SOIL CHARACTERIZATION AND PHYSICAL LAND SUITABILITY EVALUATION FOR RAINFED MAIZE AND TEF CROPS PRODUCTION AT WOLKITE UNIVERSITY AGRICULTURAL FARM GURAGHE ZONE, ETHIOPIA

M.Sc. THESIS

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As Thesis research advisors, we hereby Certify that we have read and evaluated the Thesis entitled **"SOIL CHARACTERIZATION AND PHYSICAL LAND SUITABILITY EVALUATION FOR RAINFED MAIZE AND TEF CROPS PRODUCTION AT WOLKITE UNIVERSITY AGRICULTURAL FARM GURAGHE ZONE, ETHIOPIA"** prepared under our guidance by Shibikom Desalegn Erba**.** We recommend that it be submitted as fulfilling the thesis requirement of Natural Resource Management Department for defense.

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As members of the Board of Examiners of the MSc Thesis Open Defense Examination, we certify that we have read and evaluated the Thesis prepared by Shibikom Desalegn and examined the candidate. We recommended that the Thesis be accepted as fulfilling the requirement for the degree of Master of Science in Soil Science.

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DEDICATION

I would like to dedicate this thesis to my family who always support me and are eager to see my success.

STATEMENT OF THE AUTHOR

In the signature below, I declare that this thesis is my own work. I have followed all ethical and technical principles of scholarship in the preparation, data collection, data analysis and compilation of the thesis. Any scholarly matter that is included in the thesis has been recognition through citation.

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BIOGRAPHICAL SKETCH

The author, Shibikom Desalegn Erba, was born on 21 March 1985 E. C. at Buee district, Guraghe Zone, South National and Nationalities Peoples Regional State (SNNPRS), Ethiopia. He attended primary education (grade 1-8) at Ejersa Lele General Primary School from 1993-2000, and secondary and preparatory education (grade 9-10) at Buee town from 2001-2003. He then joined Wolaita Sodo ATVET College, in October 2004 and graduated with Diploma in Natural resource Development Extension Techniques in June 2006.

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ABBREVIATIONS AND ACRONYMS

AGP	Agricultural Transformation Program
ATA	Agricultural Transformation Agency
BD	Bulk Density
CEC	Cation Exchange Capacity
CGS	Council of Graduate Studies
DGC	Department Graduate Committee
ESP	Exchangeable Sodium Percentage
FAO	Food Agricultural Organization
GIS	Geographic Information System
GTP	Growth Transformation Program
masl	Meters Above Sea Level
IFPRI	International Food Policy Research Institute
IUSS	International Union of Soil Sciences
LUTS	Land Utilization Types
LC	Land Characteristics
LGP	Length of Growing Period
OC	Organic Carbon
PBS	Percent Base Saturation
RSG	Reference Soil Group
SOM	Soil Organic Matter
SNNPRS	Southern Nations Nationalities and Peoples Regional State
TOC	Total Organic Carbon
TP	Total Porosity
TN	Total Nitrogen
USDA	United State Department of Agriculture
WRB	World Reference Base
LMU	Land Mapping Unit

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Soil Characterization and Physical Land Suitability Evaluation for Rainfed Maize and Tef Crops Production at Wolkite University Agricultural Farm Guraghe Zone, Ethiopia.

ABSTRACT

*For precision agriculture, land use planning, and management, the major information sources are soil characterization, classification, and land suitability evaluation. The study was conducted at Wolkite university agricultural farm, Guraghe Zone, Ethiopia, to characterize, classify the soils and physical land suitability evaluation for the crop production. Three representative pedons from three slope categories (0-5, 5-10 and 10-15%) were opened and described. Two major crops (maize(zea) and tef(*eragrotis*) were used for physical land suitability evaluation using simple maximum limitation approach. Thirteen undisturbed and disturbed soil samples were collected from all identified genetic horizon for laboratory physical and chemical soil parameters analysis. The result of study showed that the textural class of the study area entirely clay. The pH of the soils showed acidic to alkaline reaction (pH 5.02- 8.04). The soils were very low in available P (0.9-0.38), high OC% (4.8), very high TN% (1), high K (7.93-9.85*(cmolc kg^{-1} soil)*, medium Mg (2.14-2.31*(cmolc kg^{-1} soil). *In all pedons the soil was developed from vertic subsurface horizon and is classified as Calcic Vertisols (Hypereutric) according to the World Reference Base for Soil Resources (WRB). Regarding physical land suitability, mapping unit 1Ac was marginally suitable (S3) for maize production due to CEC and pH as limiting factors and not suitable (N) for tef production due to LGP as limiting factor. mapping unit 2Ac was moderately suitable (S2) for maize CEC and pH as limiting factors and not suitable (N) for tef production due to LGP as limiting factor. mapping unit 3Ac was not suitable (N) for maize and tef production due to high pH and LGP as limiting factors. The mapping units could potentially be highly suitable (S1) for maize production if the soil be treated with lime to raise the pH. All mapping units (1Ac, 2Ac and 3Ac) were not suitable for tef production due to long length of growing period being the limiting factor. It is advisable to search crops that suit the climatic (very long maturing crops, >210 days), soil and landscape situation of the study area. cropping, cultivation and fertilization should be implemented so as optimize and sustain the agricultural production.*

Keyword: *Horizon, Vertic, Limitation method, morphological, Physical, Chemical*.

1. INTRODUCTION

1.1 Background and Justification

Agriculture is the main economic activity in Ethiopia providing food for people and domesticated animals, raw materials for industry, and aiding in the acceleration of developing countries' economic progress (Sajjad *et al.*,2014). As a result, there is a rising need for knowledge about soils in order to produce food in the best and most sustainable way possible. Additionally, much effort should be done on soil characterization due to the expansion of agriculture and the rising need for experimental data. In order to solve some specific soil issues in an ecosystem, this gives the fundamental knowledge required to develop useful soil classification schemes and estimate soil fertility (Lekwa *et al.*, 2000).

For the planning and implementation of sound management techniques that enable to restore degraded lands and maintain soil fertility status, data on soil characteristics and suitability evaluation are essential (Msanya, *et al.*,2007). Systematic field observation, evaluation and identification can be used to gather information on the soil, which provide the potentials and limitations of the land (Msanya, *et al.*,2007). The development of functional classification schemes for the management of soils in an ecosystem is made possible by basic knowledge of soil. Since soils have a wide range of morphological, physical, chemical, and biological characteristics, their characterization and classification are very important for an appropriate utilization and management of soils.

Soil characterization refers to the assessment of soil attributes by laboratory processes and other accepted methods using soil samples from pedons for soil classification (Negassa, 2003). All soil investigations must start with soil characterization since it is a key tool for classifying soils which is done based on soil properties. It also provides information for understanding of the physical, chemical, mineralogical and microbiological properties of the soils (Ogunkunle, 2005). It is a major building block for understanding the soil environment consequently; there have been many studies on soil characterization and suitability for various crops. Soil characterization uses to get detailed information on soil properties to determine their potential for food, fodder and fiber production (Osujieke 2018).

In order to categorize soils, understand their features and the environments in which they exist, soils characterization is also a major step (Esu, 2005). Soil types and characteristics show great variations across the regions of Ethiopia because of the country's wide range of topographic, geologic, and climatic features. Various studies on soil properties at a watershed level as well as in farmlands of Ethiopia also confirm that topographic position largely governs the change in types and characteristics of soils. Pedogenesis influences soil type and characteristics, which in turn influence the use and productivity of the soils (Assefa, 2015).

Soil classification aids in the organization of people's knowledge, makes it easier to transfer expertise and technology from one location to another, and aids in the comparison of soil properties (Dorronso, *et al.,* 2000). Additionally, it is employed to create classes with either comparable characteristics or a similar reaction to outside stimuli. As a result, high quality soil classification is a key component of understanding the soil, classifying it, and gaining the best understanding of the environment (Dinku *et al.,* 2014). It also serves as a foundation for effectively evaluating the suitability of a piece of land and managing its fertility.

The evaluation of land suitability, which has excellent physical and chemical land qualities, is crucial for improving food security in Ethiopia and for the global food production in general (Mishra 2015). Pressure on the land has increased as a result of both an increase in population and human activity. Farmlands in watersheds deteriorate as a result of farming operations carried out without adopting adequate management techniques, such as applying organic matter to restore nutrients, collecting rainwater, reducing soil erosion losses (Hailu, 2008). In rain-fed agricultural production systems, natural resources need to be used in such a manner that the productive potential of the watershed is optimized.

Land suitability evaluation is very important to provide information on the constraints and opportunities for the use of the land and therefore guides decisions on optimal utilizations of the resources, whose knowledge is an essential prerequisite for land use planning and development (Rabia *et al.,* 2012). Characterizing the soils in a given location for a certain land use type is part of the soil suitability evaluation process. According to Aduloju (2009), a parcel of land is suitable if it can be used naturally for a particular land use, such as rain-fed agriculture, raising cattle, or forestry. Predicting a land unit's innate ability to support a certain land is the primary goal of land evaluation. Evaluation of a certain watershed's land suitability is essential to determining its potential and limitations. In view of this fact, the present study was initiated to characterize, classify and evaluate the land suitability of wolkite university agricultural farm, which would help for formulating the soil management alternatives and in land use decision making.

1.2. Statement of Problem

In developing country, agriculture is the backbone of the national economy (Shimeles, 2012), and agriculture production has been highly dependent on natural resources for centuries (Amsalu, 2007). Degradation of soil resources is very common and low soil fertility is one of the bottlenecks to sustain agricultural production and productivity. Hence, understanding the soil properties and their distribution over an area is crucial to plan and implement site-specific soil management practices for efficient utilization of limited soil resources (Buol *et al.*, 2003). However, this valuable soil resource information is not properly investigated and documented, particularly at wolkite university agricultural farm.

Furthermore, in Wolkite University agricultural farm, soil characterization and suitability evaluation studied to provide basic soil data that can help to manage soils according to the local variability (Hailu *et al.*, 2015). However, the soil morphological, physical, and chemical characteristics at Wolkite University agricultural farm are not thoroughly studied. Moreover, the soil fertility in the selected farm is declining, due to continuous cultivation practices, inappropriate soil management practices and uses the land inappropriate soil characteristics, poor soil and water conservation measure? Therefore, soil characterization, classification and land suitability evaluation study at Wolkite University agricultural farm area is important. In view of this, the present study is initiated with the following general and specific objectives:

1.3 Objectives

1.3.1 General Objectives

The general objective of this study was to characterize and classify soils of Wolkite University agricultural farm area and to evaluate the land suitability of the area for major crops.

1.3.2 Specific Objectives

- ✓ To describe and characterize the soils of the study area.
- ✓ To classify the soils of the study area.
- ✓ To evaluate the land suitability of the soils of the study area for production of Maize and Tef crops.

2 LITERATURE REVIEW

2.1 Soil Forming Factors

Soil is a three-dimensional entity on the earth's land surface generated over time by the interaction or combined influence of soil forming variables such as parent material, climate, biota, and topography (Buol *et al.* 2011). Soils differ geographically due to variances in the distribution of soil-forming elements and processes. Soil qualities in a specific location are influenced by factors such as parent materials, geography, biota, and climate, as well as numerous anthropogenic activities.

These Russian workers stated that properties of soils reflect the combined effects of the particular set of genetic factors responsible for their formation (SSDS, 2000). Hence, soils are found to be the same whenever all the elements of the soil-forming factors and the respective soil forming processes are the same, so that under similar environments in geographically different places, soils are similar (SSDS, 2000). As soil is a complex mixture of various components, its formation is also more complex (Mohammed *et al.*, 2017). The formation of a particular type of soil depends upon the physicochemical properties of the parent rock, intensity and duration of weathering, climatic and other parameters (Stanley and Southard 2003). Soils are dynamic, forming continuously over a long period of time.

According to Jenny (1980), soil formation is the function of soil forming factors: namely climatic, geologic, biotic and topographic factors acting over a certain period of time. Any particular combination of these factors will give rise to a certain soil forming process, a set of physical, chemical and biological processes that create a particular soil (Boul, 2006). According to Ahmed (2002), all soil forming factors in combination with various anthropogenic activities act on and affect soil properties in a given locality. Thus, soils are the same wherever all elements of these factors are the same in degree, type and intensity, indicating the possibility of formation of different soils whenever one or more of these factors vary (Boul, 2006).

2.1.1 Parent Material

As is known, the parent material is the substrate, from which the soil is formed. It determines most of the properties of soil: the mineral and chemical contents of soil depend on the composition of the parent material; the density and porosity of parent materials determine the nature of the soil structure; the soil depth, its composition in vertical and horizontal directions, water content, thermal and physical properties also depend on the parent materials. Thus, the parent material is considered as a substrate from which soils form because the parent material provides the geochemical foundation of the soil (Gamkrelidze 2018).

In the process of soil formation, the original features of the parent material change in different ways. Some are almost unchanged in the soil while others experience significant transformation. Young soils with their composition and structure are close to those of the parent materials. The older the soil is, the longer the process of soil formation and exhaustion is going on and the greater the difference between the soil and their parent materials (Graham and Indorante,2017). The diversity in petrographic composition of parent materials causes the diversity of soils in general. Soils formed in the same bioclimatic and geomorphological conditions might be different when they are formed of different soil-forming parent materials. The minerals that compose the parent material are the sources of elements that serve as nutrients for plants (Graham and Indorante, 2017).

The character and chemical composition of the parent material plays an important role in determining soil properties, especially during the early stages of development (Steenhuis, 2009). Soils developed on parent material that is coarse grained and composed of minerals resistant to weathering are likely to exhibit coarse grain texture. Fine grain soils develop where the parent material is composed of unstable minerals that readily weather. Parent material composition has a direct impact on soil chemistry and fertility.

If parent materials are low in soluble ions, water moving through the soil removes the bases and substitutes them with hydrogen ions making the soil acidic and unsuitable for agriculture (Brantley, 2011). Soils developed over sandstone are low in soluble bases and coarse in texture which facilitates leaching. Parent material influence on soil properties tends to decrease with time as it is altered and climate becomes more important. Soil organic matter affects chemical, physical, and biological properties and processes in soil.

2.1.2 Climate

Precipitation and temperature are the two most important climatic variables influencing soil formation (Brady and Weil, 2002). Precipitation and temperature have a significant impact on soil formation and differentiation in many parts of the world, including Ethiopia, because both control the chemical and physical reactions that occur in the soil. The kind of climate in a specific place influences the depth of the soil profile, OM content, pH, percent base saturation, and type of clay mineral.

Fast hydrolytic weathering of minerals and humification and mineralization of organic matter are enhanced under warm humid conditions, primarily in the western and southern areas of Ethiopia where considerable rainfall occurs. Climate governs the development of organic substances, mineralization of OM, leaching of nutrients, hard pan and crust formation in southern Ethiopian soils, according to (Van Ranst, 2005). The amount of water the soil receives and the amount of evapotranspiration that occur influence water movement (Maher *et al.,* 2009). Climate is the most important factor in determining the type of soil that will form in a particular area. Temperature and precipitation have a direct influence on the nature of soil, while vegetation and topography have an indirect influence (Van Ranst, 2005).

2.1.3 Topography

slope position is the most important topographic factors in distinguishing soil types and their features. Due to changes in topographic positions, significant differences in chemical characteristics can arise amongst Pedons. Vertisols form on almost level to very softly sloping terrain in the northern Ethiopia. The same evidence was found in different parts of Ethiopia, as topographic positions such as backslopes, foot slopes, and toe slopes have a strong influence on the formation of various soil types This is because erosion removes materials from the upper slopes and deposits them in the lower slopes, resulting in the occurrence of different soil types along the slope (Buol, 2006).

Topography as one of the soils forming factors, exerts a strong control on the balance between erosion and deposition, soil organic matter additions and decomposition, water movement and residence time within the soil profile, leaching and accumulation and even oxidation and reduction acting in general as a major factor controlling both hydrological and soil processes (Schoonover and Crim, 2015). In land evaluation, topography includes relief or slope and elevation. The relief is related to land management and erosion hazard and elevation is related to temperature and solar radiation and thus closely linked to plant requirements (Ritung *et al.*, 2007). Landscape position is the topographic attribute in differentiating soil types and their characteristics. Significant differences can occur in chemical and physical properties between Pedons due to differences in topographic positions.

