CLIMATE CHANGE IMPACT ON LAND SUITABILITY FOR RAINFED CROP PRODUCTION IN LAKE HARAMAYA WATERSHED, EASTERN ETHIOPIA

MSc. THESIS

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MAY 2015

HARAMAYA UNIVERSITY, HARAMAYA

Climate Change Impact on Land Suitability for Rainfed Crop Production in Lake Haramaya Watershed, Eastern Ethiopia

A Thesis Submitted to the School of Natural Resources Management and Environmental Sciences, School of Graduate Studies

HARAMAYA UNIVERSITY

In Partial Fulfillment of the Requirements for the Degree of

MASTER OF SCIENCE IN AGROMETEOROLOGY AND NATURAL RISK MANAGEMENT

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May 2015

Haramaya University, Haramaya

HARAMAYA UNIVERSITY

SCHOOL OF GRADUATE STUDIES

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DEDICATION

This thesis work is dedicated to my daughter, Anita Liam Wanjiku.

STATEMENT OF THE AUTHOR

By my signature below, I declare and affirm 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 this Thesis. Any scholarly matter that is included in the Thesis has been given recognition through citation.

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ACKNOWLEDGMENT

I am very fortunate to have performed my graduate work at Haramaya University, Ethiopia. Foremost, greatest gratitude goes to the School of Natural Resource Management and Environmental Sciences for accepting me to undertake my graduate work; therefore, there are many people to thank for their part in my success. I would first like to thank my advisor, Dr. Kibebew Kibret, for his guidance and the opportunities he has afforded me. He is incredibly organized and a great problem solver, both of these qualities were immensely helpful in moving my project forward. Under his mentorship, I have learned the particulars of research work, which is an invaluable tool to have as my career moves forward. I would also like to thank my Co-advisor, Mr. Beneberu Shimelis, for his contribution to this work. Over the year, each has given me superb scientific guidance, many insightful suggestions and demonstrated a sincere interest in my work. I am fortunate to have such a group of intelligent scientists.

I would like to recognize the members of the Soil chemistry lab who have all contributed to the progress I have made. I would also like to pass my sincere gratitude to Mekonen Keneni and Berhanu Mengitsu for the immense help during fieldwork. I am also grateful to all who I have not mentioned but have supported me in one way or another to this point.

I would like to thank my friends and family for their continued support and encouragement, especially my mother, Lenah Naliaka for the myriad of ways in which, throughout my life, you have actively supported me in my determination to find and realize my potential, and to make this contribution to our world. To my brother Kinda Jeremiah, you have played a special role in my life, seeing me through all the financial difficulties, I shall forever be grateful.

Finally, I would like to pass my gratitude to the scholarship, Africa Share Capacity, for giving me this opportunity to further my career.

ACRONYMS AND ABBREVIATIONS

AEZ	Agro Ecological Zone
CDBm	Climate Database
CSIC	Consejo Superior de Investigaciones Científicas
DSS	Decision Support System
Eng and Tec	Engineering and Technology
Ero and Con	Erosion and Contamination Modelling;
FEWS NET	Famine Early Warning System Network
GCMs	Global Circulation Models
GIS	Geographical Information System
GPS	Global Positioning System
Ha	Hectare
Imp and Res	Impact and Response Simulation;
Inf and Kno	Information and Knowledge Databases;
IPCC	Intergovernmental Panel on Climate Change
LCs	Land Characteristics
LQs	Land Qualities
LUTs	Land Use Types
MDBm	Management Database
MICROLEIS	Microcomputer Land Evaluation Information System
NMA	National Meteorological Agency
Pro and Eco	Production and Ecosystem Modelling;
RCP	Representative Concentration Pathway
SDBm plus	Soil Database
WRB	World Reference Base

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ABSTRACT

Understanding the effects of climate change on land suitability for crop production has become an important issue with respect to food security. The main objective of this study was to evaluate the impacts of climate change on land suitability for rainfed crop diversification under current and future climate change scenario in Legambo sub-watershed. Land utilization types (LUTs) selected for this study were, sorghum (Sorghum bicolor L.), maize (Zea mays L.), bread wheat (Triticum aestivum L.), sweet potato (Solanum tuberosum L.) and soybean (Glycine max L.). MicroLEIS DSS through the application of Almagra and Terraza models were used. Almagra model assesses the suitability of different soil types to a specific crop. Terraza model provides an experimental prediction for the bioclimatic deficiency. Soil morphological and analytical data were obtained from 4 representative soil profiles and stored in the SDBm database. Agro-climatic data, referred to temperature and precipitation (monthly average values) for 20 consecutive years (1995-2014), were obtained from National Meteorological Agency and incorporated to the CDBm database. A future scenario of climate change was calculated according to the predictions of Intergovernmental Panel on Climate Change (IPCC) on regions of East Africa under scenario RCP8.5 by 2100. The results show that, the most suitable crops to grow in the study area are sweet potato >sorghum >maize>soybean>wheat in respect of that order. The main limitation factors for land suitability are soil texture and drainage conditions. Bioclimatic deficiency evaluation showed a positive response to climate change, with percent yield reduction decreasing. Accordingly, results show the following trend from low to high suitability to climate change: sorghum> maize> sweet potato>soybean>wheat. The net effect of climate change on land suitability is positive for both hypothetical scenarios and therefore, the study area is suitable for rainfed crop production for the selected LUTs.

1. INTRODUCTION

Climate change refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. It refers to any change in climate over time, whether due to natural variability or as a result of human activity (IPCC, 2014).

