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Soil mapping and classification: a case study in the Tigray Region, Ethiopia

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Abstract: Soil map is one of the basic tools for planning any agricultural development. Soil maps are even more effective and productive for natural resources evaluation. Moreover, remote sensing and geographical information systems (GIS) have added different concepts and enforcements to soil classification. This study aimed to produce soil maps following different classification systems (Soil Taxonomy and the World Reference Base for Soil Resources) and to define the spatial distribution and characteristics of the soil in the study area, which is deemed indispensable for any future development planning. This work was part of the 29th Professional Master Course at the Istituto Agronomico per l'Oltremare (IAO), Florence, Italy. The study was carried out in the Kilte Awulaelo district, located in the Tigray region of Ethiopia. The area is characterized by different topographies and geomorphologies with diverse agro-ecological conditions. Eleven main soil groups and sixty soil types were identified in the study area. The main soil groups are: Leptosols, Vertisols, Fluvisols, Stagnosols, Kastanozems, Phaeozems, Calcisols, Luvisols, Arenosols, Cambisols and Regosols. Regosols and Cambisols are the dominant soils in the study area; these are characteristic soils of rain-fed agriculture and are affected by erosion. The spatial distribution map of each soil group was very helpful to relate soil characteristics to soil forming factors. Lastly, GIS and remote sensing were very effective tools in this study and gave higher value for the final study results.

Keywords: soil maps, soil classification, GIS & Remote Sensing, Ethiopia

Introduction

Soil classification is one of the most important stages in natural resources assessment. Considering the geographic context of the study area, there are a number of theoretical soil forming processes that determine the prevailing soil types. Soil patterns can be understood using soil-landscape models that provide a key to establish or predict soil type occurrences using different soil environmental attributes (Vargas and Alim, 2007). In other words, each soil formation factor, i.e. geology, geomorphology (landform, exposure and elevation), vegetation, land use and time, determines the different stages and paths of soil development. Moreover, soil classification can present a basis for soil-related agro-technology transfer (Braimoh, 2002, Buol and Denton, 1984). Shi *et al.*, 2005, revealed that systematic soil classification links research results and their beneficial extension to field applications. They also showed that soil classification and mapping is an important base for agricultural planning and for the implementation of environmentally sound land use practices.

So far there is no universally accepted soil classification system. However, at international level, the World Reference Base for Soil Resources (FAO/ISRIC/ISSS, 1998) and the Soil Taxonomy (ST, Soil Survey Staff, 1992) are more widely adopted (Shi *et al.*, 2005).

Many studies of soils in the Tigray region showed that Regosols, Leptosols, Arenosols, Vertisols, Luvisols, Phaeozems, Cambisols and Calcisols are the dominant soil groups (Descheemaeker *et al.,* 2005; Gebremichael *et al.,* 2005; Gebrehiwot *et al.*, 2005; Mintesinot *et al.,* 2004; Nyssen *et al.,* 2004). In a recent study of Enderta district in Tigray, ten soil groups were found, namely Luvisols, Cambisols, Calcisols, Vertisols, Phaeozems, Regosols, Arenosols, Fluvisols, Kastanozems and Leptosols (IAO, 2008).

Indeed, there is a relation between the combined physical, geological and meteorological conditions and the soil formation processes (Nyssen *et al.* 2000). For example, Aerts *et al.* (2004) found that in the upper reaches, Leptosols associated with Vertic Cambisols are the dominant soils. On the other hand, the foot-slopes are characterised by Vertic Calcisols, Calcaric Phaeozems, Vertic Cambisols, and Calcaric Regosols. Nyssen *et al.* (2000) found that the lower tracts of the valleys on limestone are characterized by Calcisols, other Calcaric soils and some Vertisols. In addition, many of these soils show shrinkage cracks during the dry season (Moeyersons *et a.l*, 2006). In this sense, field work is an important step to get the primary land information since soil is one of the most important factors within the framework of a holistic approach.

Aim of this study is to develop soil maps for the study area using both the ST and WRB classification systems considering the spatial distribution of soil classes and their characteristics, which will be essential for future development planning. This work was part of a larger study on natural resources evaluation, i.e. Land evaluation in Kilte Awulaelo District – Tigray Region, Ethiopia. It was the result of the students' work in 29th Professional Master's Course in Geomatics and Natural Resources Evaluation, carried out at the Istituto Agronomico per l'Oltremare in Florence, Italy (IAO, 2009).

Materials and Methods

Study Area

Kilte Awulaelo District is situated in the eastern part of the Tigray Region; one of the nine Regional States of Ethiopia. It is located in the north-eastern part of the country and is subdivided into seventeen "Tabia" (parishes). The district is located between 13°33' and 13°58' latitude North and 39°18' to 39°41' longitude East (Figure 1). The elevation ranges from 1760 to 2720 m above mean sea level (a.m.s.l). The estimated total population in 2008 was 121,260 inhabitants, which represents of the 12% of the country's population. The urban population was around 28.56% of the total, over an area of 987.83 km² (FDR, 2008).

Agriculture is the most important source of subsistence for the majority of the population. To support the local economic activities, tannery factories have been established in the district. The growth of activities related to tourism and mining is recently impacting the local economy. Wukro town is situated in the central-eastern part of the district, at an altitude of 1972 m a.m.s.l. and it is the largest settlement in the Woreda. In the last ten years Kilte Awulaelo district has been growing rapidly, and the increasing number of inhabitants is resulting in growth of public services and infrastructures.