Steep, long slopes mean water will run down faster and potentially erode the surfaces of slopes. The effect will be poor soils on the slopes, and richer deposits at the foot of the slopes (Womer, 2002). Also, slopes may be exposed to more direct sunlight, which may dry out soil moisture and render it less fertile. Root growth can help prevent erosion as the roots act to keep the soil in place. This phenomenon leads to soils on slopes being thinner and less developed than soils found on plains or plateaus.

2.1.4 Organisms

A biological factor (living organisms) is an integral part of the soil-formation process. No soil exists without biological influence. Many living organisms and their products are immediate components of soil. Their unity, despite the minor amount in relation to the mass of our planet, guides the geochemical processes and is the major factor in the formation of the Earth landscapes. In the course of vital activity of the organisms, the major chains of soil formations are realized: synthesis and degradation of organic substances, degradation of minerals, migration, accumulation, and other phenomena being the essence of soil formation and determining the principal property of soil fertility (Graham and Indorante,2017).

The soil formation may occur under the influence of biological factor on the parent materials. The geography of plant communities has much determined the geography of soils. It is the living organisms engaging the solar radiation energy in the process of soil forming by transforming it in to potential energy and later into kinetic energy of geochemical processes (Graham and Indorante,2017). Biotic agents have greatly affected the soil formation process through OM addition, mixing and protection of soil from erosion and this tends to significantly affect soil structure, color, pH, CEC, infiltration and water holding capacity of soils (Sumner, 2000). Hence, soils formed under grass vegetation have thicker and, dark surfaces, while soils developed under forest tend to have thinner A-horizons (Buol, 2006).

For example, microorganisms can facilitate chemical reactions or excrete organic substances to improve water infiltration in the soil. Other organisms such as gophers slow soil formation by digging and mixing soil materials, and destroying soil horizons that have formed (Tsafe, 2013). Generally, soils have been formed under two major types of vegetation: Forest and prairie. Soils formed under forests tend to be more weathered (older in soil terms) because forests grow in higher rainfall areas. There's more water movement in the root zone, and a smaller amount of organic matter forms. Soils formed in prairie tend to be in areas with less precipitation (Williams *et al.*, 2010). Grasses tend to use the provided moisture, reducing the water movement through the soil profile. Organic matter forms in large quantities and to a deeper depth in the soil surface than forest soils.

2.1.5 Time

The time of soil formations begins as soon as parent materials is acted upon by climate and organisms (Jenny, 1941) and the time required for the formation of soils depends on whether ability of the parent rock, composition of transported parent materials and climate. Time is considered as a soil-forming factor since time in combination with the intensity factor (climate) has been responsible for the development of soils and specific soil properties (Buol *et al.*, 2003). Not all soils have been developing for the same length of time.

Terraces above the active floodplain, while similar to the floodplain, are older land surfaces and exhibit more development features. Additions, removals, and alterations are slow or rapid, depending on climate, landscape position, and biological activity. Based on weathering and the degree of soil formation, soil development stage has been employed as a relative measure of soil age. For example, dominating soils (Nitisols and Acrisols) of Ethiopia's southwest highlands exist under warm humid circumstances and are well developed or highly weathered (ancient) soils, where silica is replaced by kaolinite/gibbsite due to the leaching action. Regosols, Leptosols, and Cambisols found on steep slopes, on the other hand, are considered little developed (young) soils due to instability caused by erosion. As a result, terminology like well developed, immature, and old are utilized as relative time markers in soil formation (Sumner, 2000).

2.2 Soil Classification

Soil classification is the categorization of soils into groups at varying levels of generalization according to their physical, mineralogical, and chemical properties (Buol *et al.*, 2003). The classification of soils is based on soil properties defined in terms of diagnostic horizons, diagnostic properties and diagnostic materials, which to the greatest extent possible should be measurable and observable in the field (Buol *et al.,* 2003). The objectives of soil classification include organization of knowledge, ease in remembering properties clearer understanding of relationships and ease of technology transfer and communication.

Classification of soils is also useful to facilitate technology transfer and information exchange among soil scientists, decision makers, planners, researchers and agricultural extension advisors (Mohammed and Solomon, 2010). Today, there are several approaches and classification schemes in the world such as the USDA Soil Taxonomy, Australian, Canadian, South African and most have been on a national basis (Foth, 1990). The most common classification systems used worldwide are the FAO/WRB (2006) and (2015) soil map of the world and the USDA Soil Taxonomy of the United States (Buol *et al.,* 2003). These classification systems are also commonly used in Ethiopia for all soil studies. Knowledge of either system makes use of the other system possible with minimal adjustment (Foth, 1990). Soil classification is one of the most important stages in natural resources assessment and soil map is one of the basic tools for planning any agricultural development (Rabia *et al.,* 2013).

The purpose of soil classification is to organize our knowledge that the properties of soil be remembered and their relationships may be understood most easily for specific objectives. Accordingly, the presence or absence of specific diagnostic horizons, properties and materials were used to distinguish soil units and subunits as given in the employed classification system (FAO/WRB, 2006). The classification schemes differ because they are based on soil formation, use different criteria, and different hierarchical sub-divisions. (Buol *et al.*, 2003). Also soil classification systems were developed for different purposes. It is common to use hierarchical schemes because there are many soils and they have numerous physical, chemical, and biological properties (Issam, 2007).

2.3 Physical Properties of Soils

The physical properties of soil, in order of decreasing importance for ecosystem services such as crop production, are texture, structure, bulk density, porosity, consistency, temperature, color and resistivity (Moret *et al.*, 2012). Soil texture is determined by the relative proportion of the three kinds of soil mineral particles, called soil separates: sand, silt, and clay. These properties vary through the depth of a soil profile through soil horizons. Most of these properties determine the aeration of the soil and the ability of water to infiltrate and to be held within the soil.

2.3.1 Particle Size Distribution

The mineral components of soil are sand, silt and clay, and their relative proportions determine a soil's texture. Properties that are influenced by soil texture include porosity, permeability, infiltration, shrink-swell rate, water-holding capacity, and susceptibility to erosion (Shrinkant, 1993). In the illustrated USDA textural classification triangle, the only soil in which neither sand, silt nor clay predominates is called loam. Soil texture affects soil behavior, in particular, its retention capacity for nutrients (cation exchange capacity) and water.

Soil texture is an inherent characteristic of soils, and textural classifications are difficult to change in the field. This feature, however, is vulnerable to alter as a result of various soil management activities, which may contribute to indirect changes in particle size distribution. Soil textural class is known to change with soil position in the landscape. Soil erosion preferentially transports fine particles, resulting in a higher concentration of clay and silt in sediments than in the original soil (Brady and Well, 2002).

2.3.2 Soil Color

Soil color is one of the important basic properties that help to identify the types of soils and recognize the successive distinction in horizonation of soil profile, it has long been used for soil identification and qualitative measurements of soil properties it is helpful in characterizing soil types in field to indicate that (Hossain *et al.*,2015) reported that the alternate wetting and drying conditions in the soils resulted in the reduction and subsequent release of iron oxides, which where accumulated in the form of brown, light olive brown, dark brown and dark yellowish-brown mottles in the soil matrix of the profiles. Dark color of soils could be related to the strong impregnation of profile by organic matter during pedogenesis or to prolong water logging (Dengiz *et al.*, 2015).

These variations in soil color appear to be a product of chemical and mineralogical composition as well as textural make up of soils conditioned by Landscape position and moisture regime. Soil color is a significant morphological property of soil that can be greatly altered by Landscape changes According to (Mohammed *et al.*, 2005). Soil is naturally gray to white in color when it is first formed. Over time, soil develops other colors. Soil particles become coated with inorganic substances or organic matter that is Trans located or moved through the soil profile (Dengizet, 2015). Soil color is a very useful tool for investigations of soils for on-site wastewater disposal because color can indicate the wetness of a soil. Soils that are too wet are inappropriate for siting an on-site system.

2.3.3 Soil Structure

The term structure refers to the arrangement of primary and secondary soil particles in to aggregates or Pedon's. Soil structure is one of the soil morphological or physical properties, which is very sensitive to soil management practices. (Ashanafi *et al.*, 2010) reported that higher clay content could be the reason for better development of soil structure. Aggregate dynamics is mostly intensively influenced by soil OM and particle size distribution (Tobiaova *et al.*, 2013). Soil texture has strong influences on soil aggregation by (Brady, 2002). A well-aggregated soil improves soil aeration, water penetration, root growth, nutrient assimilation and release of gasses from the soil. Single-grained and massive soils have no structure. In single-grained soils, such as loose sand, water infiltrates into and percolates through very rapidly (Moorman, 2000). Water moves very slowly through massive soils, such as some clay. Prismatic, blocky and granular structures allow for greater movement of water, while a platy structure impedes the downward movement of water.

2.3.4 Soil Consistency

The soil consistency of pedons varied largely among soil types, depths and also spatially. It varied from slightly hard to very hard when dry, very friable to firm when moist, slightly sticky to very sticky and slightly plastic to very plastic when wet. The consistency became harder, firm, sticky and plastic with increasing depth owing to progressive increase in clay content with depth. The land attribute and relief were reported to have significant bearing on soil consistency (Mahapatra *et al.*, 2005). Among special features, the degree of effervescences increased with depth evidencing progressive increase in free lime content with depth.

2.3.5 Soil Depth

Soil depth is determined by the total thickness of soil horizons that are significant to soil use and management. It is normally the depth to which plant roots develop. Soil depth is described as deep, moderate, shallow, or very shallow to a restrictive layer (Singh and Mishra, 1996). Restrictive layers include cemented horizons, clay pans, bedrock, and sometimes abrupt textural changes. Soil depth influences both water and nutrient storage for plant growth. Mostly the depth of soil in Ethiopia is affected by relief. Soils on gentle slope have thicker sola than soils of sloppy land.

2.3.6 Soil Bulk Density and Porosity

Bulk density is defined as the dry weight of soil per unit volume of soil. Bulk density considers both the solids and the pore-space; whereas, particle density considers only the mineral solids. Tillage can increase bulk density if it breaks down aggregates and allows soil separates to pack more tightly. Adding organic material decreases bulk density because organic material has a lower bulk density. However, additions are typically so small in proportion to the weight of soil that they do not markedly influence bulk density except at the soil-atmosphere interface. The soil would be less aggregated and the bulk density would be increased. As a result, that total porosity would be decreased following the general relationship of soil bulk density to root growth (Shapouri *et al.,* 2001).

Soil particle density is typically 2.60 to 2.75 grams per cm3 and is usually unchanging for a given soil. Soil particle density is lower for soils with high organic matter content and is higher for soils with high iron-oxides content. Soil bulk density is equal to the dry mass of the soil divided by the volume of the soil; it includes air space and organic materials of the soil volume (Blake, 1986). Thereby soil bulk density is always less than soil particle density and is a good indicator of soil compaction. Contrary to particle density, soil bulk density is highly variable for a given soil, with a strong causal relationship with soil biological activity and management strategies.

Pore space is that part of the bulk volume of soil that is not occupied by either mineral or organic matter but is open space occupied by either gases or water. Soil texture determines total volume of the smallest pores; clay soils have smaller pores, but more total pore space than sands, despite of a much lower permeability. Soil structure has a strong influence on the larger pores that affect soil aeration, water infiltration and drainage (Brady, 2002). The pore size distribution affects the ability of plants and other organisms to access water and oxygen.

2.3 Soil Chemical Properties

The chemistry of a soil determines its ability to supply available plant nutrients and affects as physical property and the health of its living population. Some of these soil chemical properties are soil reaction (pH), electrical conductivity (EC), soil organic matter (organic carbon), total nitrogen, phosphorus, Cation exchange capacity, exchangeable bases (Ca, Mg, K and Na), percent base saturation, and concentration of available forms of micro nutrients (Grisso *et al.*, 2006).

The chemical side of a soil is extremely important of the correct balance of the available nutrients in the soil. This is largely determined by the organic-matter content and its humus percentage; this is the 'store house' of nutrients on any farm (Martinez. 2014). The extent to which minerals have a dominant presence or not, affect the release of specific nutrients. Supplementing shortages is important, but the right balance is even more important. The soil only produces nutrients if you have the right balance Chemical and physical properties impact biological properties.

2.3.1 Soil pH

Soil pH is influenced by chemical reactions between soil components and water. Soil pH is affected by the varied combinations of positively charged ions (sodium, potassium, magnesium, calcium, aluminum, manganese and iron) and negatively charged ions (Sahrawat, 2005). Soil reaction (pH) in particular, can be considered a key variable due to its influence on many other soil proprieties and processes affecting plant growth. Indeed, microorganism activity as well, as nutrient solubility and availability, is some of the most important processes that depend on pH. Soil pH directly affects the concentration of major nutrients and the forms of microelements available for plant uptake and can result in deficiencies or toxicities. Soils can be naturally acid or alkaline, and this can be measured by testing their pH value.

Having the correct pH is important for healthy plant growth. Being aware of the long-term effects of different soil management practices on soil pH is also important. Soil pH is a measure of the acidity or alkalinity of the soil. A pH value is actually a measure of hydrogen ion concentration. Soil pH was measured using a digital pH meter in the supernatant suspension of 1:2.5 soil liquid ratios. Generally, soil nutrient availability was affected by soil pH, while chemical reactions and the physical and biological environment in the soil were modified by SOC (Behera 2018).

2.3.2 Soil Organic Matter

Soil organic matter (SOM) is a heterogeneous mixture of organic compounds mainly derived from plant litter that has gone through several biochemical transformation cycles over centuries to millennia. Organic matter improves soil structural stability in addition to providing mineral nutrients for plants and microorganisms through the mineralization process or biochemical oxidation of organic substrates. For this reason, soil OM content is the result of equilibrium between the processes supplying new organic inputs and the rate of mineralization of the existing OM (Stockdale *et al*., 2006).

The development of soil organic N pools results from the balance between N input and output fluxes. In the absence of geological sources such as minerals of the mica group, the main N inputs in forest soils are plant and animal litter, root litter and exudates, free and symbiotic N-fixation as well as atmospheric N deposition. The main N outputs are plant root uptake, leaching of dissolved inorganic and organic N, wildfires, and gaseous losses such as N volatilization and denitrification (Shimeles, 2006).

2.3.3 Total Nitrogen

Nitrogen (N) is one of the most essential elements that is taken up by plants in greatest quantity after carbon, oxygen and hydrogen and considered to be one of the key crop growths limiting factors (Tadele *et al,* 2013). Soil total N composed of inorganic (NH4 +, NO3 - and NO2 -) and organic forms, is subject to change due to various factors. Management (cropping, fertilization, erosion and leaching) and climatic conditions (Temperature and moisture) determine the level and dynamics of N found in soils (Moody *et al*., 2008). Previous investigations on soil properties along landscapes affected by long-term tillage indicate that soil total N and OC contents are lower in areas of soil removal than in areas of soil accumulation (Shimeles, *et al*., 2010).

2.3.4 Cation Exchange Capacity

Cation exchange capacity (CEC) is a useful indicator of soil fertility because it shows the soil's ability to supply three important plant nutrients: calcium, magnesium and potassium. Soil nutrients exist as positively charged or negatively charged ions when dissolved. The positively charged ions are known as cations (Martel *et al.*, 1978). Cation exchange capacity (CEC) is a soil chemical property. It is the ability of the soil to hold or store cations. When soil particles are negatively charged, they attract and hold on to cations (positively charged ions) stopping them from being leached down the soil profile. The cations held by the soil particles are called exchangeable cations.

Cation-exchange capacity (CEC) a measure of how many cations can be retained on soil particle surfaces. Negative charges on the surfaces of soil particles bind positively-charged atoms or molecules (cations), but allow these to exchange with other positively charged particles in the surrounding soil water (Hazelton, 2007). This is one of the ways that solid materials in soil alter the chemistry of the soil. CEC affects many aspects of soil chemistry, and is used as a measure of soil fertility, as it indicates the capacity of the soil to retain several nutrients (K^+, Ca^{2+}) in plant-available form.

2.3.5 Availability of Phosphorous

Plants can't do without phosphorus. But there is often a 'withdrawal limit' on how much phosphorus they can get from the soil. That's because phosphorus in soils is often in forms that plants can't take up. That affects how healthy and productive the plants can be (Dong, *et al*. 2012). One influence on phosphorus availability is the soil's pH level. If soils are too acidic, phosphorus reacts with iron and aluminum. That makes it unavailable to plants. But if soils are too alkaline, phosphorus reacts with calcium and also becomes inaccessible.