Climate change is a widespread challenge affecting many parts of the world (Mudzonga, 2011; Okonya *et al*., 2013). This changes will not occur without marked impacts upon various sectors of our environment, and consequently of our society (Chavas *et al*., 2009). The changes in climate in Eastern Africa region, where Ethiopia is geographically located will appear and will have an important impact on land suitability and in particular, for rainfed crop production. Changing patterns of temperature and precipitation and manmade land degradation affect the suitability of land for agricultural use. For example, 19-23 ha of suitable land are lost per minute due to soil erosion and desertification (UNCCD, 2014). Climate change has raised much concern regarding its impacts on future global agricultural production, varying by region, time, and socio-economic development path (Schlenker and Lobell, 2010).

The principle purpose of agricultural land suitability evaluation is to predict the potential and limitation of the land for crop production (Pan and Pan, 2012). Land suitability evaluation determines the ability of a piece of land to provide the optimal ecological requirements for a specific land use type. Therefore, suitability is a function of crop requirements and land characteristics (Mustafa *et al*., 2011). The information on the spatial distribution and suitability of various types of soils to various types of crops is crucial for planners and agricultural scientists to initiate and encourage farmers to practice cropping systems based on soil potential to various crop categories in the context of climate change.

Agriculture in Ethiopia has long been a priority and focus of national policy, such as Agricultural Development-Led Industrialization (ADLI), and various large-scale programs, such as the Plan for Accelerated and Sustained Development to End Poverty (PASDEP) (Teshome *et al*., 2013). The recent renewed attention on ‘food security’ due to growing global demand (Beddington, 2010) has meant that the discrimination and safeguarding of land quality for food production is again a priority for policymakers.

Abera (2008) stated that, one of the most important and urgent problems in Ethiopia are to improve agricultural land management and cropping patterns to increase the agricultural production with efficient use of land resources. Moreover, for these resources to be sustainable over the longer term, both the policymaker and the land manager require information on how management options are influenced by the risks and opportunities associated with global drivers such as climate change.

In an area such as Lake Haramaya watershed, largely occupied with rural population, substantial reliance on small-scale agriculture, and significant degraded lands, the need to assess the likely impacts of climate change on land use suitability has been recognized, but separating these impacts from those driven by other factors, such as population growth and economic development remains a problem. In the context of an increasing population, the effects of climate change can become dramatic. Continuous utilization of agriculture land in past decades, regardless of land suitability has caused much more destruction than provide the resources (FAO, 1976; 1983; 2007). Therefore, there is a need to identify potential changes in climate and land suitability that may result from climate change, and to identify some of the current and future impacts of climate change on land suitability. Exploration of climate change impacts on land suitability can identify areas where the range of options is changing or may be expected to change in the future and explicitly where this inherent flexibility is increasing or decreasing (Brown *et al*., 2008).

Current and future climate change on the land suitability and bioclimatic deficiency for rainfed crop production was investigated in this study. Although, Yihenew *et al*. (2014) demonstrated that different soils are variably suitable for different crops, they did not consider long-term climatic trends and did not show how land suitability is sensitive to climate variability. Ethiopia has a wide regional variation in both climate and land quality and the planning and management implication of any changes therefore make it a highly suitable case study. In this sense, MicroLEIS DSS, a relational database management system offers a convenient platform for performing land suitability and bioclimatic analysis and as a tool critical in decision support.

Sudden crop diversification or a change in cropping patterns is inflexible and risky. Therefore, this study was devised whilst keeping in mind the rigidity of the existing land use pattern and integrating the available resource information in a spatial domain to categorize land suitability in the watershed.

The main objective of this study was to evaluate the impacts of climate change on land suitability for rainfed crop production to achieve sustainable agriculture in the long term. The specific objectives were to (1) identify potential land suitability for specific crops for diversification and (2) to estimate crop yield reduction in rainfed condition in the study area under changing climate.

2. LITERATURE REVIEW

2.1. Climate Change

The world has awakened to the reality that our climate shows alarming signs of changing more rapidly and more dramatically than at any time in recorded history (FAO, 2011a). The general scientific consensus is that a significant climate change will occur during the next 100 years although there remain quantitative uncertainties in the climate models (Shahbazi *et al*., 2009a).

The fifth assessment report of Intergovernmental Panel on Climate Change (IPCC, 2013), projections for medium to high emissions scenarios indicates, that maximum and minimum temperatures over equatorial East Africa will rise and that there will be more warm days compared to the baseline by the middle and end of this century (IPCC, 2014). However, scientific view is that increases in global temperatures must be below 2° C if governments are to combat climate change in the context of sustainable development (UNFCCC, 2010).

Temperatures in Africa are projected to rise faster than the global average increase during the 21st Century (James and Washington, 2013). Climate models predict that if emissions go on unabated (the RCP 8.5 scenario), then global temperature is likely to rise by 2.6 to 4.8° C with a mean of 3.7° C during the 21st century, reaching 3.2 to 5.4° C above pre-industrial levels (IPCC, 2013). While the projected mean temperatures for Africa is 4.8° C with a likely range of 3.5 to 5.9° C. Based on the mean projections of the seven GCM models, IPCC (2013) predicts that there will be a significant increase in annual minimum and maximum temperatures throughout the country and in all four seasons.