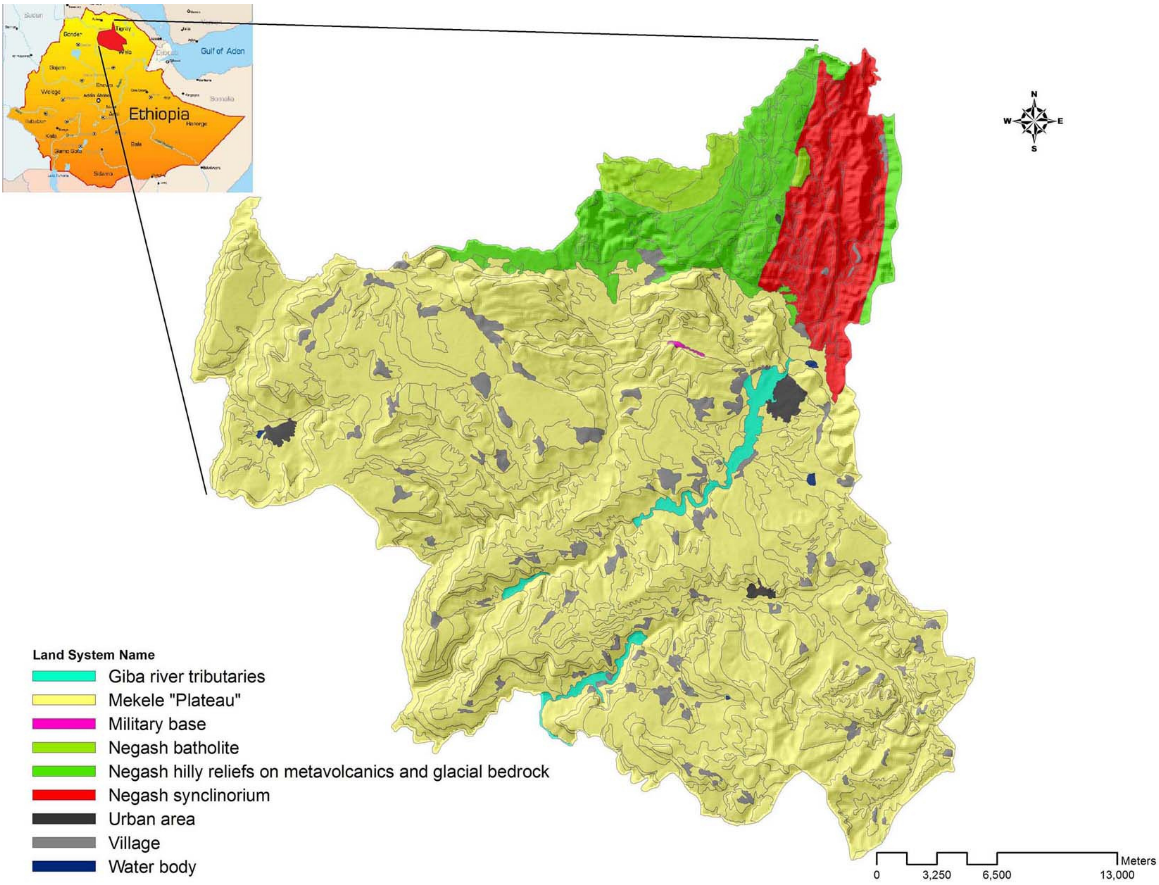

Figure 1 - Land Systems of the study area

The study area presents different topographies, geomorphologies, and agro-ecological conditions. The district is characterized by two main agro-climatic zones; Weyna Dega and Dega, which influence the land-cover and land use of the Woreda. The Weyna Dega is a cool sub-humid altitudinal climatic zone. The altitudes vary between 1500 and 2500 m a.m.s.l.; annual rainfall ranges between 800 and 1200 mm. This climatic condition is favorable for the cultivation of wheat, maize, teff and pulses. The Dega cool humid highland zone is located in altitudes above 2500 m, and is characterized by the presence of crops such as barley and wheat. The temperature range in Kilte Awulaelo is between 16°C and 34°C and the annual rainfall range is within the range of 500 mm to 1200 mm. Vegetation types and the agriculture production are influenced by the marked seasonality in rainfall distribution, with a long rain season between June and September (Kiremt), a dry season (Bega) between October and January which includes the main harvesting period (Meher), and a short rainy season (Belg) between February and May.

The mean annual soil sediment accumulation with stone bunds is estimated in 119 t ha^{-1} yr^{-1} and the use of stone bunds resulted in a reduction of annual soil loss due to the water erosion of about 68% (Gebremichael *et al.*, 2005). Another report published by NEDECO (1997) claimed that the dramatic increases in land degradation and soil erosion were the result of population increase during the latest 50 to 100 years.

The study area is covered by igneous and metamorphic rocks (Precambrian, Paleozoic), and by an extension of the Mekele Outlier, i.e. Mesozoic sedimentary rocks, laying over 80% of the study area, separated by clastic formations dated from Ordovician to lower Jurassic, called Enticho (On) and Adigrat Sandstone (Ja), respectively. The younger formations date back to Tertiary and Quaternary. In the basement, corresponding to the Precambrian rocks (Beyth, 1972) two major sequences are identified: the Tsaliet Formation, an older predominantly metavolcanic/metavolcanoclastic sequence (Lower Proterozoic), and the Tambien Formation, a younger slate and carbonate succession (Precambrian). The age of these formations is between 400 million and 700 million years. The lithological succession of the Paleozoic consists of the Forstaga and Mareb formations, which represent the lower Paleozoic, while Enticho Sandstone and Edaga Arbi Glacial are known from Ordovician (Girmay, 2006). Enticho sandstone is exposed to the east and north of the glaciogenic deposits and seems to have been deposited in a different basin than the glacial sediments (Bussert and Schrank, 2007). The Mesozoic sedimentary sequence is composed mainly of four formations, which from bottom to top are called: Adigrat Sandstone (Ja), Antalo Limestone (Jta, Jtb, Jtc, Jtd, Jte), Agula Shale (Jg) and Amba Aradam formation. The lithology of these formations is well described in Bosellini *et al.* (1997). Tertiary volcanism is represented by the Mekele Dolerite, while Quaternary formations are lacustrine, alluvial and colluvial deposits.

Geomorphologically, the Awulaelo District can be divided into five main landscape systems (Figure 1), individuated according to the main geological formations, morphological aspects and geographical location. On the North-West, close to the border and only partially enclosed in the study area, a big circular structure of plutonic rocks, called Negash Batholite is observed. It is surrounded by the heterogeneous area of the Negash hills on metavolcanics and glacial deposits, composed of many different geological units and landforms. On the North-Eastern area, another landscape is encountered: the Negash Synclinorium, which is a complex system of rugged hills and valleys on dolomite and slate. Then, all the southern part belongs to the largest landscape system, the Mekele "Plateau", a vast region with a complex morphology but of almost homogenous geological origin, mainly from the Jurassic era. The main lithologies are Agula and Antalo limestones, but relieves are also present due to

Table 1 - Classes considered for each parameters

Parameter	Very low	Low	Medium	High	Very high	Source
EC ($dS.m^{-1}$)	0.15-0.4	0.4-0.8	0.8-1.6	1.6-3	> 3	FAO, 1976
CEC ($meq.100g^{-1}$)	< 5	5 -15	15 -25	25 -40	> 40	
Exchangeable Ca ($cmolc^{+}. kg^{-1}$)	< 2	2 -5	5 -10	10 -20	> 20	
Exchangeable Mg ($cmolc^{+}.kg^{-1}$)	< 0.5	0.5 - 1.5	1.5 -3	3.0 -8.0	> 8	Landon, 1991
Exchangeable K ($cmolc^{+}.kg^{-1}$)	< 0.1	0.1 - 0.3	0.3 -0.6	0.6 -1.2	> 1.2	
Exchangeable Na ($cmolc^{+}.kg^{-1}$)	< 0.1	0.1 - 0.3	0.3 -0.7	0.7 -2.0	> 2	
Organic Carbon (OC) ($g\cdot kg^{-1}$)	< 2	2 -4	4 -10	10 -20	> 20	
Total Nitrogen (N) ($g\cdot kg^{-1}$)	< 0.1	0.1 - 0.2	0.2 -0.5	05 -10	> 10	
Available P ($mg\cdot kg^{-1}$)	-	< 5	5 -15	> 15	-	Olsen; Dean, 1965
$CaCO_3$ ($g\cdot kg^{-1}$)	< 2	2 -5	5 -10	> 15	> 40	FAO, 2006

Dolerite outcrops (on the south-eastern part) and Adigrat sandstones (by the northern border). Finally, the last landscape system distinguishes the alluvial valleys of the main tributaries of the Giba River.

Soil data and analysis

In order to interpret soil characteristics, soil physical properties were described in the field and soil samples were collected from each horizon in order to determine physicochemical properties. For the determination of organic carbon (C), nitrogen (N), phosphorus (P), texture, exchangeable bases and Cation Exchange Capacity (CEC), only the upper 50 cm of soil were considered since it is the useful root depth for most agricultural crops, and so it is useful for the evaluation of agricultural land. To obtain the texture the Gravimetric Method (pipette) and United States Department of Agriculture (USDA) Soil Textural Classification System was followed. In order to interpret laboratory analytical results, five classes for each parameter were considered (Table 1).

Considering the site characteristics and the profile description, a preliminary soil classification was made in field. The samples taken from each horizon of each described profile were an important input for determining the physicochemical properties of soil and soil classification. Once soil laboratory results were available, soil profiles were reclassified considering all soil properties observed in the field and in the laboratory. Soils were classified at the reference group, and at prefix–suffix qualifiers levels.