The Olsen NaHCO3 extraction method was used to quantify plant available P (Olsen *et al.* 1954), as the method was recommended for all types of Ethiopian soils (Steiner, *et al.* 2007). Phosphorus; is a major essential plant macro nutrient which is needed for plant growth and development. The two methods most commonly used for determining the available P in soils are: Bray's Method No. II- Suitable for acid soils and Olsen's method - for both acid and nonacid soils.

2.4 Evaluation of Land Suitability

Land includes the physical environment, such as climate, relief, soils, hydrology, and vegetation, to the extent that these determine land use potential. It encompasses both historical and present human action (FAO, 1976). As a result, land requires cautious and suitable use in order to achieve maximum productivity and ensure environmental sustainability for future generations. Because land is a non-renewable natural resource, this necessitates the effective and operational management of land information on which such decisions should be founded (Kalogirous, 2002).

The appraisal and valuation of land when used for specific purposes is the focus of land evaluation (Sys *et al.*, 1991). It entails carrying out and interpreting basic surveys of data on climate, soils, vegetation, and other features of land in relation to the requirements of alternative land uses. According to FAO (1976), land suitability is the adaptability of a specific type of land for a specific application. The land can be evaluated in its current state or following upgrades.

The process of land suitability classification is the appraisal and grouping of specific areas of land in terms of their suitability for defined uses. So, suitability is a function of crop requirements and land characteristics and it is a measure of how well the qualities of land unit match the requirements of a particular form of land use. Suitability analysis can answer the question (what to grow where?). In order to define the suitability of an area for a specific practice, several criteria need to be evaluated (Belka, 2005).

Inappropriate land use results in inefficient natural resource extraction, resource damage, poverty, and other societal ills. Society must ensure that land is not degraded and that it is used to meet the requirements of current and future generations while also preserving the earth's ecosystems. Land evaluation in support of rational land use planning and suitable and sustainable use of natural and human resources is part of the solution to the land-use problem (Rossiter, 1996). As a result, the evaluation process gives information on the primary limits and opportunities for the use of land for specific use types, guiding decision makers on how resources are best managed.

Land suitability has been defined by several researchers, with the majority of definitions adhering to the FAO (1976) definition: "the fitness of a given type of land for a specified kind of land use." According to Ritung *et al*. (2007), land suitability is the degree to which a piece of land is suitable for a particular use. It could be evaluated in its current state (actual land appropriateness) or after improvement (potential land suitability). Land appropriateness is frequently confused with, and even considered synonymous with, land capability. However, land capability refers to a far broader range of applications such as agriculture, grazing, and urban development. Some define capability as the intrinsic ability of land to perform at a specific level for broad use.

The land may be assessed in its current condition or following improvements in land use appropriateness assessments. The process of establishing the suitability of a given land area for a specific type of use and the level of suitability is known as land use suitability analysis. The determination of the criteria that determine the suitability of the land is an important aspect of this process (Ritung *et al*. 2007). The process of land suitability classification is the appraisal and grouping of specific areas of land in terms of their suitability for defined uses. Land use suitability is also confused with land evaluation which refers to the process of assessing the performance of land when used for a given purpose.

Planning and management of the land use suitability mapping and analysis is done by application of GIS (Geographic Information System) (Collins *et al*., 2001). Considering the rapid growth of the world's population, which results limitation of arable lands around the world, the need for effective and efficient application of the croplands have been felt more than ever (Behzad *et al.*, 2009). Hence, much attention is given to selection of crops, which suits an area the best. Soil data are of primary need necessary as a first step in sustainable land use and soil management decisions (Chukwu, 2013).

The GIS-based land use suitability analysis has been applied in a wide variety of situations including ecological approaches for defining land suitability/habitant for animal and plant species (Kangas, 2001), geological favorability suitability of land for agricultural activities (Kalogirou, 2002), landscape evaluation and planning environmental impact assessment selecting the best site for the public and private sector facilities (Church, 2002).

3 MATERIALS AND METHODS

3.1 Description of the Study Area

3.1.1 Location

The study was conducted at Wolkite University agricultural farm which is located at Awan Kebele, Cheha district, Guraghe zone, SNNPRS, Ethiopia at about 169 km south of Addis Ababa and 15 km East of Wolkite town (the capital city of Guraghe zone). The experimental site is located at 8^{0}12'56'' to 8^{0} 12' 56'' N and 37^{0} 49'18'' to 37^{0} 49'21'' E and elevation ranging from 1939 to 1953 meters above sea level. The total area is 81.3 hectares (ha) of land. The topography of the farm generally characterized as flat to sloppy.

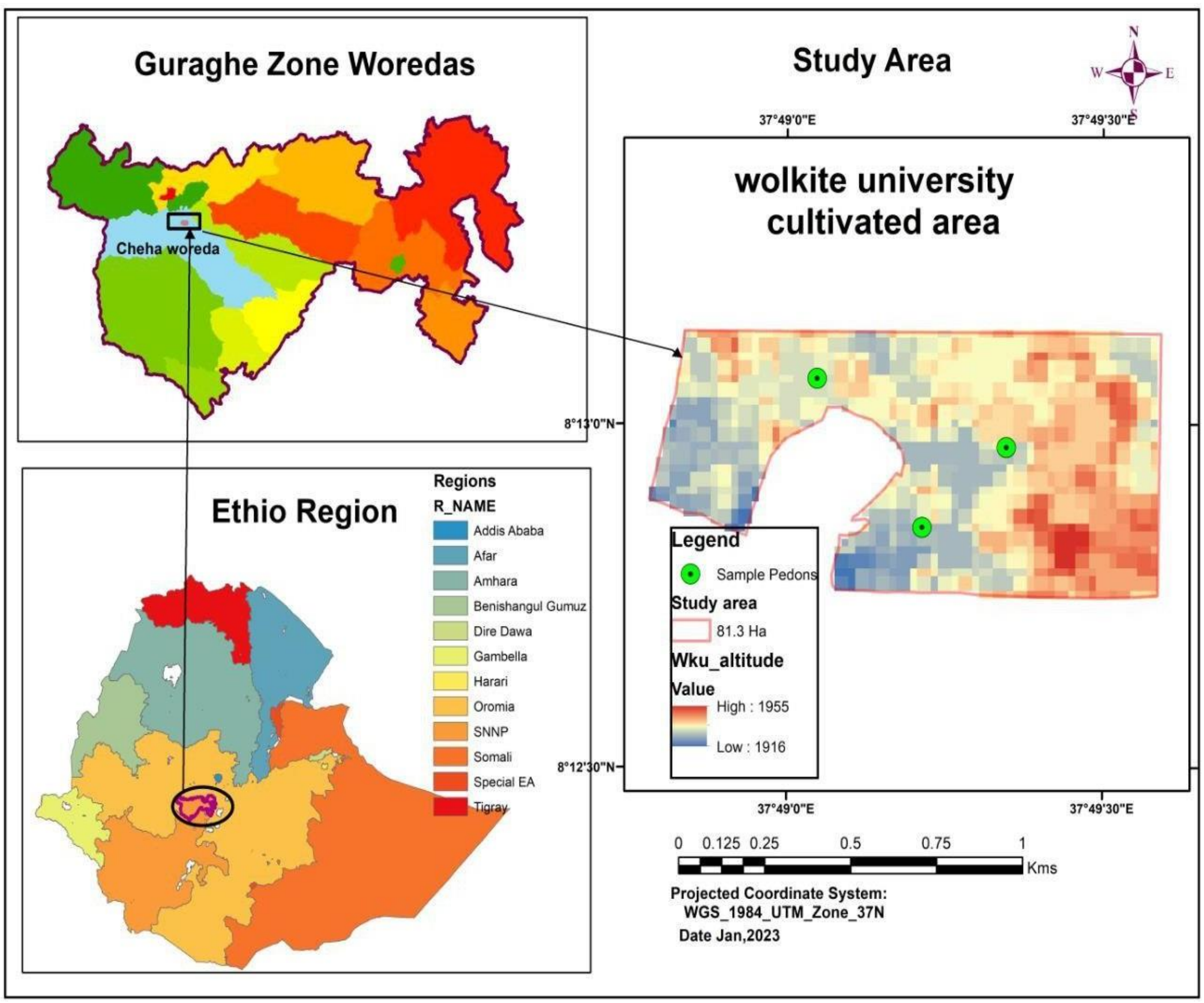

Figure 1 Location map of the study area

3.1.2 Climate

According to the weather records from Southern Nation, Nationality and Peoples' Region State Meteorological Agency and Emdibir sub-station, the mean annual rainfall; annual mean minimum and maximum temperatures of the study area based on the last 10 years (2012- 2022) records were 1100 mm and 10.51C^0 and 24.62C^0, respectively. The effective rainy season is from May to the end of September.

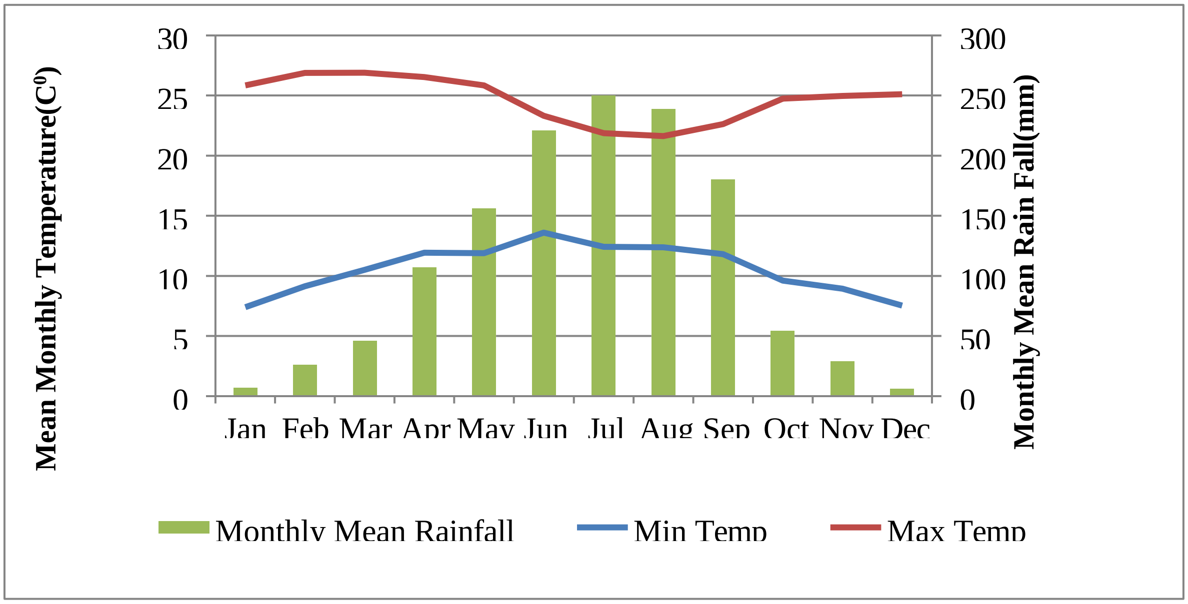

Figure 2 Source: Southern Nation, Nationality and Peoples' Regional State Meteorological Services Agency (2021).

3.1.3 Land use/cover

The land use of the study area includes cultivated land and open grassland. The major annual crops grown in the study area include Maize (zea) and Tef **(**eragrotis). Most of the land around Wolkite University agricultural farm area is occupied by cereal crops.

3.1.4 Topography

The topography of Wolkite University farm is characterized by flat or strongly slope. It is extensively cultivated and small parts are being used for pasture. The study area, Wolkite University farm has flat to strongly slopping landscape.

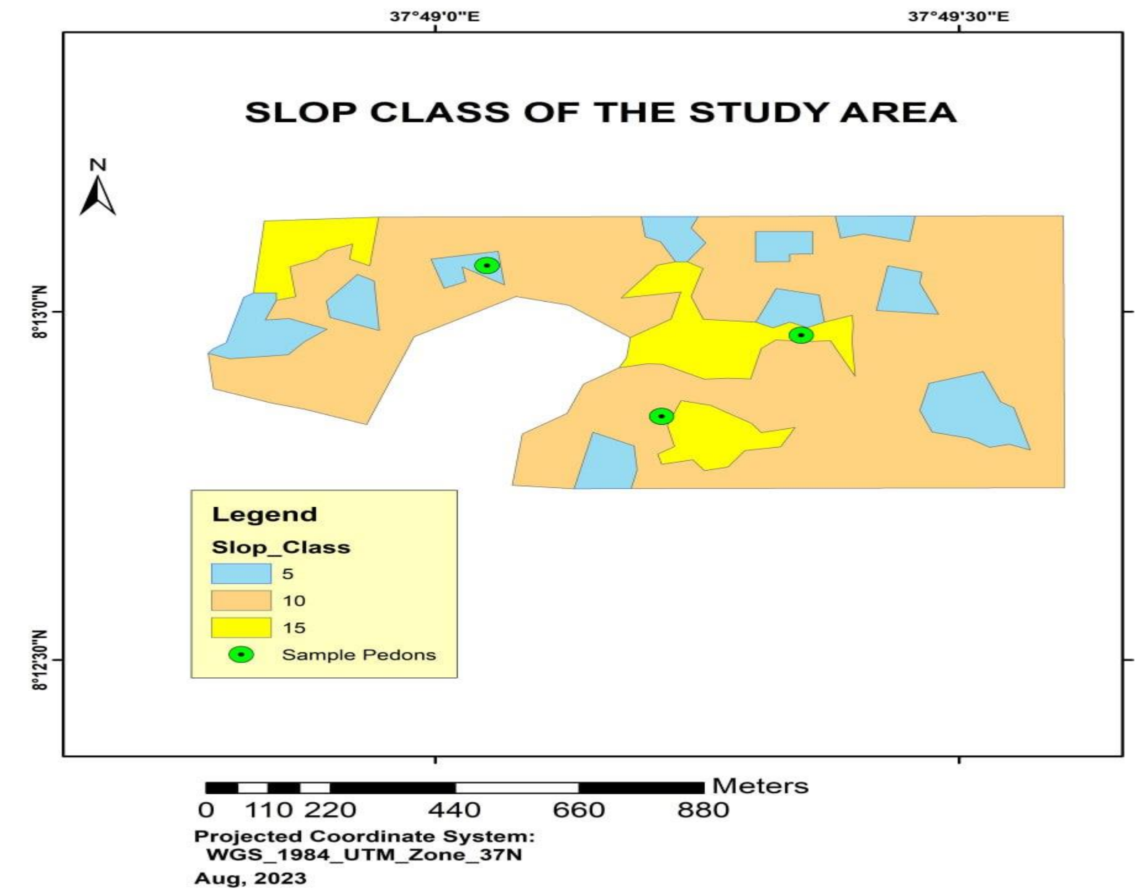

Figure 3 Slope class of the study area

3.2 Field Work

Field observation and augur inspection were carried out to locate for representative pedons/pits. Land units were delineated based on the field observation and augur inspection result. Three representative pedons were opened with 2m length, 1.5m width and 2m depth for each representative area. The soil was described using soil description guideline (FAO, 2006) and soil samples (disturbed and undisturbed) were collected from each identified horizon. Based on the morphological properties and the laboratory analysis, the soils of the study area were classified according to WRB (IUSS Working Group, 2014).

3.3 Soil Sample Preparation and Laboratory Analysis

The soil samples were air-dried in shade, ground with pestle and mortar, and made to passed through a 2-mm sieve and stored using plastic box. For organic carbon (OC) and total N, the soil samples were passed through 0.5 mm sieve to remove the coarser materials. the soil pedon samples were analyzed for selected agriculturally relevant soil physicochemical properties in Soil Laboratory following the standard analytical procedures and soils of the study area were finally classify and characterize based on morphological, physical, and chemical properties.