Climate models show warming in all four seasons over Ethiopia, which may result in heat waves that are more frequent (IPCC, 2014). Similarly, recent reports from the Famine Early Warning Systems Network (FEWS NET) indicate that there has been an increase in seasonal mean temperature in many areas of Ethiopia, Kenya, South Sudan, and Uganda over the last 50 years (Funk *et al*., 2012). If climatic modeling is anything to go by, then findings have shown that temperatures for the Eastern African region, where Ethiopia is geographically located will increase. Average annual minimum and maximum temperature has increased by 0.25 and 0.1° C every ten years. By 2060, average annual temperature is expected to increase by 3.1° C and 5.1° C by 2090 (Deressa, 2007).

Projections for rainfall are less certain than projections for temperature (IPCC, 2013). Most areas of the African continent do not show changes in annual average rainfall under low-emissions scenarios (IPCC, 2014). However, likely increases in annual average rainfall are projected over areas of central and eastern Africa beginning in the mid-21st century for high-emissions scenario (IPCC, 2014).

Global projections also suggest that by the end of the 21st century, the climate in eastern Africa will be wetter, with more intense wet seasons and less severe droughts in October-November-December and March-April-May, a reversal of recent historical trends (IPCC, 2014). Regional models projections indicate shorter spring rains in the mid-21st century for Ethiopia (IPCC, 2014). Projections over Ethiopia indicate a wide range of rainfall spatial pattern changes (Conway and Schipper, 2011). Cook and Vizy (2013) indicate truncated boreal spring rains in the mid-21st century over eastern Ethiopia, Somalia, Tanzania, and southern Kenya.

2.2. Land Suitability

Land suitability is the fitness of a given type of land for a defined use. The land may be considered in its present condition or after improvements. The process of land suitability classification is the appraisal and grouping of specific areas of land in terms of their suitability for defined uses (FAO, 1976). In principle, the known physical suitability evaluation emphasizes more to the physical properties than economic conditions. It indicates the degree of suitability for a particular land use type (Rossiter and Wambeke 1997).

Land suitability evaluation involves characterizing the soils in a given area for specific land use type (Ande, 2011). The suitability of a given piece of land is its natural ability to support a specific purpose and this may be major kind of land use, such as rainfed agriculture, livestock production, forestry (Ande, 2011). According to FAO (1976), two stage approaches is often used in resource inventories for broad planning purposes and in studies for assessment of biological productive potential. A land evaluation framework developed by the FAO (1976), which is widely used in land suitability analyses, suggests that we should consider the biophysical (landforms, soil, vegetation, climate, etc.), economic, and social aspects in classifying land suitability. However, this framework does not elaborate on the criteria and/or indicators to be used for evaluating economic and social suitability. Consequently, many land suitability studies have mainly focused on investigating the biophysical aspects only (Walke *et al*., 2011).

The fundamental purpose of land evaluation is to predict the positive or negative consequences of change. Land evaluation can be a formal, structured method to assess land degradation risks caused, for example, by long-term changes in climatic conditions and/or agricultural systems (Shahbazi *et al*., 2009a). With advances in information and communication technology, computer based decision support models have been developed towards land evaluation (Bandyopadhyay *et al*., 2009). Land evaluation results from a complex interaction of physical, chemical, and bioclimatic processes and evaluation models are reliable enough to predict accurately the behaviour of land (Shahbazi *et al*., 2009a). The increased need for food production and the shortage of resources stimulate a need for sophisticated methods of land evaluation to aid decision-makers in their role to both preserve highly suitable lands and satisfy producers' demands for increasing profits (Abagherzadeh and Mansouri, 2011).

Land evaluation requires information from different domains: soil, climate, crop, and management. The relationship between climate, soil, topography, and agricultural suitability has long been recognized (Zabel *et al*., 2014). As such, suitability analysis combine heterogeneous soil, terrain and climate information and determine whether specific crop requirements are fulfilled under the given local conditions and assumptions. A variety of national suitability studies for specific crops exists (Kasa and Mulu, 2012; Ebrahim, 2014), while a few exist for a broad variety of crops (Teshome *et al*., 2013; Yihenew *et al*., 2014). Unfortunately, many of these researches do not consider long-term climatic trends and their impact on the suitability of the crops.

2.3. Climate Change and Land Suitability

Climatic constraints are key metrics of most agricultural land suitability systems, either by restricting ecological processes such as plant growth rate, or by limiting management activities, especially those related to the timing of specific practices, such as ploughing, sowing or harvesting (Brown *et al*., 2008). These climate metrics are an important link between prevailing meteorological conditions, as measured at weather stations, and their specific relevance for land-use activities. A change in climatic constraints implies that new opportunities for, or risks to, land use could become manifest, based solely on the intrinsic conditions (Stone and Meinke, 2006). The presence of climatic data within land use suitability classification systems means that such systems can accommodate climate parameters projected into the future. Thus, climate change scenarios can be used to identify future changes in land suitability (Brown *et al*., 2008).

Understanding the effects of climate change on land suitability for crop production has become an important issue with respect to food security in areas undergoing increasing population sizes. Effects of climate change on land use refers to both how land use might be altered by climate change and what land management strategies would mitigate the negative effects of climate change (Dale, 1997). Climate change can affect land degradation risks in agricultural areas, soil erosion, and contamination corresponding to tropical regions (Shahbazi *et al*., 2010a). Increased land degradation is one possible, and important, consequence of global climate change. Therefore, the prediction of global environmental change impacts on these degradation risks is a priority (De la Rosa, 2008).