Table 2 - Statistical description of the main analytical results

Statistical Parameters	pH	EC(dS.m^{-1})	CEC (meq.100g^{-1})	O.C. (g· kg^{-1})	CaCO3 (g· kg^{-1})	N (g· kg^{-1})	P (mg· kg^{-1})
Max	8.53	1.91	55.64	6.72	73.10	0.59	18.20
Mean	7.81	0.19	25.02	1.56	17.07	0.12	2.23
Min	6.80	0.05	2.16	0.10	0.00	0.01	0.50
Median	7.95	0.17	23.25	1.47	7.52	0.10	1.55
Std Dev	0.39	0.17	11.68	1.07	19.19	0.10	2.37
Number Of Samples	138	138	138	138	138	138	138

The major physical properties of the soil used as a base for classification were texture, depth, color, mottles, cutans, mineral nodules, drainage characteristics, and profile development. The most important chemical characteristics of the soils used as a base for classification were cation exchangeable capacity, base saturation, organic carbon, exchangeable sodium percentage, free carbonates, pH, and electrical conductivity. Sixty nine soil profiles were sampled and described during the survey, including both site and profile descriptions. A statistical description of the main analytical results can be found in Table 2. Based on what mentioned above, a final soil classification was feasible. In accordance with the share of its distribution in a given land unit, a soil can be defined as dominant when it covers more than 85% of the land unit. The name "mixed" refers to proportions between 65% and 85% and an association of soils is when the proportion within the land unit is less than 65%.

Soil mapping

Remote sensing data such as aerial photographs and satellite images provide important inputs for a landscape system approach based on a holistic interpretation of the geomorphologic aspects. Once the geomorphologic units were defined, they were converted into land units containing all the environmental variables acting as soil formation factors (Appendix I). Furthermore, once defined the land units, a field-based natural resources inventory was carried out with the objective of land evaluation assessment, which included a specific soil survey aimed at collecting soil data. Soil profiles were described along with the different landforms previously identified. At each site, a standard soil pit was dug and using the IAO soil description form, site formation, soil attributes and pedogenetic indicators such as geology and land cover were described. The sampled soils were classified using the World Reference Base (WRB) for Soil Resource (IUSS Working Group WRB, 2006). Soil types, location and extent are shown in the description. A two-tier system was used for the qualifier level,

Table 3 - Description of mapping codes

Soil Mapping Codes	Parameter Codes	Parameters
	LPha	Dominant soil
LPha2-2b	2	Refers to the soil components described on the map (associated soil: CMha covering more than 20% of the mapping unit and inclusions: NTcc, CLhc covering 20% or less of the mapping unit);
	2	Texture classes of the dominant soil
	b	Slope classes of the dominant soil

i.e. prefix and suffix which are the formative elements for second-level of WRB. The ones found in the study area are shown in the technical soil description.

The soil map of the Kilte Awulaelo district was prepared on the bases of the Land Unit (LU) map at a nominal scale of 1:100,000 using the Transverse Mercator projection and Adindan UTM Zone 37N as coordinate system in a GIS environment. The legend was extracted from the original soil map of the World (FAO, 1974) comprising globally an estimated 4,930 different map units, which consist of soil units or associations of soil units. The soil associations are indicated by the symbol of the dominant soil unit, followed by a number which refers to the descriptive legend of the map, where the full composition of the association is given. These numbers are simply progressive, and their use is to distinguish the different cases in which one dominant soil is found alone or with associated soils or with inclusions. They do not correspond to those of the Soil Map of the World due to the impossibility to have a perfect match between the soil classes derived from the FAO WRB soil classification (2006) and the FAO legend. As an example, Table 3 show the case of three haplic Leptosols; one occuring alone (LPha2-2b), one in association with Cambisols (CMha), and, one in association with Nitosols (NTcc) and Calcisols (CLhc).

The code of dominant soils (e.g. LP) and the prefixes (e.g. ha) are retrieved from the FAO WRB classification (2006) and the codes used are shown in Appendix II.

When the texture (0-30 cm) of the dominant soil is available, the textural classes follow the association symbol, separated from it by a dash. Three textural classes are recognized as below:

- coarse (1): sands, loamy sands and sandy loams with less than 18% clay and more than 65% sand;
- medium (2): sandy loams, loams, sandy clay loams, silty loams, silt, silty clay loams and clay loams with less than 35% clay and less than 65% sand. The sand fraction may be as high as 82% if a minimum of 18% clay is present;
- fine (3): clay, silty clays, sandy clays, clay loams, with more than 35% clay.

Where two or three texture classes are indicated, each is considered to account for 50 or 33% respectively of the dominant soil unit.

Slope classes indicate the slope that dominates in the area of soil associations. Three slope classes are distinguished: i) level to gently undulating, with generally less than 8 percent slope (a); ii) rolling to hilly with slopes between 8 and 30 percent (b); and iii) steeply dissected to mountainous, with more than 30 percent slope (c). Where two or three slope classes are indicated, each is considered to account for 50 or 33% respectively of the dominant soil unit. Slope classes are indicated by a small (lower case) letter: a, b or c, immediately following the texture notation.

In complex areas where two or three types of topography occur which cannot be delimited on the map, two or three letters may be used.

Results and discussion

Eleven main soil groups and sixty soil types were identified in the study area. The identified soil groups are: Leptosols, Vertisols, Fluvisols, Stagnosols, Kastanozems, Phaeozems, Calcisols, Luvisols, Arenosols, Cambisols and Regosols. A considerable amount of Calcisols (15.84%) and Leptosols (36.8%) are found, which are characteristic soils of the dry and sloping areas. Regosols (5.83%) and Cambisols (9.01%) are also found, which are the characteristic soils for rainfed agriculture and are typically affected by erosion processes. Vertisols (14.64%) and Arenosols (5.72%) are found mainly in agricultural areas. Fluvisols (2.17%) and Luvisols (3.44%) are also present, in a considerable extension, located mainly in the fluvial system of the area and alluvial plains. Phaeozems (5.13%) and Kastanozems (1.26%) are found in areas with an undisturbed accumulation of organic matter. Stagnosols (0.16%) are prevalent in the swampy areas. Descriptive legend of the map units based on FAO soil classification is shown in Appendix III. The Soil Map of Kilte Awulaelo district is shown in Figure 2 according to FAO-UNESCO (FAO, 1988) classification system and in Figure 3 according to WRB 2006 classification system.