The particle size distribution of the soil was determined by the Bouyoucos hydrometer method (Day, 1965). Sand, silt and clay content of the soil was calculated and textural class was determined by using USDA textural triangle. The Bulk density (ρb) was determined from undisturbed soil samples collected using a core sampling method after drying the soil samples in an oven at $105C^0$ to constant weight as described by Blake (1965). Total porosity was then estimated from the values of bulk density (ρb) as follows:

$$\text{Total porosity (\%)} = \left(1 - \frac{\rho b}{\rho s}\right) * 100$$

Soil moisture was estimated following the procedure of Blake (1965). The soil samples were dried in oven at $105\ C^0$ until constant weight was obtained and dry weights of the samples were record and determined with the following formula.

$$\text{Moisture content (on volumetric basis)} = \frac{\text{Wt(mass)} - \text{Dry(mass)}}{\text{Dry(mass)}} * 100 * \rho b$$

The parameters soil pH, total N, soil organic matter, cation exchange capacity (CEC) and available phosphorus were analyzed in the laboratory. Soil pH was measured using a pH meter method in the supernatant suspension of 1:2.5 soils to water ratio described by Carter and Gregorich (2008). Organic carbon was determined by the wet digestion method as described by Walkley and Black (1934), whereas the percentage of organic matter of the soils was determined by multiplying the percent OC value by 1.724. Soil total nitrogen (TN) was analyzed by using the Kjeldahl digestion, distillation and titration method (Black, 1965). The available phosphorus was determined by the standard Olsen method (Olsen *et al.*, 1954).

Cation exchange capacity was determined at soil pH 7 after displacement using the 1-N ammonium acetate method in which it was, subsequently, estimated titrimetrically by distillation of ammonium that was displaced by sodium (Chapman, 1965). Exchangeable Ca and Mg was measured from the extract with atomic absorption spectrophotometer, whereas exchangeable K and Na was determined from the same extracts with flame photometer as described by Rowell (1994). Percent base saturation (PBS) was calculated using the following Equation (Hazelton and Murphy, 2007):

$$PBS= (\text{sum of Exchangeable base})/ (CEC) *100$$

3.4 Land Utilization Types and their Requirement

The land utilization types considered for the study were under rain fed condition cultivation of Maize and Teff varieties. Maize variety was BH546 with growing period of 145 days. The Teff variety was Kuncho with growing period of 100 days. The crop requirements were established following the approach of FAO (1983), Sys *et al*. (1993; FAO/UNDP (1984) and Lupia, 2012). The principle of the maximum limitation factor approaches was used in combining land suitability ratings. to obtain information about the potential and limitation of land in the study area for rain-fed production of principal crops: maize (*Zea*), and tef (*Eragrostis*) land use requirement of each crop was established using procedures. The Agro-climatic and land requirements for Maize and Teff crops are depicted in the Appendix Tables 5, 6 and 7.

3.5 Agro-Climatic Analysis

The length of growing period was determined by comparing monthly rainfall with reference evapotranspiration (ETo) (Sys *et al.* 1991). The start and end of the growing period, and start and end of the moist period was determined using linear interpolation technique as described in Sys *et al.* (1991). The climatic resources data was obtained from Ethiopian Meteorological Agency. The climatic data were obtained from 2012 to 2021, and the reference evapotranspiration was estimated following CropWat Version 8.0 for Windows based on FAO Penman-Monteith method. The start of the growing period and end of rain were calculated using the following formula of Sys *et al*. (1991):

$$t = \frac{(R1 - E1/2) * 30}{(R1 - R2 + E2/2 - E1/2)} \text{\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_} Eq.1$$

t = time in days starting from the middle of the first month.

R = rainfall

E = Evapotranspiration

The beginning and end of the humid period was calculated using the following formula:

$$t = \frac{(R1 - E1) * 30}{(R1 - R2 + E2 - E1)} \text{\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_} Eq.2$$

The end of the growing period was determined by the number of days that are required to consume 100 mm of water since the likely end of rains.

3.6 Description and Characterization of Land Mapping Units

Identification of the land mapping units (LMUs) was based on slope, soil depth and soil texture which are the main data source for the land suitability evaluation of selected land utilization types. The entire study area was categorized into three slopes, one soil depths and one textural class. Three representative pedons (1 to 3) were opened across the study area. The study area was categorized into three LMUs: 1Ac, 2Ac and 3Ac (Figure 4) for the purpose of land suitability evaluation. The first number and the last small letter in the LMU designation indicate the slope (1= 0-5, 2= 5-10 and 3= 10-15%) and texture (c= clay), respectively, whereas the middle capital letters indicate the soil depth (A= >150 cm).

3.7 Land Suitability Classification and Mapping

The land suitability classification was made following the methods of FAO (FAO, 1976; 1983; 2007). The land suitability evaluation was made for two crops: Maize and Tef. Digital data of selected land characteristics of the area and classifier tables for crop land use requirement were properly encoded to the Microsoft Office Excel sheet as database file to be used in ArcGIS 10.3 for spatial analysis. The land characteristics were reclassified based on crop land use requirements and GIS model builder uses maximum limitation method so that the most limiting climatic or soil parameter dictates the final level of suitability (Sys *et al.*, 1991). Hand held GPS was used for geo-referencing soil pedons.

3.8 Statistical Analysis

The laboratory analysis result of the selected soil physicochemical properties was subjected to simple linear correlation analysis to check the degree and magnitude of relationships between the selected attributes among the study Pedons. The analysis was performed using Statistical Software (SAS, 2014).

4. RESULTS AND DISCUSSION

4.1. Characteristics of the Study Area

The site characteristics of the pedons indicated differences in slope: pedon 1 represents lower slope (0-5%), pedon 2 represents middle slope (5-10%) and pedon 3 represents upper slope (10-15%). The physiographic characteristics of the representative pedons are presented in Table 1, the site and soil description are presented in Appendix Tables 1, 2 and 3.

Table 1. Physiographic characteristics of the site and location of representative pedons

Pedon	S (%)	Latitude	Longitude	Altitude (masl)	Slope class	Drainage class	Physiographic position	Parent material
1	0-5	$8^{0}12^{'}58^{''}$	$37^{0}49^{'}21^{''}$	1939	Flat to gently sloping	Poorly drained	Lower slope	Not observed
2	5-10	$8^{0}13^{'}04^{''}$	$37^{0}49^{'}03^{''}$	1949	sloping	moderately drained	Middle slope	Not observed
3	10-15	$8^{0}12^{'}51^{''}$	$37^{0}49^{'}13^{''}$	1950	strongly sloping	good drained	Upper slope	Not observed

4.2 Morphological Properties of the Study Area

Morphology of a soil is one of the most important tools of soil classification, since it is performed under natural undisturbed soil condition. In order to place a soil in its correct position in the classification system. Soil morphological characteristics were described following the Guidelines for soil description (FAO, 2006). The color, texture, consistency, structure, plant rooting patterns and other soil features were examined to determine which horizons are present and at what depth their boundaries occur. Both disturbed and undisturbed soil samples were collected from each genetic horizon.

Soil color was then determined using the help of the Munsell color chart (Munsell, 2000). Soil structure was described in terms of the sequence; grade, size, and type (shape) of aggregates whereas horizon boundaries were described in terms of depth and distinctness. The soil consistency was identified at dry, moist and wet moisture conditions. The pedons of lower slope (P-1), middle slope (P-2) and upper slope (P-3) had deep soils (> 150 cm) and almost similar horizons sequence. The B horizons of all the pedons had exhibited slickenside, which is the typical feature of swelling and shrinking soils. In the lower horizons of the pedons, white concretions were observed, which indicate the presence of calcium carbonate ($CaCO_3$). The 10% HCl test indicated strong visible effervescence in P- 1, while Visible effervescence in the case of P-3 and audible effervescence but not visible in the case of P-2 (Appendix Table 1-3).

4.2.1 Soil Color

The surface horizons moist color of the pedons were black (10YR 2/1) for pedon 1, dark gray (10YR 4/1) for pedon 2 and very dark grayish brown (10YR 3/2) for pedon 3. The subsurface horizons color of the pedons were black (10YR 2/1) and dark gray brown (10YR 4/2) for pedon 1; very dark gray (10YR 3/1) and very dark grayish brown (10YR 3/2) for pedon 2, and black (10YR 2/1), very dark braw (10YR 2/2), very dark grayish brown (10YR 3/2) and brown grayish (10YR 5/2) for pedon 3. 10YR4/1 (dark gray) dry, 10YR 4/1 (dark gray) dry, (10YR 4/1) Dark gray dry and (10YR 5/3) Brawn dry for pedon 1. 10YR5/1 Gray dry, 10YR 4/1 Dark gray dry, 10YR 4/1(dark gray) dry and 10YR 4/2 (dark gray brawn) dry for pedon 2. (10YR4/2) dark grayish brawn Dry for pedon 3.

Surface horizons were relatively darker as compared to the subsoil layers and not observed parent materials. Generally, this variation of color can be attributed to the relatively higher amount of organic matter in the surface soil (Dinku *et al.*, 2014). Soil color differences were also observed among the slope position. The pedon at lower topographic position had darker color as compared to others, which might be due to the differences in organic matter content at topographic positions (Dengiz *et al*., 2012).

4.2.2 Soil Structure and Consistence

In all pedons at respective topographic positions, the biological activity and plant root density were higher in the surface horizons and decreased with depth due to decrease in root biomass (Table 2). Plant roots in different horizons of each pedon also varied from very fine to course in size and few to common in quantity. There were also some variations in the grade, size and shape of the soil structure among pedons. The subangular blocky to angular blocky structure of the subsurface horizons could be due to the relatively higher clay content in consent with this finding, Tobiasova *et al.* (2013) also indicated that soil structure is affected by soil organic matter and clay content.

The structure of the soils in the surface layers of the pedon were moderate granular fine and medium (Pedon 1, 0-20 cm), moderate Granular Fine and medium (Pedon 2, 0-27 cm) and Moderate Granular Fine and medium (Pedon 3, 0-20 cm). The angular blocky to Very coarse structure of the subsurface horizons could be due to the relatively higher clay content and lower OM content than that of the surface horizons and also indicated that soil structure is affected by soil organic matter and clay content (Tobiasova *et al.* 2013). The better developed structure of the subsurface layers could be due to the relatively higher clay content of the subsurface horizons than that of the surface horizons (Ahn, 1993).

The soil consistence in the pedons varied among the topographic positions, whereby it varied from hard to very hard (dry), firm to very firm (moist), sticky/ plastic to very sticky/ plastic. The surface horizons of the three pedons had similar structural and consistence condition. The observed differences in soil consistence could probably be explained by the differences in particle size distribution, particularly clay content, OM and nature of the clay particles. The findings of this study agree with the results reported by Moradi (2013) who indicated that soil consistence varied with soil texture. Mulugeta and Sheleme (2010) also pointed out that the friable consistence observed in the surface soils of the pedons could be attributed to the higher soil OM content.

4.2.3 Horizon Boundary and Depth

The distinctness of horizon boundary between surface and subsurface horizons in all pedons was clear with smooth topography (Table 2). The differences in nature of the horizon boundaries may indicate the existence of variations in processes that have formed the soils and partly reflecting anthropogenic impacts (Cools and De Vos, 2010). The thickness of the solum varied along the topo sequence, which may limit the root penetration. Based on abundance of roots, biological activity was relatively higher in the surface horizons and decreased with depth of the pedons. This, indeed, could be associated with decreasing root biomass, aeration, nutrients and management effects down the soil profiles. The roots in different horizons of the pedons also varied from very fine to coarse in size and few to common in quantity (Cools and De Vos, 2010).

The differences in depth of the solum might have been due to the shape and slope length, which are important in influencing the rate at which water flows into or off the soil if the sites are unprotected. The running water may erode soils on slopes and form thinner surface layer, Mulugeta and Sheleme (2010) also reported that landscapes position influences runoff, drainage, soil temperature, soil erosion, soil depth and hence soil formation.

Table 2 Selected morphological characteristics of pedons.

Horizon	Depth (cm)	Color		Soil morphological characteristics						Texture (Feel method)	Horizon boundary		Diagnostic properties
		Dry	Moist	Structure			Consistence				Distinctness	Topography	
				Grade	Type	Size	Dry	Moist	wet				
Pedon1: Lower Slope													
AP	0-20	10YR4/1	10YR2/1	MO	G	FM	HA	FR	ST/PL	Clay	C	S	Cracking
Bi1	20-99	10YR 4/1	10YR 2/1	ST	AB	VCO	V HA	VFR	VST/PL	Clay	Gr	S	Slickensides
Bi2	99-165	10YR 4/1	10YR 2/1	ST	AB	VCO	V HA	VFR	VST/PL	Clay	C	S	Slickensides
Bw	165-200+	10YR 5/3	10YR 4/2	ST	AB	VCO	V HA	VFR	VST/PL	Clay			-
Pedon2: Middle Slope													
AP	0-27	10YR5/1	10YR4/1	MO	G	FM	HA	FR	ST/PL	Clay	C	S	Cracking
Bi1	27-68	10YR 4/1	10YR 3/1	ST	AB	VCO	V HA	VFR	VST/PL	Clay	Gr	S	Slickensides
Bi2	68-157	10YR 4/1	10YR 3/1	ST	AB	VCO	V HA	VFR	VST/PL	Clay	Gr	S	Slickensides
Bk	157-200+	10YR 4/2	10YR 3/2	ST	AB	VCO	V HA	VFR	VST/PL	Clay			-
Pedon3: Upper Slope													
AP	0-20	10YR4/2)	10YR3/2	MO	G	FM	HA	FR	ST/PL	Clay	C	S	Cracking
Bi1	20-78		10YR 2/1	ST	AB	VCO	V HA	VFR	VST/PL	Clay	C	S	Slickensides
Bi2	78-105		10YR 2/2	ST	AB	VCO	V HA	VFR	VST/PL	Clay	C	S	Slickensides
Bw	105-147		10YR 3/2	ST	AB	VCO	V HA	VFR	VST/PL	Clay	C	S	-
Bk	147-200+		10 YR 5/2	ST	AB	VCO	V HA	VFR	VST/PL	Clay	C	S	-

G= granular, MO = moderate, FM = Fine and medium, HA = hard, FR = firm, ST/PL = sticky/ plastic, C = clear, S= smooth, AB angular blocky, VCO = very coarse, VHA= very hard, VFR = very firm, VST/PL = very sticky/ plastic, Gr = gradual, ST = strong

4.3 Physical Properties of Soils

4.3.1 Particle Size Distribution

Considerable differences in soil particle size distribution within and among pedons were observed in the study area (Table 3). According to particle size distribution rating proposed by Hazelton and Murphy (2007), the soils of the study area was characterized by textural class of the surface and subsurface horizons of all the pedons was clay. Across the profiles, the highest (87%) clay content was recorded in the subsoil horizons of Pedon 3 and the lowest (55%) clay content was recorded in the subsoil horizons of Pedon 1 (Table 3). There was an increasing trend in the clay content of all the pedons down the profile, On the other hand, the sand and silt fractions showed inconsistent increase with depth in all Pedons.

The highest sand content (24%) was obtained at the lower Pedon 1; while the highest silt content (41%) was recorded at middle and lower Pedons. a positive and no significant ($r= 0.09$, $p > 0.05$) correlation was observed between clay and sand, positive and no significant ($r= 0.144$, $p > 0.05$) correlation also prevailed between clay and silt (Table 11) indicating that upon weathering, some silt sized particles may contribute to an increase in clay percentage.

4.3.2 Bulk Density

The bulk density value of the surface horizon ranged from 1.23 to 1.26 g/cm^3 and the subsurface horizons 1.25 to 1.31 g/cm^3. The values of bulk density showed increasing trend depth wise owing to a reduction in soil OM content and pressure of the over laying horizons. The optimal and critical limits of soil ρb are dependent on soil texture, particle size, management practices, and organic matter content. A ρb of less than or equal to 1.3 g/cm^3 is good, between 1.3 and 1.55 $g\ cm^3$ is fair, and greater than 1.8 $g\ cm^{-3}$ is considered extremely bad (Reichert *et al.*, 2009).

Therefore soil bulk density determines the infiltration, available water capacity, soil porosity, rooting depth/restrictions, soil microorganism activity and nutrient availability. An increasing bulk density implies a decrease of macro pores and the resultant changes impacted on hydraulic conductivity (Fuentes *et al.*, 2004). Thus, the bulk density affects the pore diameter and its distribution and resultantly affects the soil hydraulic properties (Dec *et al.*, 2008). Dec *et al.* (2008) reported that the increasing bulk density not only induces changes in the pore-size distribution but also affects the ability of soil to shrink and to conduct water in the soil. The correlation analysis also revealed negative and highly significant (r= -0.729, p<0.01) relationship between bulk density and OC (Table 11). Additionally, the bulk density Values of cultivated soils were higher than the uncultivated soils, which could be associated with degradation of OM and compaction by tillage implements.