Internationally, many studies have considered the impacts of climate change on future agricultural land use through scenario modelling and their consequent policy impacts (e.g. Ewert *et al*. 2005), but there is remarkably limited literature on the impacts of potential changes in land suitability, a key factor influencing a country or region's ability to adapt agricultural practices to a changing climate. Lefroy *et al.*, (2010) evaluated the potential impacts of climate change on land use in the Lao PDR. The results showed that the change in bioclimatic suitability for the predicted 2050 climate was positive for some crops (sugarcane, cassava, rubber, banana, teak, and paddy rice), negative for some crops (maize, soybean, chilli, common bean, sweet corn, Arabica coffee, Jatropha, and eucalyptus), no change for some crops (peanuts and upland rice), and positive and negative, in different parts of the country for Robusta coffee. Another study was performed using GIS to model and map current and future land suitability for potato production in England and Wales (Daccache *et al*., 2012). The outputs identified regions where rainfed production is likely to become limiting and where future irrigated production would be constrained due to shortages in water availability. The results suggested that by the 2050s, the area of land that is currently well or moderately suited for rainfed production would decline by 74 and 95% under the "most likely" climate projections for the low and high emissions scenario respectively, owing to increased droughtiness.

Therefore, exploration of climate change impacts on land suitability can provide information that can be used as a platform to explore the social and economic implications of climate change, alongside other pressures and drivers, by examining individual perceptions and experiences against the potential land-use responses. A land Suitability approach therefore emphasizes the practical implications of climate change on land-use potential for farmers, land managers, planners or other stakeholders.

2.4. MicroLEIS Agro-ecological Decision Support System

Computer aided land evaluation and classification systems provide capability/suitability assessments. MicroLEIS (De la Rosa, 2005) is a system of agro-ecological land evaluation and interpretation of land resources and agricultural management. It has been extended to a decision support system, providing a multifunctional evaluation of soil quality using soil survey input data (De la Rosa *et al*., 2009).

Decision support systems (DSS) are systems that are very informative, they combine information from different sources and therefore helps in the organization and analysis of information, and in the facilitation of evaluation. MicroLEIS DSS provides a computer-based set of tools for an orderly arrangement and practical interpretation of land resources and agricultural management data. Two components have been added in order to comply with rising environmental concerns (De la Rosa *et al*., 2001): prediction of global change impacts by creating hypothetical scenarios; and incorporating the land use sustainability concept through a set of tools to calculate current status; potentiality and risks; impacts; and responses (Shahbazi and De la Rosa, 2010).

The design philosophy follows a toolkit approach, integrating many software tools: databases, statistics, expert systems, neural networks, web and GIS applications, and other information technologies. It is divided in to five packages: i) Inf and Kno; ii) Pro and Eco iii) Ero and Con; iv) Eng and Tec; and v) Imp and Res, while the packages related to climate observation and its perturbation were used to assessing the new agriculture for the climate change era in north-west of Iran (Shahbazi and De la Rosa, 2010). As land evaluation focuses on global change, this MicroLEIS DSS could be used to investigate the impact of climate change on potentialities and vulnerabilities of agricultural land.

Since 1998, MicroLEIS DSS is considered a well-suited model and has evolved significantly towards an interface user-friendly agro-ecological system for sustainable land management (De la Rosa *et al*., 2004). Lastly, it is used as a useful considerable tool in evaluating selected areas for agricultural purpose. Overall, the knowledge-based decision support system approach used in MicroLEIS DSS appears to be a very useful method for responding to the need to bring agriculture and land resources sciences together for decision-makers. Although many of the models have been calibrated with Mediterranean region information, other major components allow universal application. (De la Rosa, 2005). MicroLEIS DSS software, has been used in some countries with different climatic conditions such as semi-arid region of Iran (Shahbazi *et al*., 2008). The Almagra model has been recalibrated and revalidated in semi-arid regions in west Asia (Shahbazi *et al*., 2009a). Sharififar (2012) tested the Almagara model with other parametric land suitability evaluation methods and found that, the Almagra model as an application of maximum limitation method can be considered a sound method for land suitability classification.

Today, MicroLEIS is a set of useful tools for decision-making which in a wide range of agro-ecological schemes. Some case studies have used the Almagra model for land suitability evaluation (Darwish *et al*., 2006; Salem *et al*., 2008; Shahbazi *et al*., 2008; 2009a; Jafarzadeh *et al*., 2009; Aldabaa *et al*., 2010). Darwish *et al*., (2006) evaluated the soils of Farafra oasis, Western desert, Egypt using MicroLEIS program. Their output data did demonstrate that most of Typic Haplogypsids soil map units were highly suitable for wheat, sweet potato, and sunflower crops, while the rest showed low suitability. MicroLEIS model has been used to predict the agricultural land suitability in many areas. Salem *et al*. (2008) found that the soils of El-Bostan, El-Nubariya region, can be diagnosed into highly suitable, moderately one and not suitable with respect to soil texture and the exchangeable sodium percent (ESP). Shahbazi *et al*., (2008) applied MicroLEIS DSS to evaluate the land use planning in Ahar area, East Azarbaijan. Results showed that in Ahar area, 45% of the total extension was classified as good capability land for agricultural uses and almost 12% of the area must be reforested by suitable shrub species, and not dedicated to agriculture, to minimize the land degradation.

