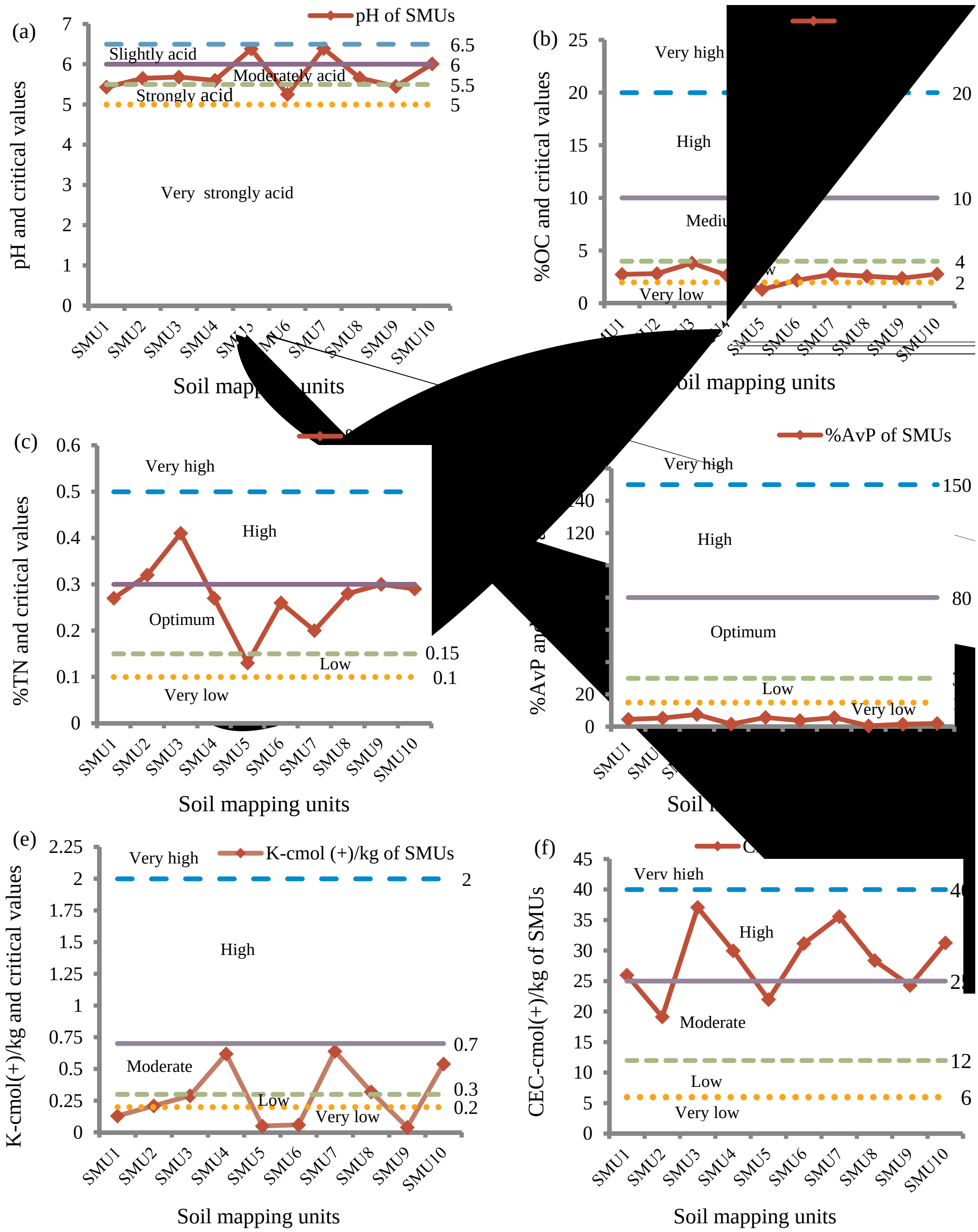


Fig. 2. Critical values of soil fertility parameters adopted by Bruce and Rayment (1982) for soil pH, London (2014) for OC, Karltun et al. (2013) for TN and Av.P, and Metson (1961) for K and CEC.