4.3.3 Total Porosity

The total porosity of the surface horizons soils ranged from 54.5 % (pedon 3) to 55.3% (pedon 2). 54.4 % (pedon 2) to 52.3% (pedon 3) Subsurface horizons Nevertheless, this variation did not exhibit any consistent trend with topographic position. On the other hand, a general decrease in total porosity with soil depth was observed in all pedons. The decrease of total porosity with soil depth could be attributed to compaction due to the overlaying layers, limited penetration of crop roots into subsurface layers as well as the relatively low OM contents in the subsurface horizons. This finding is in agreement with Pravin *et al.* (2013) and Zeleke and Kibebew (2009) who reported that decreasing in total porosity with soil depth as a result of increasing compaction, decreasing of rooting effect and OM content with depth.

Table 3 Selected physical characteristics of soils of the study area.

Depth (cm)	Horizon	Particle size distribution (%)			Textural class	BD(g/cm^3)	TP (%)	DR	(%) MC	FL
		Sand	Silt	Clay						
Pedon 1: Lower slope										
0-20	AP	17	36	55	clay	1.26	54.0	P	5.9	N
20-99	Bi1	10	24	71	clay	1.28	53.5	P	7.0	N
99-165	Bi2	15	19	81	clay	1.29	53.0	P	7.1	N
165-200$^+$	Bw	24	30	85	clay	1.31	52.2	P	7.6	N
Pedon 2: Middle Slope										
0-27	AP	13	24	57	clay	1.23	55.3	M	5.1	N
27-68	Bi1	19	36	66	clay	1.25	54.4	M	6.1	N
68-157	Bi2	20	41	78	clay	1.26	54.0	M	7.0	N
157-200$^+$	Bk	22	29	82	clay	1.30	52.7	M	8.0	N
Pedon 3: Upper slope										
0-20	AP	20	25	59	clay	1.25	54.5	G	5.3	N
20-78	Bi1	10	18	71	clay	1.26	54.2	G	5.6	N
78-105	Bi2	12	22	79	clay	1.27	53.6	G	5.9	N
105-147	Bw	9.0	33	83	clay	1.30	52.7	G	6.1	N
147-200$^+$	Bk	17	41	87	clay	1.31	52.3	G	6.4	N

SL= sandy loam; L=loam; SC=sandy clay; C= clay; HC= heavy clay; BD= bulk density; TP=total porosity; DR=drainage; FL=flooding; WD= well drained; N=none; MC = Moisture content, M= moderate; P = poor, M = moderately drainage, G = good

4.4 Soil Chemical Characteristics

4.4.1 Soil pH

The soil pH values showed generally an increasing trend with depth in all pedons (Table 4). Increasing soil pH values with soil depth may indicate presence of translocation of exchangeable bases and carbonates. The surface soils horizons pH ranged from moderately acidic (5.47) in the lower slope pedon to strongly acidic (5.05) in the upper slope pedon based on the rating of Hazelton and Murphy (2007) (Table 4). The subsurface horizons pH ranged from neutral (6.8) in the lower slope pedon to strongly alkaline (8.04) in the middle slope pedon based on the rating of Hazelton and Murphy (2007). The soil pH was positively and highly significantly correlated with both Ca and K ($r = 0.649$; $r=0.757$, $p<0.01$) (Table 11). Shimeles (2006) suggested, increasing soil pH values with depth could be ascribed to seasonal soil water saturation that might have resulted in leaching of bases and contributed to higher pH value of the under lying horizons.

Table 4 Soil reaction (pH), organic carbon, total nitrogen, organic matter and available phosphorous of the soils

Depth (cm)	Horizon	pH (H2O)	OC (%)	OM %	TN (%)	Av.P (mg kg^{-1})
			Pedon1: Lower Slope			
0-20	AP	5.47	4.6	7.9	0.19	0.45
20-99	Bi1	6.80	2.2	3.8	0.18	0.43
99-165	Bi2	7.80	1.6	2.8	0.16	0.41
165-200^{+}	Bw	6.90	1.4	2.4	0.13	0.38
			Pedon2: Middle Slope			
0-27	AP	5.50	4.4	7.6	0.26	0.90
27-68	Bi1	6.95	1.8	3.1	0.21	0.67
68-157	Bi2	8.01	1.4	2.4	0.15	0.52
157-200^{+}	Bk	8.04	0.8	1.3	0.15	0.42

Pedon3: Upper Slope						
0-20	AP	5.05	4.8	8.2	1.00	0.49
20-78	Bi1	7.56	1.6	2.7	0.81	0.48
78-105	Bi2	7.98	1.2	2.0	0.67	0.46
105-147	Bw	8.02	0.4	0.6	0.16	0.41
147-200$^+$	Bk	7.35	0.2	0.3	0.15	0.39

OC= Organic carbon, TN= Total nitrogen, O.M= organic matter, Av.P= Available Phosphorus

4.4.2 Soil Organic Carbon and Total Nitrogen

The organic carbon (OC) content of surface horizons varied from 4.4% in the middle slope pedon to 4.8% in the upper slope pedon and rated as high as per the rating of Tekalign (1991). The OC contents of the soils decreased with soil depth in all the pedons (Table 4). It did not show consistent trend across topographic positions, but it decreased with soil depth in all pedons. The higher OC content of the surface horizons could be ascribed to the presence of biomass production from crops, grasses, weeds and the activity of soil organisms, all of which improve the organic matter status of the soils.

The total N content of the surface soils ranged from 1.00 to 0.15% in the upper slope pedon (very high to medium), 0.26% to 0.15% in the middle slope pedon (very high to medium) and 0.19 to 0.13 % in the lower slope pedone could be rated as medium to high as per the rating outlined by Murphy (1968) respectively (Table 4). It showed a decreasing trend with increasing soil depth as that of OC. This decrease generally parallels to a decrease in contents of organic matter, suggesting that the main source of total nitrogen was organic matter. In consent with the findings of this study Meysner *et al.* (2006) indicated that as much as 93 to 97% of the total N in soils is closely associated with OM.

Mohammed *et al.* (2005) also indicated that the higher content of total N corresponded with pedons and/or soil layers having high OM content, whereby pedons with lower total N had lower OM contents. According to Hartz (2007) soils with less than 0.07% total N have limited N mineralization potential, while those having greater than 0.15% total N would be expected to have a significant amount of nitrogen mineralization during the succeeding cropping cycle.

Accordingly, all of the soils in the study area have a good potential of N mineralization. The distribution pattern of total N with soil depth was similar to that of OC. This was also evident from the positive and no significant ($r=0.35$, $p>0.05$) correlation between TN and OC indicating OM is the main source of N (Table 11).

4.4.3 Available Phosphorus

Available P content of the soils in the pedons ranged from 0.38 mg kg-1 in subsurface horizon to 0.9in surface horizon which could be categorized as very low as per the rating of Jones (2003). According to Jones, (2003), the available P contents of soils of the cultivated land ranged from very low to low (Table 4). This implies that P could be a limiting nutrient for crop production in the study area and, thus, need external application of P. As observed by all pedons, crop cultivation in these soils may be limited by low P status in addition to other limiting factors. The application and management of P are equally important for sustainable use of the soils for crop production.

Generally, the available P content of the soils decreased with increase profile depth in all pedons. Relatively higher available P recorded in the surface horizons compared to the subsurface horizons could be attributed to the relatively higher OC contents in the surface layers, and residue of application of P containing fertilizer. This finding is in line with that of Awdenegest *et al.* (2013) who argued that the higher available P in the top soil layer of farm land may be related to the application of animal manure, compost, household wastes like ashes and DAP fertilizer for soil fertility management.

4.4.4 Exchangeable Bases

The amounts of exchangeable bases increase depth wise and generally, the recorded mean values of exchangeable bases could not be the limiting factors for crop growth. The variation might be due to the effect of leaching and subsequent accumulation in the down position. This is in agreement with the finding of Tadele *et al.*)2013) in Anjeni watershed, central highlands of Ethiopia, who reported relatively higher accumulation of divalent cations in down position due to washing away from the surface horizons layers and accumulations in the subsurface layers. In which plants grow well and meet their calcium and magnesium needs in soil (Brady and Weil, 2008). Ashenafi *et al.*, (2010) also reported increases in concentrations of cations with soil depth. According to the rating suggested by FAO (2006), all soils have high exchangeable Ca and medium to high K.

This could be due to the presence of Ca and K bearing parent materials and less amount of leaching. Ca and K were the predominant basic cations in the soils. According to the rating of FAO (2006), exchangeable Ca ranged medium (5.53 cmol (+) kg^{-1}) to high (12.25 cmol (+) kg^{-1}), exchangeable Mg rated as medium (2.15.to 2.43 cmol (+) kg^{-1}), exchangeable K categorized under very high status and exchangeable Na rated as low. Exchangeable bases refer to the positively charged ions, which are loosely attached to the edge of clay particles or OM in the soil. The cations that are commonly found in association with the soil exchange site include calcium (Ca), magnesium (Mg), potassium (K), and sodium (Na). Contents of calcium increased in down slope positions.

4.4.5 Cation Exchange Capacity

Cation exchange capacity is very important soil property influencing soil structure stability, nutrient availability, soil pH and the soil's reaction to fertilizer and other ameliorants (Hazelton and Murphy, 2007). The high CEC results showed that the soil of the study area had good nutrient retention and buffering capacities. The CEC of the soils ranged from medium (27 cmolc kg^{-1}) in the surface horizon of pedon 3 to very high (40 cmolc kg^{-1}) in the subsurface horizon, (27 cmolc kg^{-1} to 35 cmolc kg^{-1}) pedon 2 and (26.0 to 33cmolc kg^{-1}) pedone 1 medium to very high as per the rating of Landon (1991) (Table 5). The CEC of the soils generally increases with depth as that of clay content, which asserts the strong positive correlation of clay.

4.4.6 Percent Base Saturation

Percent base saturation (PBS) varied between (88.42 to 82.53%) pedon 3, (96.3 to 88.8%) pedon 2 and (96.3 to 82.9%) pedon 1 in surface and subsurface horizon of respectively (Table 5). According to Hazelton and Murphy (2007) rating, the soils categorized as high (82.53%) to very high (96.3%). In general, the occurrence of higher percentage of base saturation almost in all pedons could be used as an indication of good soil fertility and presence of weather able minerals in the soil (FAO-WRB, 2006). According to Landon (1991), soils having greater than 60% base saturation are rated as fertile and potentially productive soils.

Table 5: Exchangeable bases, cation exchange capacity, and percent base saturation, Exchangeable sodium percentage.

Depth (cm)	Horizon	Exchangeable bases (cmolc kg^{-1} soil)					CEC ($cmol_c$/kg soil)	PBS (%)	ESP (%)
		Ca	Mg	K	Na	TEB			
				Pedon1: Lower Slope					
0-20	AP	11.37	2.12	7.05	0.18	20.72	26.0	79.7	0.69
20-99	Bi1	10.86	2.23	7.79	0.19	21.07	28.2	74.7	0.90
99-165	Bi2	10.18	2.14	8.14	0.21	20.67	31.3	66.0	1.04
165-200^{+}	Bw	9.45	2.23	8.51	0.22	20.41	33.0	61.8	0.70
				Pedon2: Middle Slope					
0-27	AP	11.55	2.14	7.40	0.21	21.30	27.0	78.9	0.77
27-68	Bi1	11.54	2.16	8.58	0.23	22.51	29.3	76.8	0.78
68-157	Bi2	11.23	2.43	8.48	0.25	22.39	31.7	70.6	0.79
157-200^{+}	Bk	12.25	2.31	9.52	0.31	24.39	35.0	69.7	0.89
				Pedon3: Upper Slope					
0-20	AP	9.82	2.23	7.93	0.12	20.10	28.0	71.8	0.43
20-78	Bi1	10.76	2.26	8.74	0.13	21.89	31.2	70.2	0.42
78-105	Bi2	10.41	2.21	9.56	0.32	22.50	35.0	64.3	0.91
105-147	Bw	11.99	2.25	9.68	0.14	24.06	38.0	64.6	0.37
147-200^{+}	Bk	10.25	2.21	9.85	0.15	22.46	40.2	56.2	0.40

TEB= Total exchangeable bases; CEC = Cation exchange capacity; ESP = Exchangeable sodium percentage; PBS = Percent base saturation

4.5 Classification of Soils of the Study Area

Soils of the study area were classified according to world reference base for soil resources system of soil classification (IUSS Working Group WRB 2015). The classification was made based on the identified diagnostic horizons, properties and materials. All pedons had well-structured dark surface horizons of more than 20 cm in thickness having color values and had thick (>150 cm) subsurface horizons with greater than 30 per cent clay, and they were wedge shaped soil aggregates and slickensides produced by shrink and swell cracks starting at the surface qualifying for vertic horizon (FAO, 2014). Consequently, the pedons were classified as Vertisols.Cracks and slickensides were the common feature of the soils of the study area. Therefore, all the three pedons could be classified as Vertisols.

In all the three pedons subsurface horizons, effervescence was observed upon 10% HCl test, which qualified calcic principal qualifier. The percent base saturation in all the pedons were greater than 50% throughout between 20 and 100 cm from the mineral soil surface, and greater than 80% in some layer between 20 and 100 cm from the mineral soil surface, which qualified hypereutric. As a result, the three pedons classified as Calcic Vertisols (Hypereutric).

Table 6 Soil classification according to IUSS Working Group WRB (2014)

Pedons	**Diagnostic Horizon**		**Diagnostic properties and materials**		**WRB (IUSS Working Group, 2014)**
	Surface	**Subsurface**	**properties**	**materials**	
P1	-	Vertic	Shrinking –swelling	-	Calcic Vertisols (Hypereutric)
P2	-	Vertic	Shrinking –swelling	-	Calcic Vertisols (Hypereutric)
P3	-	Vertic	Shrinking –swelling	-	Calcic Vertisols (Hypereutric)

4.6 Description and Characterization of Land Mapping Unit

4.6.1 Land Mapping Unit 1Ac

Land mapping unit 1Ac had flat to gently sloping (0-5%) topography. It was characterized by a deep effective soil depth (>150 cm) with poorly drained clay textural class. The mapping unit was moderately acidic with pH of (5.47-7.8) Tekalign (1991). low to very high OC (4.6- 1.4%) contents, OM (7.9 to 2.4) and total N (0.19-0.13%), low available P (0.45-0.38 mg kg-1), exchangeable Ca (11.37- 9.45 cmol (+) kg-1) and Mg (2.12-2.23 cmol (+) kg1) contents. High content of CEC (26.0-33.0 cmol (+) kg-1), and high PBS (96.3-82.9%) Tekalign (1991) were also features of this mapping unit.

4.2.1 Land Mapping Unit 2AC

Land mapping unit 2Ac is characterized by moderately sloping (5-10%) topography. It was characterized by a deep effective soil depth (>150 cm) with moderately drained clay textural class. The LMU was moderately acidic to strongly alkaline with pH-H2O (5.5-8.04) Tekalign (1991). It had high soil OM (7.9 to 2.4%) and total N (0.26 to 0.15%), OC (4.4 to 0.8 %) contents, low contents of available phosphorous (0.9 to 0.42 mg kg-1). The soil of this LMU continents of exchangeable Ca (5.53vto 12.25 cmol (+) kg1), Mg (2.14 to 2.31 cmol (+) kg-1) and CEC (27 to 35 cmol (+) kg-1) and very high PBS (96.3 to 88.8%) Tekalign (1991).

4.2.2 Land Mapping Unit 3Ac

Land mapping unit 3Ac had strongly sloping (10-15%). It was characterized by a deep effective soil depth (>150 cm) with good drained clay textural class. The mapping unit was strongly acidic in pH (5.05 -7.35) Tekalign (1991). Very high to low OC (4.8-0.2%), OM (8.2 to 0.3) and total N (1- 0.15%) content, low available P (0.49-0.39 mg kg-1), exchangeable Ca (7.82-10.25 cmol (+) kg-1) and Mg (2.23-2.21 cmol (+) kg1) contents. High content of CEC (28-40.2 cmol (+) kg-1), and high PBS (88.42%) Tekalign (1991) were also features of this mapping unit.