Description and spatial distribution of the soil groups

Leptosols

Leptosols are found on very gentle structural slopes (Mekele plateau) and very steep ridges (Negash synclinorium) exposed to high degrees of erosion, which in turn result in further decrease of soil depth in common rock outcrop areas (Table 4). These are characterized by recently developed steep-sided trenches or channels in poorly consolidated bedrocks, and weathered sediments on sloping lands in response to intense erosion events and, at the same time, in response to water storage for improving the growth of the natural vegetation. The northern part of the district (Negash hills) is developed on metavolcanic rocks and in a few places on glacial bedrocks. These areas are made up of stony and rocky formations without soil

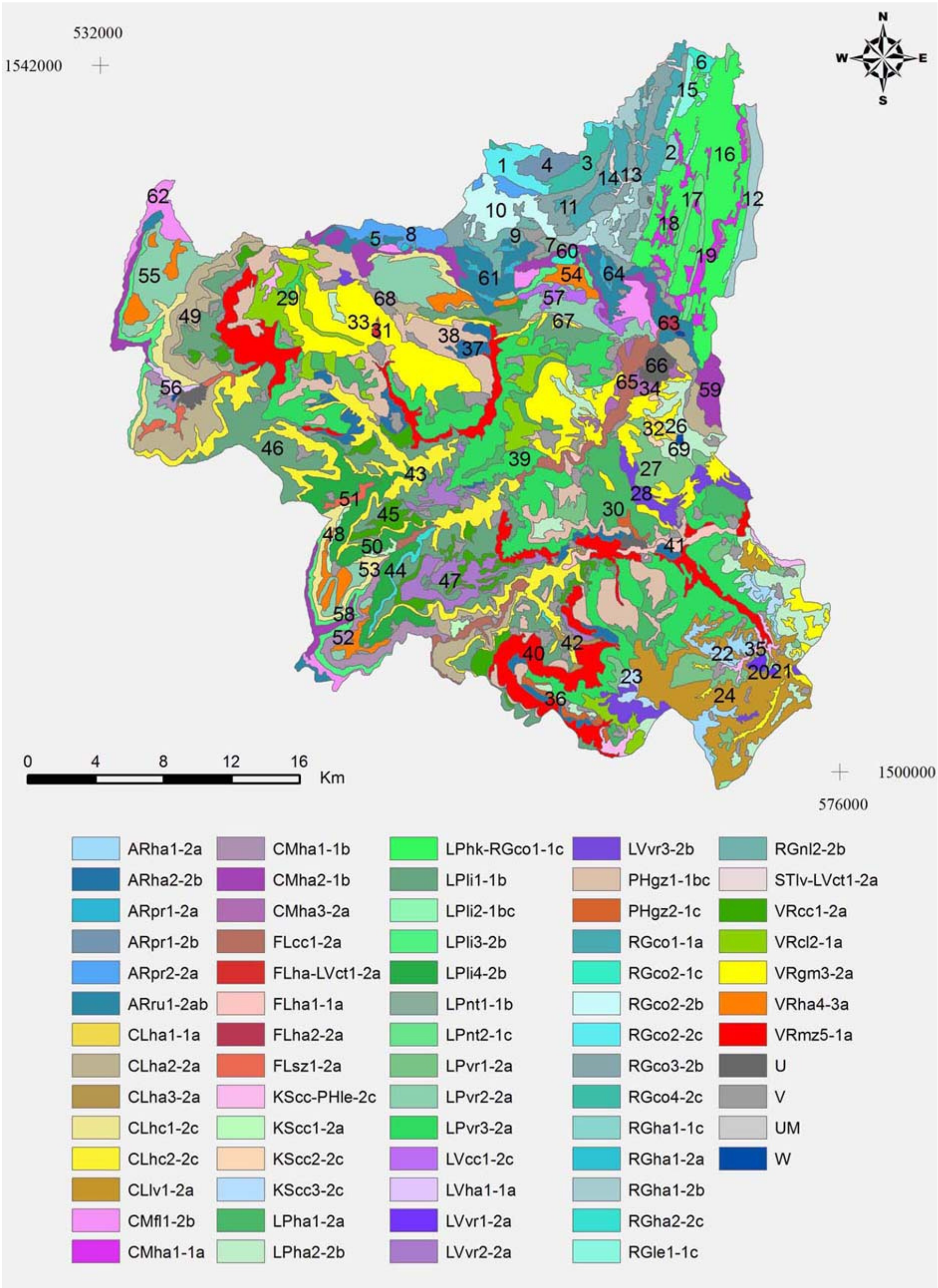

Figure 2 - Soil map according to FAO-UNESCO (1988) classification system

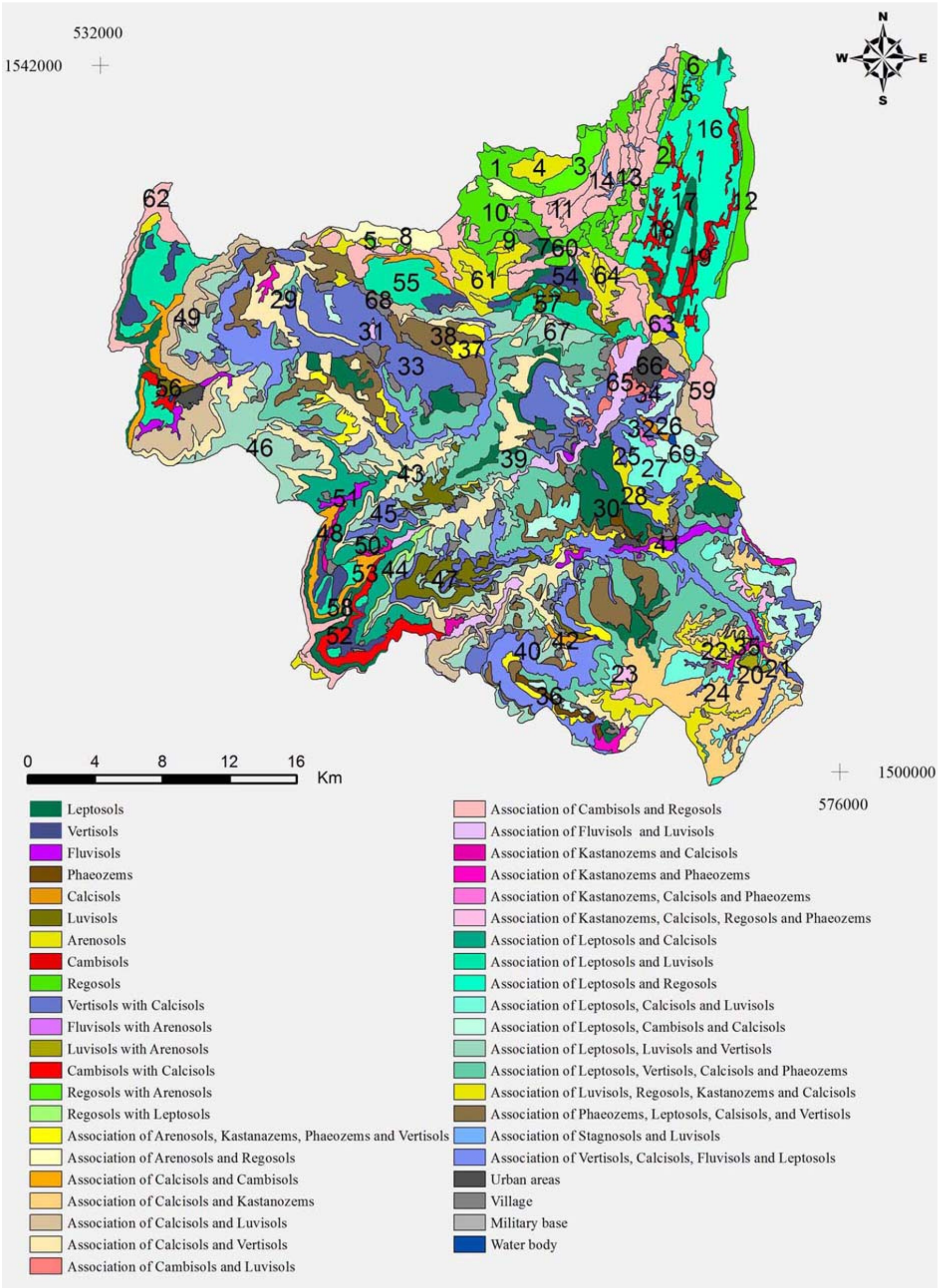

Figure 3 - Soil map according to WRB 2006 classification system

development over continuous bedrock. Many gravely and stony soil surfaces with sandy loam to silty clay texture and single grain to sub-angular blocky structure with very rapid drainage systems are present in the area. The Leptosols found in the study area have dominantly silty loam, loam, and silty clay loam textures. They have low to very high OC content ranging between 0.94 and 6.11 (Damene *et al.*, 2007), and low to medium Nitrogen. Approximately 50% of the soils in this group have medium to high available P, whereas the other 50% are with low values. In some land units, the $CaCO_3$ was found to be extremely high with a value of 81.6%, attesting the development of a calcic horizon. The pH and EC values indicate the presence of slight alkalinity as pH reaches 8.3 and EC is greater than 0.15 $dS.m^{-1}$ (Tegene, 2000). However, exchangeable sodium and ESP values showed no sign of sodicity problems as their values ranged between low and very low. Exchangeable Ca was very high in land units 58, 44 and 17, with values of 32.39 $cmolc^{+}.kg^{-1}$ (for land units 58 and 44) and 28.63 $cmolc^{+}.kg^{-1}$ (for land unit 17). Exchangeable Mg was also medium to high for the soils in the same three land units. Seventy five percent of the soils in this group have high and very high CEC, mostly attributed by the higher OC content in the enclosures (Sauer *et al.*, 2007). This suggests that enclosures are having positive effects towards the rehabilitation of degraded hills.

Table 4 - Codes, Area and spatial distribution of Leptosols

Profile	Reference Soil Groups	FAO codes	Area %
109	Hyperskeletic Leptosol	hkLP	
112	Vertic Leptosol Calcaric	vrLPca	
210	Lithic Leptosol Calcaric Humic	liLPcahu	35776,27
308	Hyperskeletic Leptosol Calcaric	hkLPca	(KM^2)
311	Lithic Folic Leptosol Humic	lifoLPhu	36,8%
407	Nudilithic Leptosol Humic	ntLPhu	
408	Nudilithic Leptosol Eutric	nuLPeu	
410	Lithic Mollic Leptosol	limoLP	

Vertisols

Vertisols are among the dominant soils on most of the farm fields in the study area (Table 5). Eight types of Vertisols are formed on colluvial deposits of Antalo limestone and Agula shale parent materials. They are distributed in seven land units most of them (>85%) on flat to very gently sloping rainfed crop lands (Assefa, 2002). These soils have the highest clay contents among the other groups.

However, the surface horizons (10-20 cm) are dominated by coarser materials of silt and sand fractions because of deposition from the slopes and clay increases significantly with depth. The OC, N, and available P contents of these soils are low to very low (Ahmad, 1996; Assefa, 2002). The Vertisols in Kilte Awulaelo district are soils

Table 5 - Codes, Area and spatial distribution of Vertisols

Profile	Reference Soil Groups	FAO codes	Area %
105	Mazic Vertisol Calcaric Pellic	mzVRcape	
113	Calcic Vertisol Gypsic	ccVRgy	
114	Calcic Vertisol	caVR	14233,53
203	Endoleptic Calcic Vertisol Pellic	nlcaVRpe	(KM^2)
204	Grumic Sodic Vertisol Humic	gmsoVRhu	14,64%
211	Haplic Vertisol Areninovic	haVRanv	
413	Calcic Vertisol Pellic	ccVRpe	
416	Grumic Salic Vertisol Humic	gmszVRhu	

rich in carbonates. pH and EC values indicate that the soils are slightly saline. However, exchangeable Na and ESP values are low or very low to cause sodicity problems. The soils have high to very high CEC and exchangeable bases because of their high clay contents (Coulombe *et al.*, 1996). From the general evaluation of the soil parameters, it is probably wise to recommend addition of nitrogen and phosphorus fertilizers with proper drainage practices to improve crop production.