The Terraza model has also been used widely (Shahbazi *et al*., 2009a). Shahbazi and De la Rosa (2010) have used the model to investigate the impact of climate change on potentialities and vulnerabilities of agricultural land. Sameh *et al*., (2013) used MicroLEIS DSS to evaluate climate change impacts on land suitability in Andalusia, Spain. The results showed that climate change is likely to cause severe water stress in cultivation. Accordingly, results showed the following trend from low to high suitability to climate change: cotton> maize> sunflower> sweet potato>soybean> wheat. Shahbazi *et al*., (2010b) used the Terraza model to evaluate the climate change impact on bioclimatic deficiency in Ahar soils, Iran. The results showed that the precipitation will increase with climate change in the future scenario, but the humidity index will be reduced because of high temperature. Therefore, climate change is likely to cause severe water stress in irrigated cultivation of alfalfa, sugar beet, sweet potato, and maize. Also, it is revealed that climate perturbation effects on rainfed conditions are more serious than those on the irrigated conditions in the area.

A computerized land evaluation techniques are a correct way to predict land productivity and land degradation, and to assess the consequences of changes such as climate (Shahbazi and De la Rosa, 2010). Therefore, other biophysical factors, mainly referred to monthly or daily climate parameters, are also considered as basic information or climate attributes (De la Rosa *et al*., 2004). There are various approaches to analyze the enormous complexity of land resource and its use and management from an agro-ecological perspective. Within the new MicroLEIS DSS framework, land evaluation is considered as the only way to detect the environmental limits of land use sustainability (Shahbazi *et al*., 2010a). Today, MicroLEIS DSS is a set of useful tools for decision-making in a wide range of agroecological schemes.

2.5. Relational Database

The development of a relational database management system to facilitate the integrated use of land attributes has been critical in decision support. As an example of the basic data used to develop the MicroLEIS DSS system, it consists of SDBm Plus, CDBm, and MDBm, with inter-connectivity between the three databases.

2.5.1. Soil database (SDBm Plus)

The FAO-CSIC multilingual soil profile database (SDBm Plus) (De la Rosa *et al*., 2002) is a geo-referenced soil attribute database for storage of an exceptionally large number of morphological, physical, and chemical soil profile data. This database is the engine of the MicroLEIS DSS system. It is user-friendly software designed to store and retrieve efficiently and systematically the geo-referenced soil attribute data collected in soil surveys and laboratories.

2.5.2. Climate database (CDBm)

The CDBm developed for MicroLEIS DSS is a computer-based tool for the organization, storage, and manipulation of agro-climatic data for land evaluation. These geo-referenced climate observations, at a particular meteorological station, correspond to the mean values of such records for a determinate period (De la Rosa *et al*., 2004; 2009). The basic data of CDBm are the mean values of the daily dataset for a particular month. The stored mean monthly values correspond to a set of temperature and precipitation variables (maximum and minimum temperature, accumulative precipitation, maximum precipitation per day, and days of precipitation). Climate (CDBm) database includes software subroutines for calculating climate variables for use in agricultural land evaluation, organization, storage, and manipulation of agro-climatic data. These interpretative procedures require large quantities of input data related to site, soil, climate, land use, and management. The CDBm module has been developed mainly to help in the application of land use models, via their mechanization (Shahbazi, 2008). Such models normally use monthly data from long periods. It is thus necessary to draw up climate summaries for such long periods. For periods longer than a year, the monthly data are mean values of the monthly dataset for the years under consideration.

2.5.3. GIS spatialization

Spatialization or regionalization analysis includes the use of spatial techniques to expand land evaluation results from point to geographic areas, using soil survey and other related maps (De la Rosa *et al*., 2002). The advent of GIS has brought about a whole set of new tools and enabled the use of methods that were not available at the time when the 1976 framework (FAO, 1976) was developed (FAO, 2006).

The use of GIS technology leads to the rapid generation of thematic maps and area estimates, and enables many of the analytical and visualization operations to be carried out in a spatial format, by combining different sets of information in various ways to produce overlays and interpreted maps (De la Rosa *et al*., 2002). This technology is already a prerequisite for managing the massive datasets required for spatial land evaluation application. Tools related to environmental monitoring such as agro environmental indicators, soil landscape relationships, land cover classification and analysis, land degradation assessment, estimation of agricultural biomass production potential and estimation of carbon sequestration all have their applications in land evaluation (Shahbazi and De la Rosa, 2010). The available GIS methods are usually combined with expert knowledge or production modelling to support studies such as land suitability assessment (Shahbazi *et al*., 2009a; Jafarzadeh *et al*., 2009) and risk analysis (Shahbazi *et al*., 2009b).

3. MATERIALS AND METHODS

3.1. Description of the Study Area

Lake Haramaya Watershed is located in Haramaya and partly in Kombolcha districts, Eastern Hararghe Zone, Oromia National Region State, East Ethiopia (Figure 1). It is located at the upstream part of Wabishabele Drainage Basin. The Haramaya District where the Lake Haramaya watershed is situated is 505 kms away from Addis Ababa to the East, about 14 kms from Harar city, and 38 kms from Dire Dawa city. The Watershed lies between 9°23´12.27´´– 9°31´9.85´´ N and 41°58´28.02´´–42°8´h10.26´´ E (UTM Zone 38) and covers an area of 15,329.96 ha. It covers 13 peasant associations known as Areda in Afan Oromo. These are Ifa Bate, Damota, Tinike, Tuji Gabissa, Gobeselama, Ifa Oromia, Kerensa Dereba, Finkille, Amuma, and Kuro in Haramaya district, Kerensa Borte, and Kerensa Shanan in Kombolcha District, and Egu partly in Kombolcha and partly in Haramaya Districts. Moreover, the three kebeles of Haramaya town and the Haramaya University campus in Haramaya District are also parts of the Watershed.