Table 2
Pearson correlation matrix among selected soil fertility parameters.

Variables	pH	Na	K	Ca	Mg	CEC	EA	OC	TN	AvP
pH										
Na	**0.46**									
K	0.00	−0.17								
Ca	**0.41**	0.13	0.08							
Mg	0.19	**−0.36**	0.32	**0.60**						
CEC	**0.41**	**0.35**	0.14	**0.83**	**0.54**					
EA	**−0.63**	0.04	−0.07	**−0.47**	**−0.53**	−0.27				
OC	0.01	0.11	0.08	0.33	0.16	**0.54**	0.12			
TN	−0.05	−0.04	0.03	**0.33**	0.23	**0.54**	0.14	**0.86**		
AvP	−0.04	**0.38**	−0.09	0.17	−0.26	0.16	0.22	0.23	0.11	

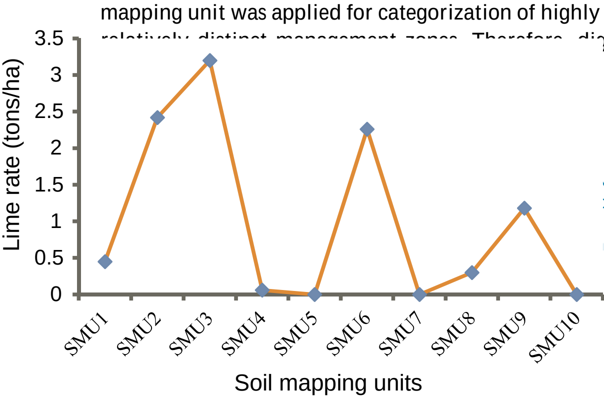
Values in bold are significantly correlated at significance level = 0.05.

Ca and Mg. Nevertheless, Ca:Mg ratio adopted by Metson (1961) shows that the concentration of Ca relative to Mg was low in SMU4, SMU8, SMU9, and SMU10 depicting presence of antagonism effect of Mg over Ca in these land units. In the remaining SMUs, Ca:Mg ratio was balanced. Metson (1961) used 4 to 6 as a benchmark for balanced Ca:Mg ratio to claim the soil as healthy ensuring optimum crop growth. Soil OC was also limiting in the entire soils of the study area. Birhanu et al. (2016) suggested that traditional crop residue burning after harvest, exhaustive grazing by livestock, residue collection for fuel wood and continuous tillage practices as the main causes for extremely low soil OC in Ethiopian soils. Hence, organic farming practices that add OC into the soils and ultimately improve other soil fertility parameters are encouraged.

So far, management of soil nutrients in Ethiopia did not consider the variability of the nutrients across the field. Nutrient recommendation for an entire field depends on the analysis of samples collected from a few segments of the field, leading to low crop production. In highly variable fields, one portion of the field gives good yield while the other sections of the field give low yield for the same input and management. As indicated from figures of critical values of soil nutrients and lime rates, the present delineation of SMUs allow variable rate application between fields. As a result, we suggested that digital soil maps would assist variable rate soil acidity and nutrient management in precision agriculture.

4. Conclusions

Ten soil units or management units were identified in the study area, by using geostatistical technique. The largest portion (50%) of the study site was covered with SMU1 while SMU9 covered < 2% of the total study area. Low soil pH, deficiencies of AvP, K, and to some extent TN, and low OM were the major limiting factors in the study area. The unwise land management practices such as crop residue burning after harvest, traditional tillage, and exhaustive grazing by livestock might be the main causes of extremely low soil OC in farmlands. The status of soil parameters varied from one mapping unit to the other. Soil mapping units were the basis for nutrient and soil acidity management. Digital soil maps produced using grid techniques offer detail information about soils of a particular field and can be used for decision-making in precision fertilization and liming. Generally, the concept of soil mapping unit was applied for categorization of highly variable soils into relatively distinct management zones. Therefore, digital soil mapping



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