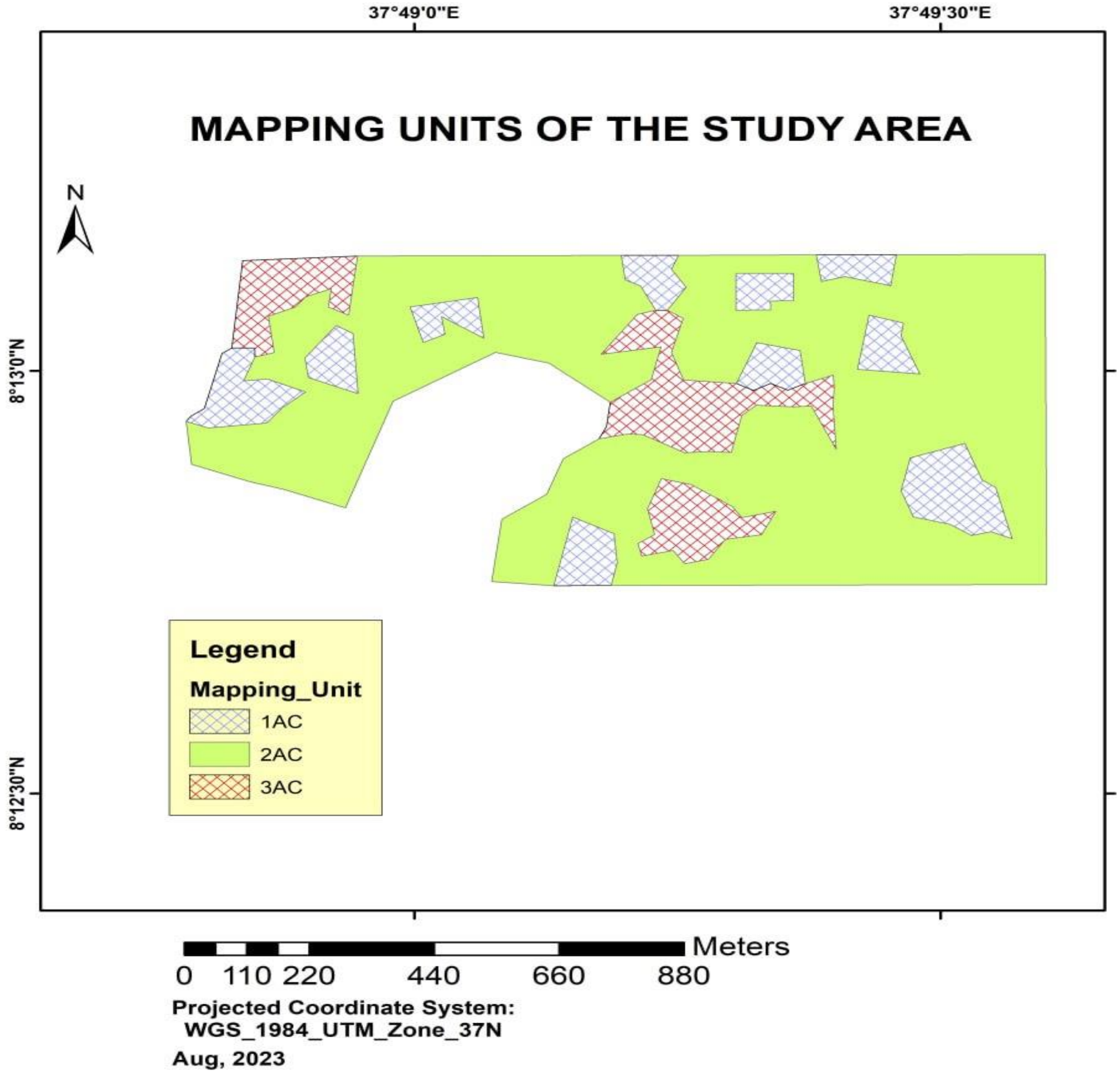

Figure 4 Land Mapping Unit of the study Area

4.2 Agro-Climatic Analyses and Suitability Evaluation

4.2.1 Agro-Climatic Analysis

The study area experienced a normal growing period that corresponds with the FAO working definition, where, humid period is the time when precipitation is exceeding potential evapotranspiration and the start of the growing period was obviously based on the rainy season.

The beginning of the growing period (BGP) and end of rain (ER) of the study area were March 19 and October 29 respectively, based on Eq.1. The beginning and end of humid period of the study area were April 26 and October 2 respectively, based on Eq.2. The end of the growing period, by considering 100 mm stored water in the soil and daily evapotranspiration of the area, was October 29. Therefore, the length of growing period (LGP) of the study area is calculated to be 220 days.

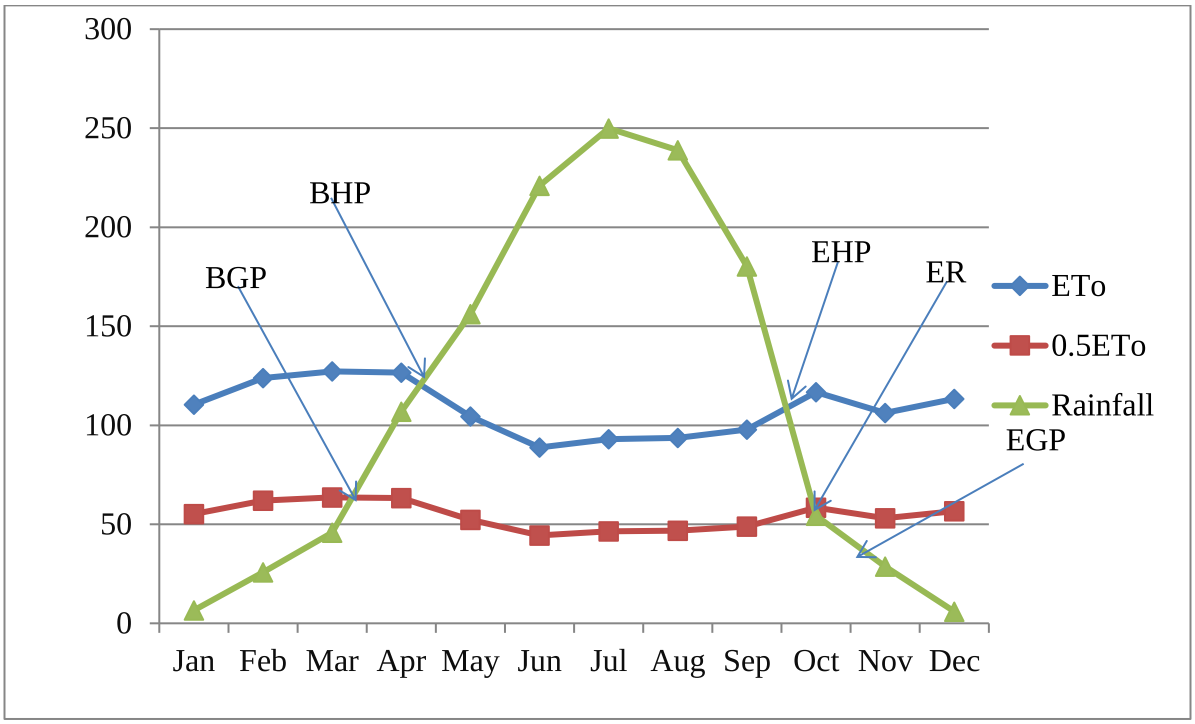

Figure 5 Determination of LGP in the watershed.

BGP = beginning of growing period, BHP = beginning of humid period,

EHP = end of humid period, ER = end of rainy season, and EGP = end of growing period.

4.2.2 Suitability Evaluation

The combination of climatic, soil and landscape parameters were used to evaluate the suitability of Maize and Tef crops at the study area for LMUs of 1Ac, 2Ac and 3Ac (Table 7). Climate characteristics were consistent across all mapping units since the study area is subject to the same climatic conditions. The climatic condition of the study area was highly suitable (S1) for Maize and not suitable (N) for Tef, length of growing period (LGP) being the limiting factor (Table 8).

Table 7 Climatic, soil and landscape characteristics of the study area

Land requirements		Land mapping units		
Land quality	**Diagnostic factor and unit**	**3Ac**	**2Ac**	**1Ac**
Moisture availability(c)	LGP (days)	220	220	220
	RF during growing cycle(mm)	1100	1100	1100
Temperature (c)	Mean temperature of growing cycle ºC	24.69	24.69	24.69
Rooting condition (s)	Texture(class)	C	C	C
	Effective soil depth (cm)	200+	200+	200+
Wetness (w)	Drainage	G	M	poor
	Flooding	N	N	N
Natural fertility (f)	CEC Cmolc/kg soil	28	27	26
	pH (H_2O)	5.05	5.5	5.47
	SOM %	8.2	7.6	7.9
	SOC%	4.8	4.4	4.6
	PBS%	88.42	96.3	96.3
	Slope%	10-15	5-10	0-5
Erosion hazard (t)	Coarse fragments%	N	N	N
Land preparation (ip)	Rock outcrops	N	N	N

Key: SC= sandy clay; WD=well drained; MW= moderately well drained; C=clay; N= none; LGP=length of growing period; RF=rainfall; CEC=cation exchange capacity; pH=soil reaction; EC=electrical conductivity; SOM=soil organic matter; SOC=soil organic carbon; PBS= percent base saturation, M = moderate, G = good

Regarding soil and landscape suitability, mapping unit 1Ac was marginally suitable (S3) for maize, pH, CEC and drainage of the soils being the limiting factors. It was also marginally suitable (S3) for tef, drainage and CEC was the limiting factor (Table 8).

Table 8. Climatic, soil and landscape suitability evaluation for Maize and Tef at Wolkite University farm area (mapping unit 1Ac)

Land requirements			Land utilization type	
Land quality	**Diagnostic factor and unit**	**Factor value**	**Maize**	**Tef**
Moisture availability(c)	LGP (days)	220	S1	N
	RF during growing cycle(mm)	1100	S1	S3
Temperature (c)	Mean temperature of growing cycle °C	24.69	S1	S3
	Overall climatic suitability		S1	N
Rooting condition (s)	Texture(class)	C	S1	S1
	Effective soil depth (cm)	200+	S1	S1
Wetness (w)	Drainage	Poor	S3	S3
	Flooding	N	S1	S1
Natural fertility (f)	CEC Cmolc/kg soil	26	S3	S3
	pH (H_2O)	5.47	S3	S2
	SOM %	7.9	S1	S1
	SOC%	4.6	S1	S1
	PBS%	96.3	S1	S1
Erosion hazard (t)	Slope%	0-5	S1	S1
Land preparation (ip)	Coarse fragments %	N	S1	S1
	Rock outcrops %	N	S1	S1
	Overall soil and landscape suitability		S3	S3

Key: SL=sandy loam; WD=well drained; N= none; LGP=length of growing period; RF=rainfall; CEC=cation exchange capacity; pH=soil reaction; EC=electrical conductivity; SOM=soil organic matter; SOC=soil organic carbon; PBS= percent base saturation; S1= highly suitable; S2=moderately suitable; S3=marginally suitable; N1=currently not suitable, M = moderate.

Mapping unit 2Ac was moderately suitable (S2) for maize pH and CEC were the limiting factors. It was also marginally suitable (S3) for tef, CEC was the limiting factor (Table 9). Similarly mapping unit 3Ac was marginally suitable (S3) for tef, slope, pH and CEC were the limiting factors. It was not suitable (N) for maize, the pH, CEC and slope of the soils being the limiting factor (Table 10).

Table 9 Climatic, soil and landscape suitability evaluation for maize and tef at wolkite university farm area (mapping unit 2Ac)

Land requirements			Land utilization type	
Land quality	**Diagnostic factor and unit**	**Factor value**	**Maize**	**Tef**
Moisture availability(c)	LGP (days)	220	S1	N
	RF during growing cycle(mm)	1100	S1	S3
Temperature (c)	Mean temperature of growing cycle ºC	24.69	S1	S3
	Overall climatic suitability		S1	N
Rooting condition (s)	Texture(class)	C	S1	S1
	Effective soil depth (cm)	200+	S1	S1
Wetness (w)	Drainage	M	S1	S1
	Flooding	N	S1	S1
Natural fertility (f)	CEC Cmolc/kg soil	27	S2	S3
	pH (H_2O)	5.5	S2	S1
	SOM %	7.6	S1	S1
	SOC%	4.4	S1	S1
	PBS%	96.3	S1	S1
Erosion hazard (t)	Slope%	5-10	S1	S1
Land preparation (ip)	Coarse fragments %	N	S1	S1
	Rock outcrops %	N	S1	S1
	Overall soil and landscape suitability		S2	S3

Key: SL=sandy loam; WD=well drained; N= none; LGP=length of growing period; RF=rainfall; CEC=cation exchange capacity; pH=soil reaction; EC=electrical conductivity; SOM=soil organic matter; SOC=soil organic carbon; PBS= percent base saturation; S1= highly suitable; S2=moderately suitable; S3=marginally suitable; N1=currently not suitable, M = moderate

Table 10 Climatic, soil and landscape suitability evaluation for Maize and Tef at Wolkite University farm area (mapping unit 3Ac)

Land requirements			Land utilization type	
Land quality	**Diagnostic factor and unit**	**Factor value**	**Maize**	**Tef**
Moisture availability(c)	LGP (days)	220	S1	N
	RF during growing cycle(mm)	1100	S1	S3
Temperature (c)	Mean temperature of growing cycle ºC	24.69	S1	S3
	Overall climatic suitability		S1	N
Rooting condition (s)	Texture(class)	C	S1	S1
	Effective soil depth (cm)	200+	S1	S1
Wetness (w)	Drainage	G	S1	S1
	Flooding	N	S1	S1
Natural fertility (f)	CEC Cmolc/kg soil	28	S3	S3
	pH (H_2O)	5.05	N	S3
	SOM %	8.2	S1	S1
	SOC%	4.8	S1	S1
	PBS%	88.42	S1	S1
Erosion hazard (t)	Slope%	10-15	S2	S2
Land preparation (ip)	Coarse fragments %	N	S1	S1
	Rock outcrops %	N	S1	S1
	Overall soil and landscape suitability		N	S3

Key: SL=sandy loam; WD=well drained; N= none; LGP=length of growing period; RF=rainfall; CEC=cation exchange capacity; pH=soil reaction; EC=electrical conductivity; SOM=soil organic matter; SOC=soil organic carbon; PBS= percent base saturation; S1= highly suitable; S2=moderately suitable; S3=marginally suitable; N1=currently not suitable, M = moderate

In the overall climatic, soil and landscape suitability, mapping unit 1Ac was marginally suitable (S3) for maize, drainage, CEC and pH are the limiting factors and it was N (not suitable for tef LGP, Temperature, rainfall, drainage, CEC and pH were the limiting factors. 2Ac was moderately suitable

(S2) for maize, CEC and pH were the limiting factors and N (not suitable for tef LGP, RF, Temperature and CEC were the limiting factors. 3Ac was not suitable (N) for Maize production; CEC, pH and slope were the limiting factors and it was marginally suitable (S3) for tef LGP, RF, Temperature, CEC, pH and slope were the limiting factors. The mapping units could potentially be highly suitable (S1) for Maize production if the soil will be treated with lime to raise the pH and if drainage works will be implemented. mapping units (1Ac and 2Ac) were not suitable for Tef production; length of growing period being the limiting factor and 3Ac was not suitable for maize production pH was the limiting factor.