This study was conducted in Legambo sub-watershed, which is one of the 28 sub-watersheds in Lake Haramaya watershed. It is 455.73 ha and is located between 9°24´25´´– 9°26´17´´ and 42°04´16´´–42°5´26´´ E (Figure 1) (UTM Zone 38). Its slope ranges from 0.4 to 37.5%, and the elevation is from 2092 to 2345 meters above sea level (m a.s.l).

Based on agro-climatological classification, Haramaya watershed has *Woina Dega* (wet and cool, 70%) and *Kolla* (dry and hot 30%) areas (Eshetu *et al*., 2014). Information obtained from Ethiopian National Meteorology Agency indicates that the mean annual rainfall and mean maximum and minimum temperatures of Haramaya watershed are 800.9 mm, 24.18 °C, and 9.9 ºC, respectively for the last 20 years (1995-2014) as presented by Figure 2. The short rainy season, *belg*, stretches from March to May, while the main rainy season, *kiremt* extends from July to September, with the peak in August. However, it has been observed recently that the rainfall distribution is so erratic, irregular and variable.

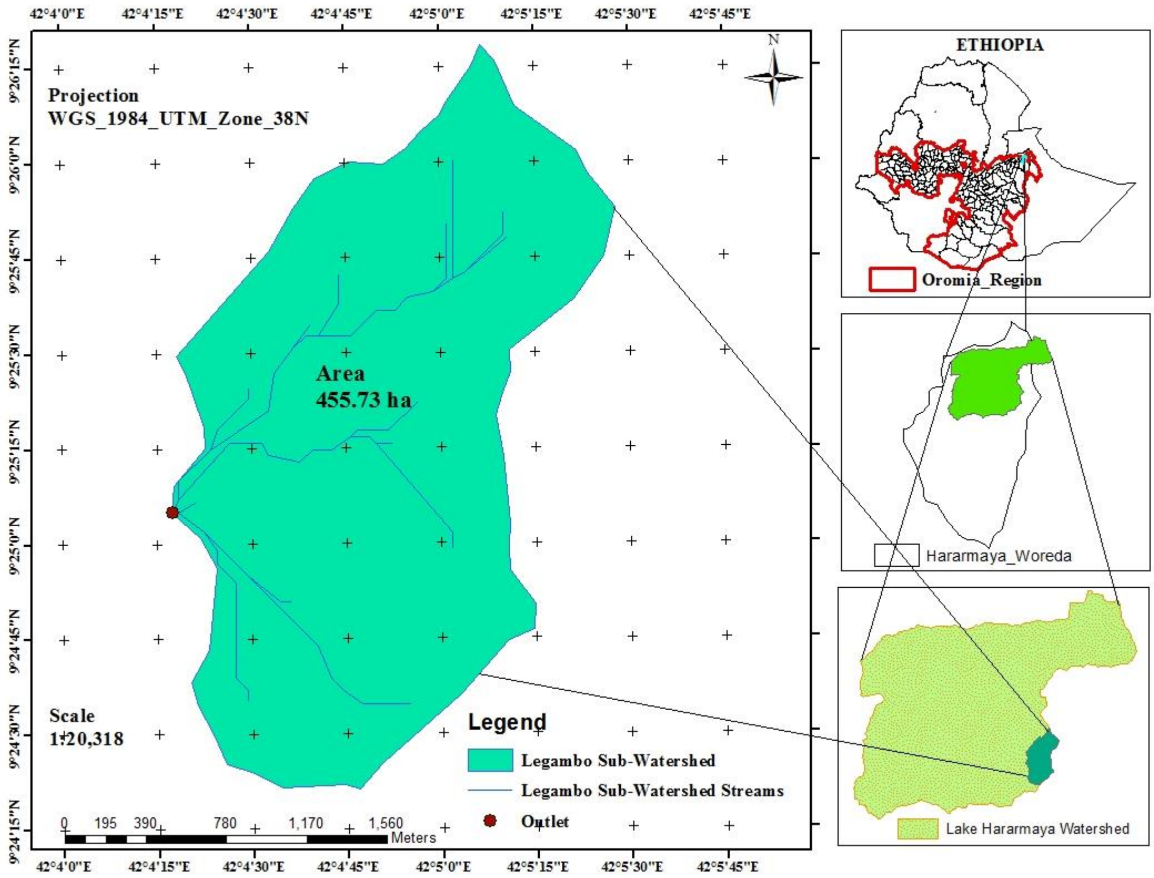

Figure 1. Location of the study area (Legambo Sub-Watershed, Ethiopia)