Fluvisols

These soils are found in irrigated areas over colluvial deposits and sandstones near the water streams of Mekele plateau, (Table 6). They have granular and simple grain structures and very rapid drainage characteristics. These types of soils are found in LU 41, 40, 63, and 51. They have dominantly loamy sand and sandy loam textures. The soils in this group are poor in OC and N, have a low available P, low $CaCO_3$ equivalent and low and very low exchangeable Na and ESP, respectively. The EC and pH values indicate that the soils are neutral to slightly alkaline (Vidal *et al.*, 2004). Available P values are in the low to medium ranges. These soils also have medium to high CEC values and significant amounts of exchangeable Ca and Mg (Khai *et al.*, 2008) which suggests that they are potentially fertile soils but need addition of organic residues and phosphorus fertilizers for improved crop production.

Table 6 - Codes, Area and spatial distribution of Fluvisols

Profile	Reference Soil Groups	FAO codes	Area %
207	Haplic Fluvisol	haFL	2113,1722
309	Haplic Fluvisol	haFL	(KM^2)
310	Haplic Fluvisol Arenic	haFLar	2,17%
313	Salic Fluvisol Sodic	szFLso	

Stagnosols

Stagnosols are characteristic of the swamp grasslands and alluvial plains on metavolcanic schist, marble and quartzite on gently undulating slopes (Negash) (Table 7). They occur only at one pocket of swampy communal grazing land. Only Luvic Stagnosols sodic are found in this area. The texture is silty loam along the profile. OC, N and available P values are low. Exchangeable Ca and Mg contents of the soils are in the range of high to very high, but exchangeable potassium is low. The soil has high CEC values. No trace of carbonates was found in the LU since the soils are developed on metavolcanics, which are poor in carbonate content. The pH values of the soils are neutral and the values of exchangeable sodium and ESP also indicate no sign of sodicity hazard in the Land Unit (Růžek *et al.,* 2009).

Table 7 - Codes, Area and spatial distribution of Stagnosols

Profile	Reference Soil Groups	FAO code	Area %	
118	Luvic Stagnosol Sodic	lvSTso	139,517 (Km^2) 0,16%	

Kastanozems

Kastanozems are found only in the Antalo limestone colluvial deposits under rainfed annual crop fields in Kilte Awulaelo district (Table 8). These are extremely calcareous soils with up to 57% $CaCO_3$ equivalent. The texture is loamy at the surface with increasing clay content with depth. Nitrogen and OC contents are low. Exchangeable P was found to be low. The pH values were slightly neutral to alkaline and the EC confirmed slightly alkaline conditions. However, exchangeable sodium and ESP values are very low indicating no problem of sodicity. CEC is high to very high, which indicates the inherent chemical fertility of the soil. The above results suggest that the Kastanozems in the study area are fertile but need addition of N and P fertilizers as the levels of these two nutrients are low and the presence of high levels of carbonates cause P fixation.

Phaeozems

Phaeozems are similar to Kastanozems but they are more intensively leached with dark humus topsoils. They are rich in bases and do not exhibit signs of secondary

Table 8 - Codes, Area and spatial distribution of Kastanozems

PROFILE	REFERENCE SOIL GROUPS	FAO CODE	AREA %
201	Calcic Kastanozem Siltic	caKSsl	1228,1877 (KM^2) 1,26%

carbonates accumulation in the upper 100 cm of the profile (Table 9). Phaeozems occur in the southern part of the study area. They have notably very dark in color and have granular structure, and developed on marl interbedded with limestone on moderately steep scarps. Two types of Phaeozems are found in the sloping scrub lands enclosures. They have silty loam, loam, silty clay and clay loam textures. The N content range from low to medium but OC is high and very high (3.40 g. kg^{-1}, 5.6 g. kg^{-1}, respectively), due to biomass decomposition. This can be a result of the rehabilitation/enclosure efforts in the area. Available P content was found to be low. The soils have high to very high $CaCO_3$ equivalent (up to 69 g. kg^{-1}), probably as a result of the weathering of the Antalo limestone parent material in the area. According to the pH and EC values, the soils are slightly alkaline to alkaline (Tegene, 2000). However, exchangeable Na and ESP values are low and very low to cause sodicity problems. CEC values of the soils are high due to the higher OM content (Ziblim *et al.*, 2012).