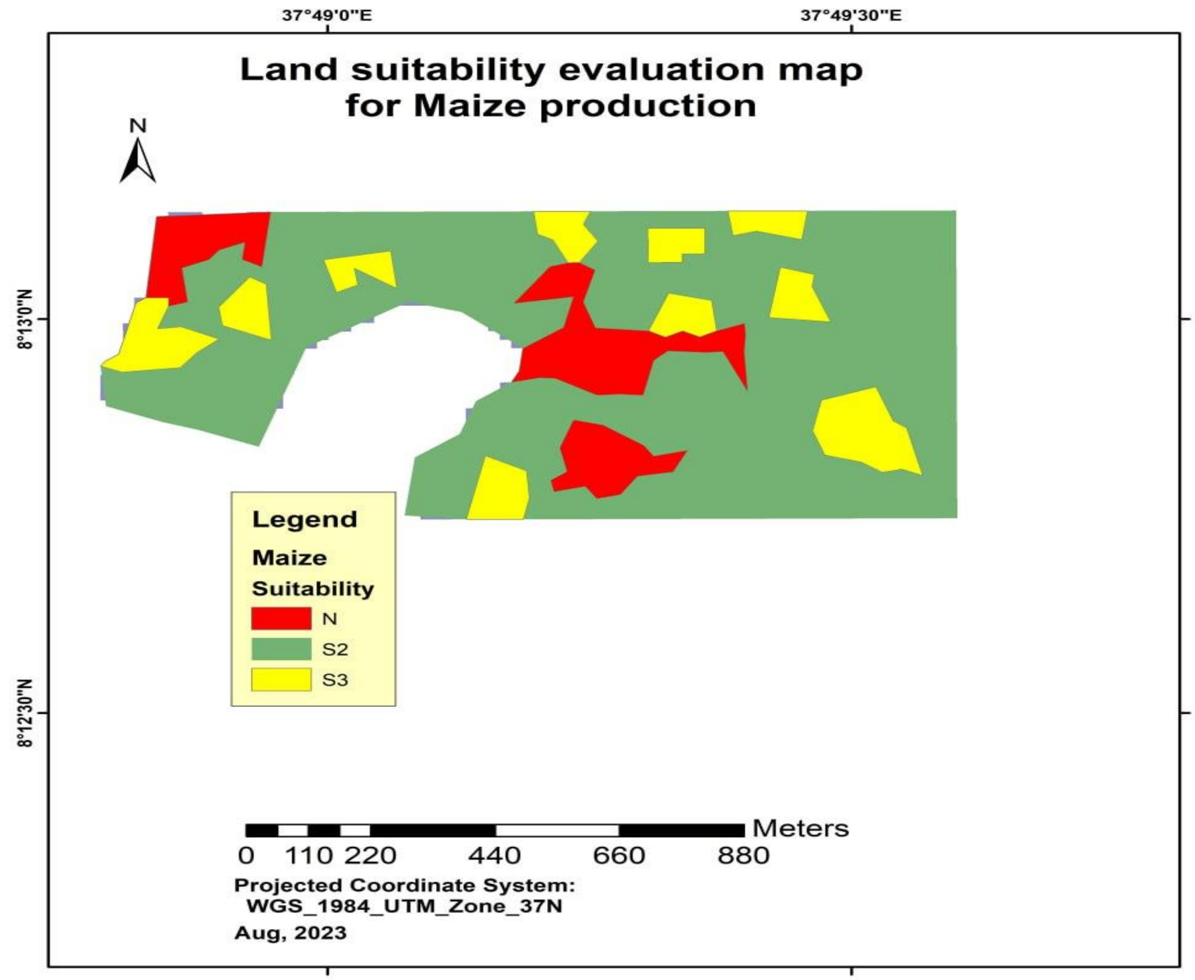

Figure 6 Overall current suitability map of study area for maize production

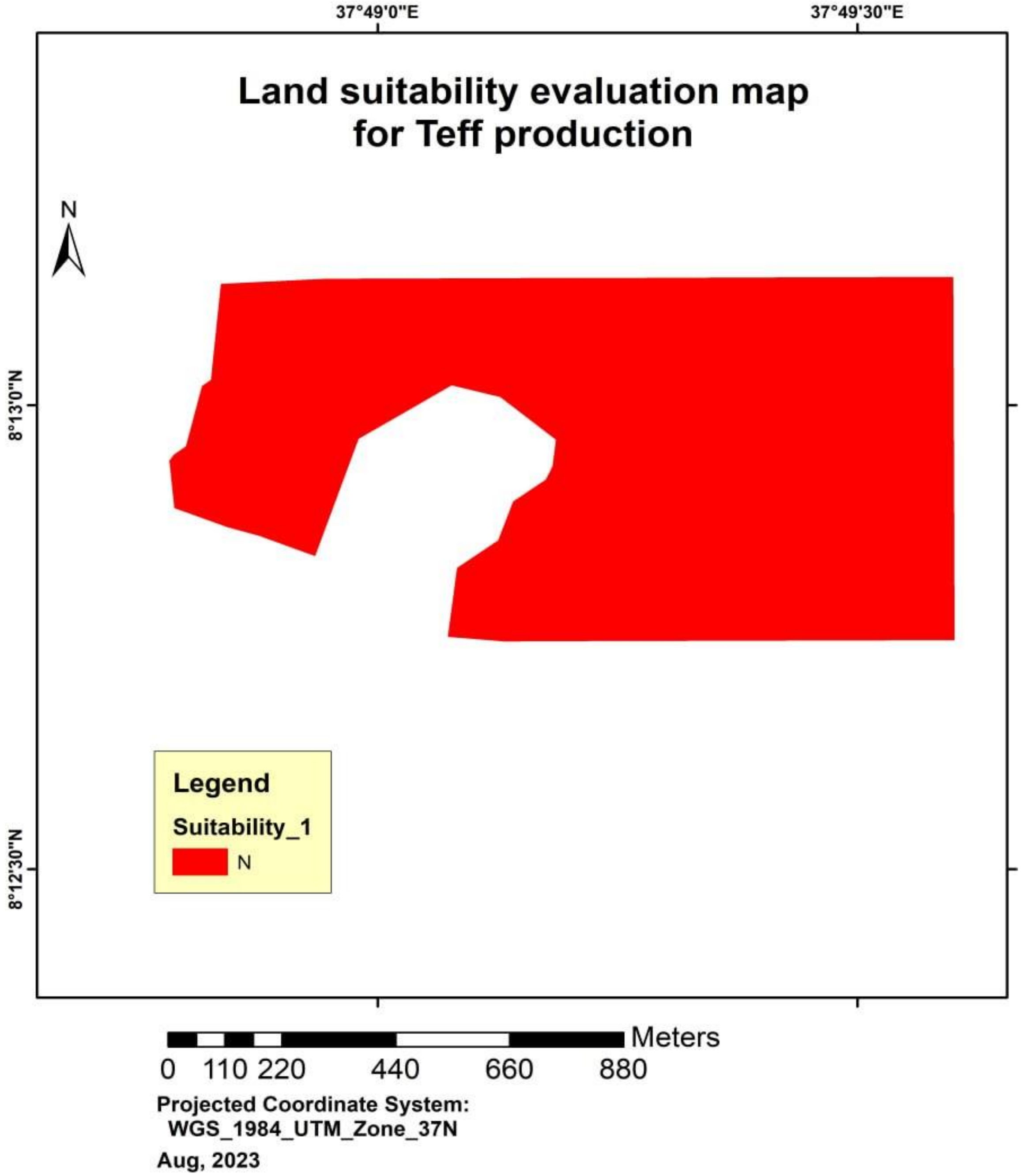

Figure 7 Overall current suitability map of study area for tef production

Table 11 Pearson's correlation coefficient (r) among selected soil physicochemical properties

	sand	silt	clay	BD	TP	MC	pH	OC	OM	TN	AP	Ca	Mg	K	Na	CEC	PBS	ESP
sand	1																	
silt	0.43	1																
clay	0.09	0.14	1															
BD	0.16	0.18	0.85***	1														
TP	-0.21	-0.22	-0.86***	-0.99***	1													
MC	0.46	0.17	0.68**	0.71**	-0.73**	1												
pH	-0.15	0.05	0.84***	0.55**	-0.56**	0.55**	1											
OC	0.06	-0.19	-0.93***	-0.72**	0.72**	-0.57**	-0.92***	1										
OM	0.05	-0.19	-0.93***	-0.73**	0.73**	-0.57**	-0.92***	0.99***	1									
TN	-0.18	-0.53	-0.35	-0.43	0.44	-0.59**	-0.28	0.35	0.34	1								
AP	-0.09	-0.07	-0.61**	-0.79***	0.80***	-0.55**	-0.43	0.49*	0.51*	0.05	1							
Ca	-0.01	0.35	0.44	0.47*	-0.49*	0.51*	0.64**	-0.61**	-0.63**	-0.32	-0.62**	1						
Mg	0.23	0.27	0.43	0.17	-0.17	0.41	0.50*	-0.42	-0.43	0.008	-0.25	0.34	1					
K	-0.039	0.19	0.79***	0.60**	-0.60**	0.29	0.75***	-0.86***	-0.87***	-0.03	-0.41	0.45	0.39	1				
Na	0.58**	0.26	0.14	0.08	-0.09	0.67**	0.21	-0.14	-0.12	-0.63**	0.17	0.18	0.28	-0.08	1			
CEC	0.29	0.44	0.89***	0.72**	-0.74**	0.70**	0.81**	-0.93***	-0.92***	-0.52	-0.41	0.55*	0.51	0.78**	0.42	1		
PBS	-0.12	-0.24	-0.91***	-0.67**	0.67**	-0.47*	-0.73**	0.87***	0.86***	0.36	0.29	-0.23	-0.37	-0.79*	-0.14	-0.88***	1	
ESP	0.17	0.35	0.93***	0.91***	-0.91***	0.63**	0.70**	-0.85**	-0.85**	-0.48*	-0.61*	0.45	0.31	0.78**	0.14	0.89***	-0.86***	1

* Significant at $p \leq 0.1$ level, ** highly Significant at $p \leq 0.05$ level, *** very highly Significant at $p \leq 0.01$ level

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. CONCLUSIONS

Soil is a vital natural resource on which the supporting life system and socio-economic development depend. To boost agricultural production and utilize the soil resource in sustainable basis, the knowledge of this resource is indispensable. Information of soil and related properties obtained from the soil survey and soil classification can help in better delineation of soil and land suitability for rain-fed production. Therefore, characterization and classification of soils and physical land suitability evaluation for rain fed agriculture was conducted in Wolkite University farm. The soils were examined and differentiated based on observable site and soil characteristics including slope, soil depth and texture following free survey method. Three soil profiles (from upper slope, middle slope and lower slope positions) were opened and described across the study area. From the identified horizons, thirteen disturbed and undisturbed soil samples were taken and analyzed for soil physical and chemical properties.

Consequently, the three pedons classified as Calcic Vertisols (Hypereutric) was identified in the upper, middle and lower slope positions, respectively. On the other hand, the formation of smectite clays was conditioned by the material and seasonally waterlogged and resulted in the formation of Vertisols. The results revealed different degrees of limitations, potentials and management requirements this consideration is fundamental for sustainable use of soil resources. The major limitations for augmenting agricultural production at the study area on sustainable basis are low level of available phosphorus and pH of the soil was found strongly acidic to moderately acidic (5.05- 5.5). Thus, integrated nutrient management should be employed to manage the cation balances and build up soil available phosphorus, as it influences the soil’s physical, chemical and biological quality.

In general, the observed relationship between features of landscape, soil characteristics and soil types will help to advance soil-landscape relations in the study area and showed less costly way of acquiring soil formation. The result of the land suitability evaluation (in this study) reflects the need to overcome land suitability threats (limitations) through application of appropriate land management options; that is, management practices that can increase the level of available phosphorus, pH and soil fertility through continuous and integrated application of manure, compost and chemical fertilizers by the university. Conversely, it is advisable to search for crop varieties that best fit the length of growing period in the study area.

5.2 RECOMMENDATIONS

To exploit the resource of the study area and produce crops in sustainable manner, different site-specific management and interventions must be implemented. Based on the findings of this study, the following recommendations are forwarded by the researcher:

- ✓ The soils under the study area were acidic and very low in available phosphors. The soil should be treated with lime to raise the pH to the suitable range and integrated soil fertility management should be implemented for optimum and sustainable agricultural production.

- ✓ All mapping units (1Ac, 2Ac and 3Ac) were potentially highly suitable (S1) for Maize production but were not suitable for Tef production; length of growing period being the limiting factor. Therefore, it is advisable to search other land utilization types which suit the climatic, soil and landscape situation of the study area.

- ✓ The land suitability evaluation has shown that all the soils under the study area are not rated as highly suitable for production of principal crops due to different limitations. Therefore, there is a need to make further study to identify other alternative land use systems.

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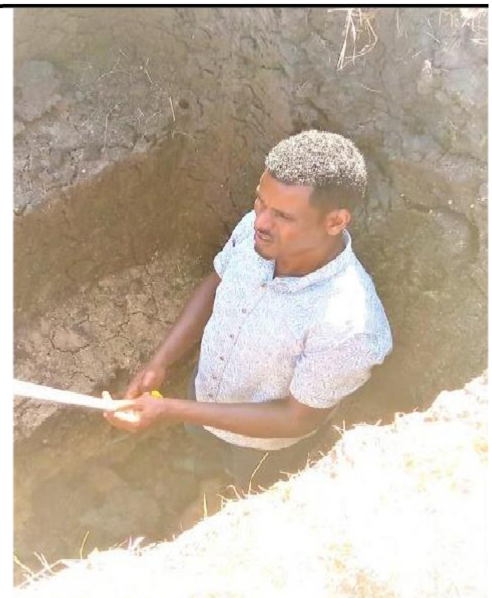
7. APPENDICES

Appendix table 1 Description of soil site and pedon 1 Lower slope

Pedon No:	1
Date of description:	13/05/2015 E.C
Author:	Shibikom Desalegn Erba
Location	WKU farm lower slope near to 2nd get
Coordinates:	$8^0 12^{'} 58^{''}$ to $37^0 49^{'} 21^{''}$
Elevation:	1939 masl
Surrounding landform:	Flat to gently sloping
Physiographic position:	lower slope
Land use/cover:	cultivated land (tef)
Slope gradient & aspect:	(0-5%) East to West
Moisture condition:	Dry
Drainage class:	Poorly drained
Parent material:	not observed
Groundwater depth:	None
Rock outcrops:	None
Erosion:	sheet Erosion
Surface stoniness:	None
Soil type: WRB:	Calcic Vertisols (Hypereutric)



Horizon	Depth	Profile description
AP	0-20	10YR4/1 (dark gray) dry; 10YR2/1 (black) moist; Moderate, Granular, Fine and medium, soil structure; Clay texture; Small and common root size and Abundance; Slickensides (mineral horizon); Cracking diagnostic Horizons. Gradual and Smooth for Horizon boundary; Clay texture; Hard dry, Firm moist, Sticky/ plastic wet soil Consistence and Visible effervescence in

		subsurface horizons, effervescence was no reaction with 10% HCl.
Bi1	20-99	10YR 4/1 (dark gray) dry and 10YR 2/1 (very dark gray) moist; Clear and Smooth for Horizon boundary; Clay texture; Angular blocky, very coarse soil structure; Fine, very few, root size and Abundance; Slickensides (mineral horizon); Cracking diagnostic Horizons, Properties. Hard dry, Firm moist, Sticky/ plastic wet soil Consistence and slightly reaction with 10% HCl
Bi2	99-165	(10YR 4/1) Dark gray dry; 10YR 2/1 (very dark gray) moist; Clear and Smooth for Horizon boundary; Angular blocky, very coarse soil structure; Clay texture; Slickensides (mineral horizon); Cracking diagnostic Horizons, Properties; very Hard dry, Firm moist, Sticky/ plastic wet soil Consistence; and Visible effervescence in subsurface horizons, and moderately reaction with 10% HCl
Bw	165-200	(10YR 5/3) Brawn dry; 10YR 4/2 (dark gray brawn); Angular blocky Very coarse soil structure; Clay texture; Very hard dry; Very firm moist; very Sticky/ plastic wet, Slickensides (mineral horizon); Cracking diagnostic Horizons, Properties and Visible effervescence in subsurface horizons and strongly reaction with 10% HCl test indicated strong visible effervescence.