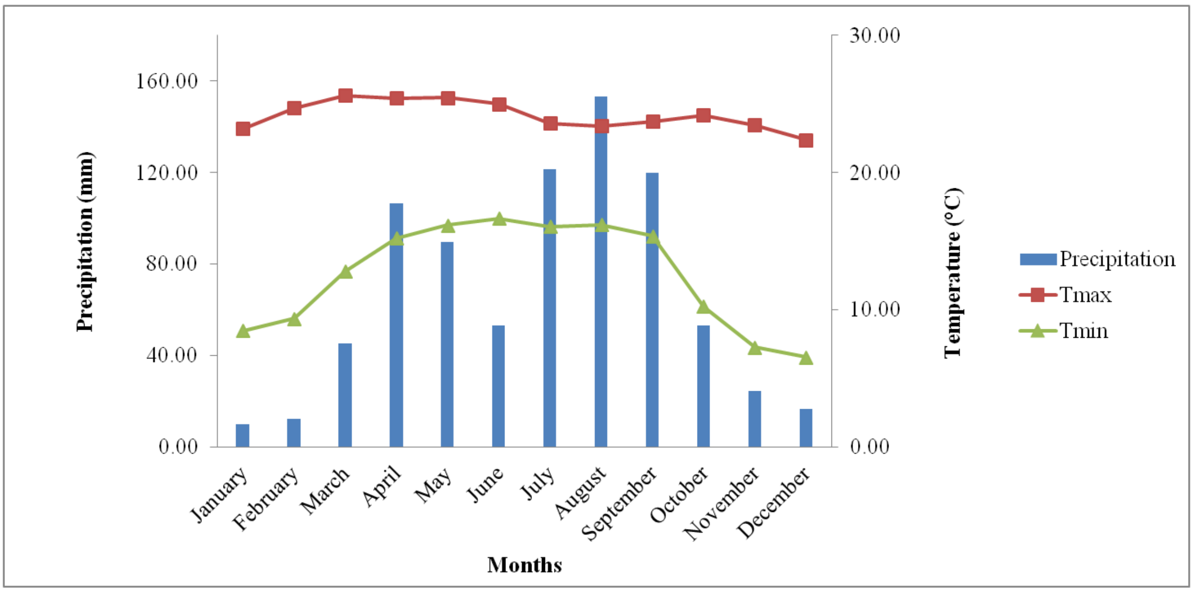

Figure 2. Mean monthly rainfall and mean monthly maximum and minimum temperature of Haramaya district (1995 - 2014)

The major portions of the agricultural soils in Legambo sub watershed are very shallow and most soils of the steeper slopes are unproductive truncates exposed to the sub soils. About 71% of the catchment is characterized by undulating and rolling topography (Muleta *et al*., 2006). Based on USDA soil textural classification scheme, the soils in the Watershed are grouped in to four different classes: clay, clay-loam, sandy clay loam and sandy-loam (Tadesse and Abdulaziz, 2009).

The components of farming systems are smallholder mixed crop-livestock production. The major annual crops are sorghum (*Sorghum bicolor* L.) and maize (*Zea mays*, L.), intercropped with legumes. Haricot bean (*Phaseolus vulgaris* L.) is the dominant legume intercropped with main crops in the cropping system of the region. Bread wheat (*Triticum aestivum* L.) and sweet potato (*Ipomoea batata* L.) are grown in small areas. Sorghum and maize are cultivated under rain-fed conditions (Setegn *et al*., 2011). The major crops grown under irrigated conditions are, *Khat* (*Catha edulis*) (a woody stimulant species), irish potato and vegetables (lettuce, carrot, onion, tomato and cabbage). Vegetables are cultivated during rainy seasons but more so in the dry seasons where underground water is available for irrigating the crops. *Khat* (*Catha edulis*), forms the main perennial cash crop of the sub-watershed.

The components of the livestock system are cattle, donkey, goats, sheep, and poultry at both farms. Livestock are used as source of food (meat, milk, and milk products) and as saving asset, while manure is used for soil fertility management to some extent. Good soil and moderate climatic conditions for the growth and productivity of a variety of crops have enabled the existence of high density human and livestock population in the area.

3.2. Site Selection, Soil Sampling and Preparation

The selection was done following a reconnaissance survey of the whole Lake Haramaya watershed. The selection decision was supported by the level of the present land degradation status, severe impact areas, population density and land use and the potential for future development and adaptation to climate change as compared to other Sub-watersheds. Plains and hills are the main physiographical units in the study area identified. The study area was delineated using the Global Positioning System (GPS) and Digital Elevation Model (DEM), and the preliminary map was produced using the Arc GIS 10.1 and the actual study area was then extracted by excluding the unrepresentative areas.

Soil surveys are the basic building blocks for developing the comprehensive data set needed to derive land evaluation, which is normally based on data derived from soil survey, such as useful depth, soil texture, water holding capacity, drainage class and soil reaction or landscape (soil and site) attributes.

Soil investigation was carried out in two successive steps (auger observation and profile sampling) based on major land/soil characteristics. In this case, with the help of the Arc GIS 10.1. The slope of the study area was reclassified into six slope classes (Figure 8). The slope classes were based on the FAO (WRB, 2014) general slope classes with some modification. Fixed-grid survey technique (100 by 100 m interval) was employed and soil auger observations made, using 'Edelman auger', at every 100 m by 100 m distance to identify variations in soil depth and texture characteristics along the slope gradient. The depth of augering was 100 cm, unless the soil depth was limited or lithic contact prevents the operation. Hand held GPS Garmin GPS MAP 62s (Garmin limited, 2011) was used for geo-referencing the augering points. The auger observations for the soil depth and surface texture were grouped into the USDA (2014) depth and texture classes. Points with the same soil depth class and surface soil texture in a given slope class were considered as a single mapping unit. Boundaries of the mapping units were then delineated into four land mapping units namely LG001 (Slope 0-4%), LG002 (Slope 4-7%), LG003 (Slope 14-32%) and LG004 (Slope 7-14%),

Following the identification of the mapping units, further soil characterization was done using 4 soil profile pits that were excavated at the representative sites in each mapping unit (Figure 3). The profiles were described in-situ (Figure 4), for morphological characteristics according to FAO WRB (2014), and soil samples taken from every identified horizon. Soil samples were collected packed in plastic bags and processed for laboratory analyses.