Table 9 - Codes, Area and spatial distribution of Phaeozems

PROFILE	REFERENCE SOIL GROUPS	FAO CODES	AREA %
104	Greyic Phaeozem Calcaric Skeletic	gzPHcask	4982,7205 (KM^2) 5,13%
316	Calcic Luvic Phaeozem Sodic	cclvPHso	

Calcisols

Calcisols are common in the study area, where they principally occur in undulating and rolling plateaus, from very gentle structural slopes to very steep scarps (Table 10). The parent material in the lower parts of the landscape is mostly alluvial and colluvial,

Table 10 - Codes, Area and spatial distribution of Calcisols

Profile	Reference Soil Groups	FAO codes	Area %
101	Haplic Calcisol	haCL	
107	Hypercalcic Calcisol Siltic	hcCLsl	
115	Hypercalcic Calcisol Clayic	hcCLce	15403,4
202	Hypercalcic Endoskeletic Calcisol Endosiltic	hcsknCLsln	(KM^2) 15,84%
213	Luvic Calcisol Cleyic	lvCLce	
214	Hypocalcic Leptic Calcisol	wcleCL	
417	Vertic Luvic Calcisol Siltic	vrlvCLsl	

consisting of base-rich weathered deposits mainly of highly calcareous sands and gravel. Kilte Awulaelo district exhibits eight different types of Calcisols distributed in nine LU. The texture of these soils is dominantly loamy, with clay content increasing with depth in some soils. These soils have low OC and N contents. Available P is low for all soils in this group except the surface horizon sample of the Hypercalcic Luvic Calcisol in the LU 50 which has a moderate content (14 ppm). The result of the analysis affirmed that the soils in this group have high to very high $CaCO_3$ values. This has led to the development of Calcaric diagnostic material and/or a calcic diagnostic horizon, except for LU 32 (Colluvial deposit) which has low $CaCO_3$ values (IUSS Working Group WRB, 2006). About 75% of the soils in this group are alkaline with pH values between 8.0 and 8.5 and the other 25% are neutral. The CEC and exchangeable K values are in the medium to high range. The EC values indicate that the soils are slightly saline, while ESP values are low and very low and not sufficient to cause sodicity hazard. Based on results assessment, addition of organic residues or organic and inorganic fertilizers is highly recommended. As the sites are highly calcareous, P fixation is expected in the area so that addition of high amount of P sources is needed.

Luvisols

Luvisols are found on colluvial deposits and on dolerites (Table 11). They have sandy clay texture, moderate to strong sub angular blocky structure; the drainage is moderate to very rapid. This group of soils occurs in flat and gently sloping farm fields, both irrigated and rainfed, and on communal grazing lands (LU 56, 34 and 13). Three different types of Luvisols are found in the study area. The soils are dominated by sandy clay loam and silty clay loam textures. Clay content increases with depth, clearly showing eluviation from the topsoil, which is typical of Luvisols. OC and N values are low and very low except the Cutanic Luvisol humic Siltic in the grazing LU (13) with high values of OC (3.6%) and moderate nitrogen (0.27%).

Table 11- Codes, Area and spatial distribution of Luvisol

Profile	Reference Soil Groups	FAO codes	Area %
106	Haplic Luvisols	haLV	3347,389
111	Cutanic Luvisol	ctLV	(Km^2)
314	Cutanic Luvisol Humic Siltic	ctLVhusl	3,44%
409	Hypercalcic Luvic Calcic	hcLVca	

The soils have low to medium available P, neutral pH in the grazing land and slightly alkaline in the farm fields. The EC values also indicate presence of slightly saline conditions in the irrigated fields. Exchangeable Ca and Mg are high in the grazing sites and medium in the rainfed farm fields. Exchangeable Na and ESP are low and very low indicating no sodicity hazards in the area. CEC values are low and medium in both irrigated and rainfed agricultural fields but high in grazing sites because of high OM (Růžek *et al.*, 2009). From the above results, addition of experimentally determined amounts of organic matter and N, P, and K fertilizers on the farm fields for better crop production is suggested.

Arenosols

In the study area, Arenosols are found in gently undulating plains (Negash hills) and undulating rises to steep slopes of Mekele plateau. They are also dominant on sandstone, colluvial deposits, diorites and dolerites (Table 12). These soils are coarse textured and granular in structure, with a rapid to very rapid drainage. Six types of Arenosols are found in the study area, distributed in LU 61, 64, 3, 4, 8, and 22. The textures of these soils are mostly sand, loamy sand and sandy loam. The soils in this group have very low and low organic carbon and nitrogen contents (Hartemink and Huting, 2008). The profile minimum and maximum OC values were found to be 0.08% and 0.68%, respectively. Similarly the profile minimum and maximum N values were 0.01% and 0.06%, respectively. The available P contents of this soil group range from very low to medium. However, in LU 3, P content in the second horizon (25-35cm) was found to be 16 ppm, the highest in the study area. The pH values are neutral (Hartemink and Huting, 2008), except the Protic Arenosol Areninovic found in LU 64, which is slightly alkaline. The CEC values of these soils are the lowest among the study area; where up to 90% of the soil samples are found to have very low or low CEC. Exceptionally, two samples from the dolerite rich rainfed farm lands were found with medium CEC values of 16.6 and 19.9 meq.100g^{-1} for the first and the second horizons, respectively. Exchangeable Ca, Mg and K contents of the soils in this group

Table 12 - Codes, Area and spatial distribution of Arenosols

Profile	Reference Soil Groups	FAO codes	Area %
121	Protic Arenosol Tephric	prARtf	
208, 301	Protic Arenosol Areninovic	prARanv	5561,49
301	Haplic Arenosol Areninovic	haARanv	(Km^2)
304,317	Protic Arenosol	prAR	5,72%
403	Rubic Arenosol Eutric	ruAReu	
412	Rubic Arenosol Areninovic	ruARanv	

range from very low to medium values except the Protic Arenosol in LU 22 which is high, with profile average values of 13.74, 3.76, and 0.65 cmolc$^+$.kg^{-1}, respectively. Exchangeable Na content was low to very low in all of the samples. All the samples in this group also showed low or very low ESP values except one sample from the Protic Arenosol in LU 61 with medium value (9.46%) in its subsurface horizon (25-35 cm), which is mainly due to low CEC value, and not to high Na concentration. It is the highest value in the study area. The EC values for this group showed no salinity problems. Based on the assessment of the results, the soils in this group are infertile. These results, therefore, indicate the need of integrated nutrients management, addition of both organic and inorganic fertilizers, for good crop production especially on farm fields.

Cambisols

Cambisols occur on strong slopes and level plains in the plateaus, on lacustrine deposits and sandstones and in gently undulating rises in Negash on metavolcanic schist, marble and quartzite in the study area (Table 13). The profiles are characterized by weak transformation of the parent material and evident changes in soil structure, color and clay content. These soils are found in ten LU. They are dominated by sandy loam and silty loam textures with some soils of silty clay loam nature. OC and N and available P contents are low or very low and the soils are also free from carbonates with the exception of some soils having traces of carbonates. Sixty five percent of the pH values of the samples in this group of soils are found to be alkaline (pH>7.5), while the rest are neutral. Exchangeable Ca and Mg were determined only for those carbonate free samples and the values were found in the range of medium to high. All the soils in this group were found to have low and very low exchangeable Na and ESP. CEC is in the range of low to medium values (Růžek *et al.*, 2009). The results, therefore, suggest the need of integrated nutrient management with addition of both organic and inorganic fertilizers for good crop and forage production in the land units in which these soils are found.