Appendix table 2 Description of soil site and pedon 2 middle slopes

Pedon No:	2
Date of description:	13/05/2015 E.C
Author:	Shibikom Desalegn Erba
Location	WKU farm middle slope
Coordinates:	$8^0 13^{’} 04^{’’}$ to $37^0 49^{’} 03^{’’}$
Elevation:	1949 masl
Surrounding landform:	Gently sloping to sloping
Physiographic position:	middle upper slope

Land use/cover:	cultivated land (tef)
Slope gradient & aspect**:**	(5-10%) north to south
Moisture condition:	Dry
Drainage class:	Poorly drained
Parent material:	not observed
Groundwater depth:	None
Rock outcrops:	None
Erosion:	sheet Erosion
Surface stoniness:	None
Soil type: WRB:	Calcic Vertisols (Hypereutric)

Horizon	Depth (cm)	Profile description
AP	0-27	10YR5/1 Gray dry; 10YR4/1 (dark gray) in moist: Clear and Smooth for Horizon boundary; Clay texture; Fine, very few; Small and common root size and Abundance. Moderate; Granular; Hard, Firm, Sticky/plastic in dry, moist and wet soil consistence and no reaction with 10% HCl.
Bi1	27-68	10YR 4/1 Dark gray dry; 10YR 3/1 very dark gray in moist: Clear and Smooth for Horizon boundary; Clay texture; Small and common root size and Abundance; Fine, very few, very hard, Angular blocky, very coarse soil structure; Very hard, very firm, very Sticky/ plastic in dry, moist and wet soil consistence and no reaction with 10% HCl.
Bi2	68-157	10YR 4/1(dark gray) dry; 10YR 3/1 (very dark gray) moist; Clear and Smooth for Horizon boundary; Clay texture. Very hard, Angular blocky, very coarse soil structure; Very hard, very firm, very Sticky/ plastic in dry, moist and wet soil consistence no reaction with 10% HCl.
Bk	157-200^{+}	10YR 4/2 (dark gray brawn) dry; 10YR 3/2 (very dark gray brawn) moist soil color; Clear and Smooth for Horizon boundary;

	Clay texture, Slickensides (mineral horizon), Cracking, Vitric. Very hard Very firm very Sticky; Very hard, Angular blocky, very coarse plastic dry, moist and wet soil consistence and slightly reaction with 10%HCl audible effervescence but not visible.

Appendix table 3 Description of soil site and pedon 3 upper lopes

Pedon No:	3
Date of description:	13/05/2015 E.C
Author:	Shibikom Desalegn Erba
Location	WKU farm upper slope
Coordinates:	$8^{0}12'51''$ to $37^{0}49'13''$
Elevation:	1950 masl
Surrounding landform:	Sloping to strongly sloping
Physiographic position:	upper slope
Land use/cover:	cultivated land (tef)
Slope gradient & aspect**:**	(10-15%) east to west
Moisture condition:	Dry
Drainage class:	Poorly drained
Parent material:	not observed
Groundwater depth:	None
Rock outcrops:	None
Erosion:	sheet Erosion
Surface stoniness:	None
Soil type: WRB:	Calcic Vertisols (Hypereutric)

Horizon	Depth (cm)	Profile description
AP	0-20	(10YR4/2) dark grayish brawn Dry; 10YR3/2 (very dark grayish brawn color in moist; Clear and Smooth for Horizon boundary; Clay texture; Moderate, Granular, Fine and medium soil structure; Hard,

		Firm, Sticky/plastic in dry, moist and wet soil consistence; Small and common root size and Abundance and no reaction with 10% HCl.
Bi1	20-78	10YR 2/1 black in moist: Clear and Smooth for Horizon boundary; Clay texture Angular blocky Very coarse soil structure; Very hard Very firm very Sticky/ plastic in dry, moist and wet soil consistence; Fine, very few; Small and common root size and Abundance and no reaction with 10% HCl.
Bi2	78-105	10YR 2/2 (very dark brawn) color in moist; Clear and Smooth for Horizon boundary; Clay texture; Angular blocky Very coarse soil structure; Very hard, very firm, very Sticky/ plastic in dry, moist and wet soil consistence and no reaction with 10% HCl.
Bw	105-147	10YR 3/2 Very dark grayish brawn color in moist; Clear and Smooth for Horizon boundary; Clay texture; Angular blocky Very coarse soil structure; Very hard, very firm, very Sticky/ plastic in dry, moist and wet soil consistence; and slightly reaction with 10%HCl.
Bk	147-200$^+$	10 YR 5/2 Brawn grayish color in moist; Clear and Smooth for Horizon boundary; Clay texture; Angular blocky Very coarse soil structure; Very hard, very firm, very Sticky/ plastic in dry, moist and wet soil consistence and moderately reaction with 10% HCl indicate Visible effervescence but not strong

Appendix table 4 Agro-climatic ratings for rain-fed maize and teff

Diagnostic factor	Factor ratings	Land utilization types	
		Maize	**Tef**
Thermal regime (^{0}C)	s1	19.5-32	15-21
	s2	16-19.5, 32-35	14-15, 21-22
	s3	14-16, 35-40	11-14, 22-25
	n	<14, >40	<11, >25
Length of growing period (days)	s1	140-220	100-150
	s2	120-140; 220-270	90-100
	s3	90-120; 270-300	75-90, 150-180
	n	<90; >300	<75, >180
Total growing period rainfall (mm)	s1	900-1200	400-550
	s2	1200-1500; 750-900	300-400, 550-800
	s3	1500-1600; 300-750	200-300, 800-1200
	n	<300, >1600	<200 >1200

Source: FAO/UNDP (1984b) Sys *et al*. (1993). Source: (FAO, 1983/1984; Sys et al., 1993; Lupia, 2012; Djaenudin *et al.*, 2003)

Appendix table 5 Soil and landscape attributes ratings for rain-fed maize

Land Use Requirements		Class, degree of limitation and rating scale			
Land Quality	**Diagnostic factor and unit**	**100-95%**	**95-85%**	**85-60%**	**<40%**
		s1	**s2**	**s3**	**n**
Rooting condition (r)	Texture (class)	SiC,SiCL,Si,SiL,CL,SC,L,C	SL,LS	SCL	-
	Effective soil depth (cm)	>80, 80-50	40-80	20-40	-
Wetness (w)	Drainage (class)	Good, moderat	imperfect	poor	Poor
	CEC (Cmolc/kg soil)	>31	31-27	27-16	<16
	pH (H_2O)	7.0-6.0	6.0-5.5	5.5-5.2	<5.2 >8.5
Natural soil			7.0-7.8	8.2-8.5	

fertility (n)	EC (dS/m)	<2.5	2.5-3.8	3.8-5.9	5.9-12
	SOM % (0-50 cm)	>3	3.0-2.5	2.5-1.0	<1
	SOC %	>2	1-2	0.5-1	<0.5
	PBS %	>80	40-80	20-40	<20
Erosion hazard (e)	Slope %	0-8	8-16	16-30	30-50
Land preparation (ip)	Rock outcrop %	<5	5-15	15-25	>25
	Coarse fragment % (0-50 cm)	<3	5-35	35-55	-

Source: (FAO, 1983/1984; Sys *et al.*, 1993; Lupia, 2012; Djaenudin *et al.*, 2003)

s1=highly suitable; s2 =moderately suitable; s3= marginally suitable; n = not suitable; CEC=cation exchange capacity; EC=electrical conductivity; PBS=percent base saturation; SOM=soil organic matter; SOC=soil organic carbon; pH=soil reaction; SL= sandy loam; L=loam; C= clay; CL= clay loam; Si=silt; SiC= silty clay; SiL= silty loam; SiCL= silty clay loam SC =sandy clay; SCL= sandy clay loam; Cm= massive clay; cS=heavy sand; SiCm= silty massive clay; FO=no risk; F1= slight; F2=common; VP= very poorly drained

Appendix table 6 Soil and landscape attributes ratings for rain-fed Tef

Land Use Requirements		**Class, degree of limitation and rating scale**			
Land Quality	Diagnostic factor and unit	100-95% s1	95-85% s2	85-60% s3	<40% n
Rooting condition (r)	Texture (class)	Si, SiC, C	SiCL	SiL, CL, L, SC	SCL, SL
	Effective soil depth (cm)	>50	30-50	20-30	10-20
Wetness (w)	Drainage (class)	Good	imperfect	poor	Poor
Natural fertility (n)	CEC (Cmolc/kg soil	>30	30-28	28-16	<16
	pH (H_2O)	5.5-7.5	5.2-5.5, 7.5-7.8	5.0-5.2,7.8-8.5	4.5-5
	EC (dS/m)	<2.5	2.5-3.8	3.8-5.9	5.9-10
	SOM%	>3.0	2.5-3.0	2.0-2.5	1.0-2.0
	SOC%	>1.74	1.45-1.74	1.16-1.45	0.58-1.16

	PBS%	>50, 50-35	35-15	<15	-
Erosion hazard (e)	Slope%	<13	13-25	25-50	50-55
Land preparation (ip)	Coarse fragment %	<3	3-10	10-15	-
	Rock outcrops %	<5	5-15	15-25	>25

Source: (FAO, 1983/1984; Sys *et al.*, 1993; Lupia, 2012; Djaenudin *et al*., 2003)

s1=highly suitable; s2 =moderately suitable; s3= marginally suitable; n = not suitable; CEC=cation exchange capacity; EC=electrical conductivity; PBS=percent base saturation; SOM=soil organic matter; SOC=soil organic carbon; pH=soil reaction; SL= sandy loam; L=loam; C= clay; CL= clay loam; Si=silt; SiC= silty clay; SiL= silty loam; SiCL= silty clay loam SC =sandy clay; SCL= sandy clay loam; FO=no risk; F1= slight; F2=common; VP= very poorly drained

Appendix table 7 Ratings of Bulk density and particle size for given soil

Rating g/cm3	Bulk density	Percent of sand silt or clay
Very low	<1	<10
Low	1.0-1.3	10-25
Moderate	1.3-1.6	25-40
High	1.6-1.9	40-50
Very high	>1.9	>50

Source: Hazelton and Murphy (2007)

Appendix table 8 Ratings of soil reaction based on pH (H2O)

Soil reaction class	pH (1: 2.5 H2O)
Very strongly acidic	<4.5
Strongly acidic	4.5-5.2
Moderately acidic	5.3-5.9
Slightly acidic	6-6.6
Neutral	6.7-7.3
Moderately alkaline	7.4-8.0
Strongly alkaline	>8

Sources: Tekalign (1991)

Appendix table 9 Ratings of soil organic matter or organic carbon and total nitrogen

Rating	Murphy (1968)	Tekalign (1991)	Murphy (2007)
	OM (%)	OC (%)	TN (%)[a]
Very low	<1.0	< 0.50	Not given
Low	1-2	0.5 - 1.5	<0.10
Medium	2.3	1.5 - 3.0	0.10 - 0.15
High	3-5	>3	0.15 - 0.25
Very high	>5	Not Given	>0.25

Sources: Murphy (1968); Tekalign (1991)

Appendix table 10 Ratings of cation exchange capacity and exchangeable cations for the topsoil Values

Rating or Class	A Landon	FAO	FAO	FAO	FAO
	CEC	Exch ca	Exch. Mg	Exch. K	Exch. Na
Very low	< 5	>2	< 0.3	>0.2	< 0.10
Low	5 – 15	2-5	0.3 - 1.0	0.2-0.3	0.1 - 0.3
Medium	15 – 25	5-10	1.0 - 3.0	0.3-0.6	0.3 - 0.7
High	25-40	10 – 20	3-8	0.6 - 1.2	0.7-2
Very high	>40	>20	> 8.0	> 1.2	>2

Sources: Landon (1991); FAO (2006b)

Appendix table 11 Ratings of base saturation and as a criterion of leaching

Ratings of base saturation as a criterion of leaching Range (PBS) (%)	Rating	Range (PBS) (%)	Rating
0–20	Very low	70-100	Very weakly leached
20-40	Low	50-70	Weakly leached
40-60	Medium	30-50	Moderately leached
60-80	High	15-30	Strongly leached
>80	Very high	0-15	Very strongly leached

Source: Hazelton, P. and B. Murphy (2007)

Appendix table 12 monthly and yearly total rainfall (mm) at the study area (2012-2021)

	Months											
Year	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
2012	0.0	0.0	77.5	57.2	238.3	312.9	257.6	221.1	115.4	8.9	41.3	0.0
2013	0.0	0.0	6.9	45.7	47.9	224.8	257.5	219.1	168.0	17.3	8.2	2.2
2014	3.8	7.0	28.9	75.3	140.1	201.1	241.5	255.5	218.0	72.3	14.6	0.0
2015	3.6	72.0	45.1	93.9	206.2	122.7	210.8	216.7	197.5	119.1	11.0	0.0
2016	0.0	0.0	25.6	10.9	178.2	277.1	209.9	214.2	158.4	22.3	16.8	28.8
2017	32.0	12.3	25.7	177.8	172.3	106.3	230.4	241.3	160.0	96.1	10.1	0.0
2018	0.0	57.9	25.8	69.6	245.1	213.5	229.3	256.7	159.7	48.2	12.7	0.0
2019	3.7	60.7	49.5	110.2	94.8	339.8	254.7	232.6	225.2	42.3	66.1	1.2
2020	0.0	31.3	54.0	228.4	104.0	219.9	235.4	270.3	237.0	51.7	81.0	2.3
2021	23.1	16.1	119.4	200.2	134.2	191.0	372.4	260.9	163.2	64.9	24.9	25.2
Total	**66.2**	**257.3**	**458.4**	**1069.2**	**1561.1**	**2209.1**	**2499.5**	**2388.4**	**1802.4**	**543.1**	**286.7**	**59.7**

Source: Southern Nation, Nationality and Peoples' Regional State Meteorological Services Agency (2021)

Appendix table 13 Mean monthly and annual maximum temperature (C0) at the study area (2012-2021)

	Months											
Year	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
2012	24.3	24.9	24.7	27.5	27.1	24.3	23.1	21.7	21.7	25.1	25.3	25.5
2013	25.6	28.0	28.0	27.0	27.5	23.0	21.0	21.4	22.2	25.2	25.2	25.3
2014	26.2	27.5	27.2	27.0	24.9	23.7	21.9	21.9	22.4	23.7	24.6	25.0
2015	26.5	26.1	26.6	26.5	24.8	25.0	22.7	21.3	22.0	24.0	24.6	24.9
2016	25.9	27.5	28.3	28.1	25.3	23.0	22.8	22.4	23.0	25.5	25.5	25.0
2017	26.0	26.5	26.4	25.5	27.3	23.3	22.2	22.0	22.9	25.4	25.4	25.3
2018	25.3	27.2	26.7	27.3	25.3	22.7	21.5	21.4	24.1	24.7	24.7	24.8
2019	25.7	26.6	27.3	25.1	25.8	22.4	21.4	21.7	23.5	25.1	24.4	25.1
2020	27.0	27.5	27.6	25.3	25.7	22.7	21.1	21.3	22.2	24.5	24.7	24.9
2021	26.0	27.0	26.2	26.0	24.7	23.0	21.0	21.3	22.3	24.4	25.3	25.5
Total	**258.5**	**268.9**	**269.0**	**265.3**	**258.4**	**233.2**	**218.8**	**216.3**	**226.3**	**247.5**	**249.7**	**251.2**

Source: Southern Nation, Nationality and Peoples' Regional State Meteorological Services Agency (2021).

Appendix table 14 Mean monthly and annual minimum temperature (C0) at the study area (2012-2021)

Year	Months											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2012	8.6	7.8	8.0	12.7	11.7	13.1	12.0	11.9	11.6	9.7	8.6	6.3
2013	8.4	6.8	9.6	12.9	11.8	12.3	12.5	12.5	11.9	9.0	8.8	6.9
2014	7.9	9.1	11.9	12.1	12.0	12.5	12.3	12.5	11.5	9.7	8.4	6.6
2015	7.1	10.3	10.2	10.8	11.5	11.3	12.1	11.7	11.9	10.7	9.0	7.7
2016	6.7	9.1	9.7	10.7	12.1	13.0	12.8	12.5	11.9	9.9	9.0	9.3
2017	6.5	9.7	10.2	10.6	11.9	12.3	12.5	12.7	12.0	9.1	9.2	7.7
2018	7.1	9.3	11.1	11.8	12.0	12.7	12.1	12.1	11.5	9.8	9.7	8.7
2019	7.8	9.8	10.9	12.6	12.4	22.4	12.3	12.3	11.3	9.4	8.9	7.0
2020	5.5	9.2	10.8	12.8	11.0	13.5	12.6	12.5	12.5	9.8	10.0	8.8
2021	8.5	10.4	12.6	12.3	12.7	12.9	13.1	13.2	12.0	9.0	7.7	6.2
Total	**74.03**	**91.5**	**105.0**	**119.3**	**118.9**	**136.0**	**124.3**	**123.9**	**118.1**	**96.0**	**89.3**	**75.3**

Source: Southern Nation, Nationality and Peoples' Regional State Meteorological Services Agency (2021)