Table 13 - Codes, Area and spatial distribution of Cambisols

PROFILE	REFERENCE SOIL GROUPS	FAO CODES	AREA %
103	Haplic Cambisol Colluvic Siltic	haCMcosl	
110, 116, 205	Haplic Cambisol	haCM	8763,46
119	Ferralic Cambisol Sodic	flCMso	(KM^2)
405	Haplic Cambisol Colluvic Escalic	haCMcoec	9,014%
406	Haplic Cambisol Colluvic	haCMco	
411	Pisoplinthic Cambisol Colluvic Sodic	pxCMcoso	
415	Haplic Cambisol Calcaric	haCMca	

Regosols

Regosols occur in variable relief types in the landscape, particularly on flat surfaces, slopes, denudational surfaces, mesas and pediments of dissected plateaus (Table 14). The topography is generally undulating to hilly. The parent material consists of unconsolidated fine-grained material originating from different rock types such as limestone and sandstone.

The soils in this group have very low to low OC, N and available P contents and the values also show a decreasing trend with depth. Both pH and EC values of the soils show neutral to slightly alkaline conditions (Tegene, 2000). No traces of carbonates were found, with the exception of the Leptic colluvic Regosol Calcaric in the dolomite sparse scrub LU with high values of $CaCO_3$ equivalent (profile average of 18.8%). The soils show medium to high exchangeable Ca and Mg values and very

Table 14 - Codes, Area and spatial distribution of Regosols

PROFILE	REFERENCE SOIL GROUPS	CODES FAO	AREA %
102	Colluvic Regosol Skeletic	coRGsk	
108	Endoleptic Regosol Skeletic	nlRGsk	
117	Haplic Regosol Arenic	haRGar	
120, 312, 414	Colluvic Regosol	coRG	5672,29
209	Colluvic Leptic Regosol Skeletic Arenic	coleRGskar	(KM^2)
212	Colluvic Regosol Arenic	coRGar	5,83%
302	Colluvic Regosol Episkeletic	coRGskp	
307	Colluvic Regosol Tephric	coRGtf	
315	Leptic Colluvic Regosol Calcaric	lecoRGca	
401	Haplic Regosol Eutric	haRGeu	
402	Colluvic Regosol Eutric	coRGeu	
404	Endoleptic Regosol Tephric	nlRGtf	

low to low exchangeable K values, with some exceptions with medium values. The CEC values of these soils are low to medium (Sauer *et al.*, 2007). No sodicity hazards are anticipated as the exchangeable Na and ESP values are very low or low. For those soils found on the rainfed farm fields, integrated nutrient management is highly recommended to improve crop production. However, these soils are not naturally suitable for crop production.

Conclusions

Results showed that the study area has a great variety of soil groups and types and this is due to the diversity of geographical, morphological and ecological conditions in the region. Eleven main soil groups and sixty soil types were found in the study area. These soil groups are: Leptosols, Vertisols, Fluvisols, Stagnosols, Kastanozems, Phaeozems, Calcisols, Luvisols, Arenosols, Cambisols and Regosols. The most widespread soil groups are Regosols and Cambisols which occur mostly in rainfed agriculture and erosion affected lands. Vertisols and Arenosols too occur mainly in agricultural areas. Calcisols and Leptosols were also found in the dry and sloping areas. Fluvisols and Luvisols are located primarily in the fluvial system of the area and alluvial plains. Phaeozems and Kastanozems are found in areas with an undisturbed accumulation of organic matter. Stagnosols are represented in the swampy areas. To end with, using spatial distribution map of each soil group was very helpful to relate soil characteristics to soil forming factors.

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Appendix I - Final Land Units legend and description

LAND SYSTEM	FORMATION	DOMINANT LITHOLOGY	LAND FORM	LU	LAND USE	LAND COVER	SOIL
Negash batholite	Mareb	Pink to grey granite and granodiorite	Undulating rises	1	Degradation control	Maytenus senegalensis open scrub	Cambisols
			Moderate steep crest	2	Artificial forest and degradation control	Eucalyptus forest plantation and open scrub woodland	Regosols
			Undulating rises	3	Degradation control	Becium grandiflora open scrub	
	Forstaga	Quartz diorite		4		Maytenus senegalensis open scrub	
Negash hilly reliefs on metavolcanics and glacial bedrock	Ehdaga Arbi	Colluvial deposit on glacial dark tillite	Foot slope	5	Agriculture	Rainfed annual crops	Calcisols
	Enticho	Glacial white quartz sandstones	Steep scarp	6	Natural vegetation	Olive trees and Becium grandiflora scrub woodland	Regosols
			Undulating hill	7	Degradation control	Open scrub	Leptosols
			Gently undulating plain	8	Agriculture	Rainfed annual crops	Association of Arenosols and Leptosols
			Gently undulating rises	9			Arenosols
	Tsaliet	Metavolcanic green schist with marble and quartzite	Moderately dissected slope	10	Degradation control	Euclea schimperi open to close scrub	Regosols
			Gently undulating rises	11	Agriculture	Rainfed annual crops	Association of Cambisols, Ferralsols and Nitisols
			Moderately dissected slope	12	Agriculture and degradation control	Rainfed annual crops and open scrub	Cambisols
			Gently undulating rises	13	Grassland	Short plant field	Association of Gleysols and Luvisols
				14	Agriculture	Rainfed annual crops	Association of Calcisols and Regosols
Negash synclinorium	Tambien	Metasedimentary pebbly slate, grey-green slate, black limestone	Moderately dissected steep hills	15	Degradation control	Becium grandiflora open scrub	Calcisols
				16			Association of Leptosols and Regosols
		Black limestone and dolomite	Very steep ridge	17			Leptosols
		Metasedimentary pebbly slate, grey-green slate, black limest	Gently undulating plain	18	Agriculture	Rainfed and irrigated annual crops	Cambisols
				19		Irrigated annual crops	Luvisols
Mekele "Plateau"	Mekele Dolerite	Dark dolerite	Steep scarp	20	Degradation control	Acacia etbaica open scrub	Association of Leptosols and Regosols
			Undulating crest	21	Agriculture and degradation control	Rainfed annual crops and Acacia etbaica open scrub	Luvisols with Arenosols
				22	Agriculture	Rainfed annual crops	Arenosols
	Agula	Shale with interbedded "black" limestone	Sloping Scarp	23	Degradation control	Acacia etbaica open scrub	Association of Calcisols, Kastanozems, Phaeozems and Regosols
				24	Agriculture and degradation control	Rainfed annual crops and Acacia etbaica open scrub	Association of Calcisols and Kastanozems
				25	Artificial forest	Eucalyptus forest plantation	Association of Kastanozems, Calcisols and Phaeozems
			Undulating rises	26	Agriculture	Rainfed annual crops	Association of Calcisols, Cambisols and Leptosols
				27	Degradation control	Open scrub	Association of Calcisols, Leptosols and Luvisols
				28	Agriculture and degradation control	Rainfed annual crops and Acacia etbaica open scrub	Association of of Leptosols, Luvisols and Regosols
			Very gentle structural slope	29	Agriculture	Rainfed annual crops	Association of Cambisols, Leptosols and Vertisols

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			30	Degradation control	Acacia etbaica open scrub	Leptosols
	Colluvial deposit	Gently undulating plain	31	Grassland	Short plant field in wetland	Association of Fluvisols and Luvisols
			32	Agriculture	Irrigated annual crops	Calcisols
			33		Rainfed annual crops	Vertisols
	Fluvial-lacustrine deposit	Level plain	34			Association of Cambisols and Luvisols
Antalo	Marl interbedded with white and "black lithographic" limestone	Moderate steep scarp	35	Degradation control	Acacia etbaica sparse scrub	Association of Kastanozems and Phaeozems
			36		Acacia etbaica open scrub	Phaeozems
		Strong slope	37	Agriculture and degradation control	Rainfed annual crops and open scrub	Association of Arenosols, Kastanazems, Phaeozems and Vertisols
			38		Rainfed annual crops and sparse scrub	Leptosols with Kastanozems
			39		Acacia etbaica open scrub and Rainfed annual crop	Association of Cambisols, Kaztanozems, Phaeozems and Vertisols
	Colluvial deposit	Footslope	40	Agriculture	Rainfed annual crops	Association of Calcisols, Fluvisols, Leptosols and Vertisols
			41		Irrigated annual crops	Fluvisols
	Fine crystalline limestone with some marl	Very steep scarp	42		Rainfed annual crops	Association of Calcisols and Cambisols
			43	Agriculture and degradation control	Open scrub and Rainfed annual crop	Association of Calcisols and Vertisols
			44	Degradation control	Close scrub	Regosols with Leptosols
		Terraced slope	45	Agriculture	Rainfed annual crops	Vertisols with Calcisols
			46	Agriculture and degradation control	Open scrub and Rainfed annual crop	Association of of Leptosols, Luvisols and Vertisols
	Colluvial deposit	Undulating rise	47	Agriculture	Rainfed annual crops	Luvisols
	Marl with black and sandy limestone	Moderate steep slope	48	Agriculture and degradation control	Rainfed annual crops and open scrub	Association of Calcisols and Kastanozems
			49		Open scrub and Rainfed annual crop	Association of Calcisols and Luvisols
			50			Association of Calcisols and Leptosols
	Colluvial deposit	Footslope	51	Agriculture	Rainfed annual crops	Calcisols
	Yellow marl and limestone	Moderate steep slope	52	Agriculture and degradation control	Rainfed annual crops and open scrub	
			53		Open scrub and Rainfed annual crop	
		Very gentle slope	54	Agriculture	Rainfed annual crops	Vertisols
			55	Degradation control	Open scrub	Luvisols with Leptosols
	Colluvial deposit	Toeslope	56	Agriculture	Irrigated annual crops	Calcisols
		Very gentle slope	57	Natural vegetation	Olive trees and Euclea schimperi scrub woodland	Luvisols
Agula	Fine crystalline sandy limestone and marl	Moderate steep scarp	58	Degradation control	Acacia etbaica open scrub	Leptosols
Adigrat	Grey, yellow to red sandstone		59		Euclea schimperi open scrub	Association of Arenosols and Regosols
			60	Natural vegetation	Olive trees and Euclea schimperi scrub woodland	Regosols
		Strong slope	61	Agriculture	Rainfed and irrigated annual crops	Arenosols

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			62	Degradation control	Euclea schimperi open scrub	Association of Ferralsols and Regosols
			63	Agriculture	Irrigated annual crops	Fluvisols with Arenosols
	Colluvial deposit	Gently undulating plain	64	Grassland	Short plant field in wetland	Arenosols
Giba river tributaries	Alluvial deposit	Level plain	65	Agriculture	Rainfed and irrigated annual crops	Association of Fluvisols and Luvisols
		Urban area				
		Military base				
		Village				
		Water body				

Appendix II- Code and prefix of different WRB Reference Groups

Reference Groups	Soil Codes	Prefix	Code	Prefix	Code
Arenosols	AR	Calcic	cc	Leptic	le
Calcisols	CL	Colluvic	Co	Lithic	li
Cambisols	CM	Cutanic	Ct	Luvic	lv
Fluvisols	FL	Endoleptic	nl	Mazic	mz
Kastanozems	KS	Ferralic	fl	Nudilithic	nt
Leptosols	LP	Greyic	gz	Pisoplintic	px
Luvisols	LV	Grumic	gm	Protic	pr
Phaeozems	PH	Haplic	ha	Rubic	ru
Vertisols	VR	Hypercalcic	hc	Salic	sz
Regosols	RG	Hyperskeletic	hk	Vertic	vr
Stagnosols	ST	Hypocalcic	wc		

Appendix III- Descriptive legend of the map units based on FAO soil classification

UNIT	DOMINANT	ASSOCIATED			INCLUSIONS		
31	FLHA-LVCT1-2A						
32	CLHA1-1A						
33	VRGM3-2A				LVVR	CLLV	
34	CMHA3-2A	LVHA					
21	LVVR1-2A	ARHA					
22	ARHA1-2A						
20	LPLI2-1BC	RGHA					
28	LVVR3-2B	LPMO	RGCO		CLLV		
27	LPVR1-2A	CLHA	LVCT				
26	LPHA2-2B	CMHA			NTCC	CLHC	
30	LPHA1-2A						
29	VRCL2-1A	CLVR					
25	KSCC2-2C	CLLV	PHHA				
24	CLLV1-2A	KSCC			PHHA	CMVR	RGHA
23	KSCC3-2C	PHHA	RGHA	CLLV			
58	LPLI3-2B						
64	ARPR1-2A						
63	FLHA2-2A				ARRU		
62	CMFL1-2B	RGCO					
61	ARRU1-2AB						
60	RGCO2-1C						
59	CMHA2-1B	RGLE					
57	LVCC1-2C						
56	LVHA1-1A						
55	LPVR2-2A	LVCC					
54	VRHA4-3A						
53	CLHC1-2C	CMHA					
52	CMHA1-1B				CLHC		
51	FLSZ1-2A						
50	LPLI4-2B	CLHC					
49	CLHA2-2A	LVCC					
48	KSCC1-2A	CLHA					
47	LVVR2-2A						
46	LPLI1-1B	LPEL	LVLI				
45	VRCC1-2A	CLVR					
44	RGHA2-2C	LPLI					
43	CLHC2-2C	VRGM					
42	CLHA3-2A	CMHA					
41	FLHA1-1A						
40	VRMZ5-1A	CLHC			LPMO	FLHA	
39	LPVR3-2A	VRMO			PHCC	KSLV	CLHC
38	PHGZ1-1BC				VRCC	CLHC	LPVR
37	ARHA2-2B	KSLV			VRMO	PHLI	
36	PHGZ2-1C						
35	KSCC-PHLE-2C						
65	FLCC1-2A	LVCC					
5	RGHA1-2A						
6	RGCO2-1C						
9	RGNL2-2B						
7	LPNT1-1B						
8	ARPR2-2A	RGCO					
4	ARPR1-2B						
10	RGCO2-2B						
13	STLV-LVCT1-2A						
14	RGCO1-1A	CMHA					
12	RGHA1-2B						
11	RGCO3-2B				CM		
1	RGCO2-2C						
2	RGHA1-1C						
3	RGCO4-2C	ARHA					
17	LPNT2-1C						
19	CMHA1-1B						
18	CMHA1-1A						
16	LPHK-RGCO1-1C						
15	RGLE1-1C						

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