Useful depth (cm), degree of profile development, drainage and carbonate content in representative soil profiles were determined and analyzed. Useful depth was measured by a tape measure and expressed in centimeters from the surface; it is that part of the soil easily penetrated by the roots. Drainage is defined as the natural process of elimination of water from the soil surface, and it was generalized into six levels from very poor to rapid. Soil drainage indicates the speed of water infiltration or the soil condition describing the duration and level of water saturation and inundation. In general, plants require good drainage soils to facilitate oxygen availability.

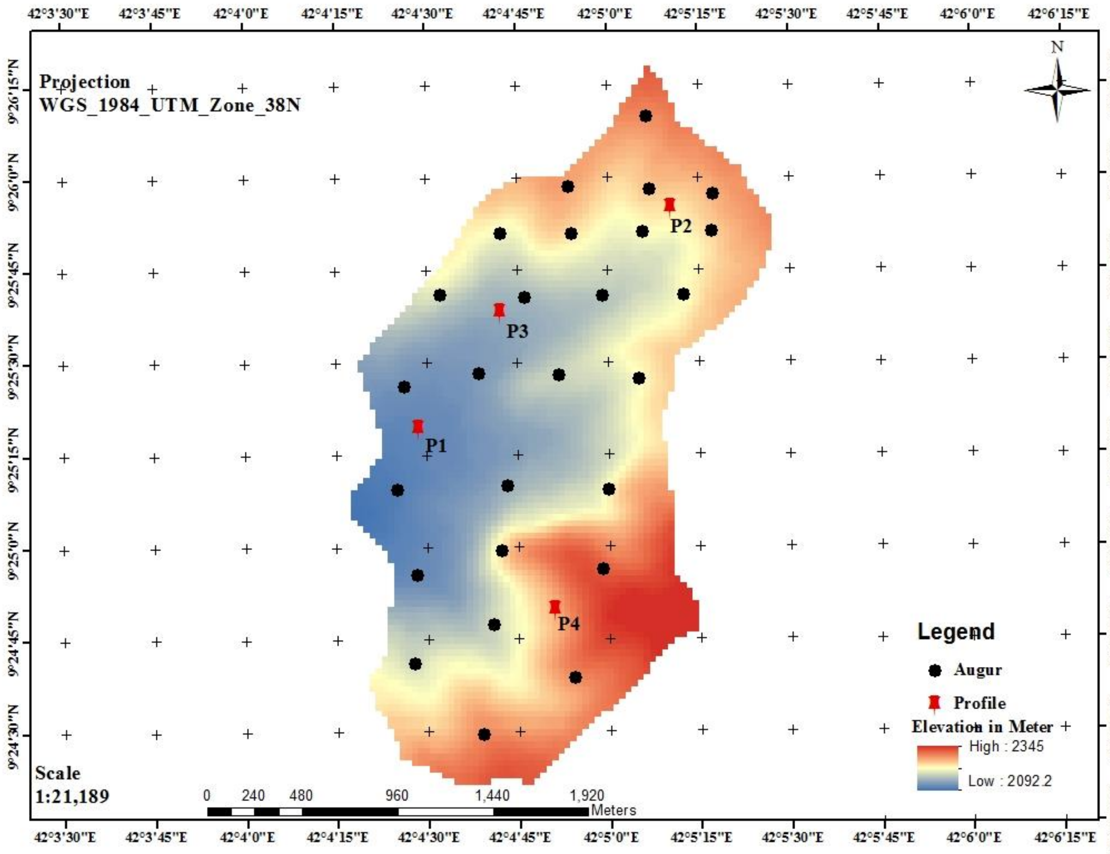

Figure 3. Soil profiles and augering location map of the study area.

Figure 4. Site and soil profile described in the study area.

Definitions of the drainage classes were based primarily on depth to low chroma colors using the Munsell color chart. Carbonate content was determined by treating the soil sample with 1 molar dilute hydrochloric acid (1 M HCl) the initial reaction observed, and after about two minutes the final extent of effervescence was assessed and appropriate effervescence class assigned (USDA, 2014). Profile development is the degree of genetic development of the profile - the state of maturity or aging, in accord with the edaphogenesis undergone by the soil - reflects the size of alterable minerals reserves and type of clay present in the solum. It was generalized into four levels of classes (USDA, 2014). The gravel content was measured by volume according to USDA (2014).

Disturbed soil samples were air-dried, crashed and sieved (<2 mm) for the analysis of all soil properties. For determinations of organic carbon and total Nitrogen, the samples were passed through 0.5 mm sieve.

3.3. Laboratory Analysis of Soil Samples

Soil pH (soil reaction) was measured in 1:1 soil: water suspension solution using the Consort pH meter model C835. Salinity (dS/m) was measured using the Jenway conductivity meter model 4510 in soil to water ratio of 1:2.5 (Van Reeuwijk, 2006). The cation exchange capacity (CEC) was determined after extracting the soil samples by ammonium acetate at pH 7.0 (Chapman, 1965). Particle size distribution was determined by hydrometer method (Bouyoucos, 1962). Exchangeable calcium (Ca) and magnessium (Mg) in the extracts were determined using Buck atomic absorption spectrophotometer (AAS) model 210 VGP, whereas sodium (Na) and potassium (K) were quantified by Corning flame photometer model 410 (Van Reeuwijk, 2006). Soil organic carbon (OC) was analyzed by wet digestion method (Walkley and Black 1934), and total nitrogen (N) determined by a modified micro- Kjeldahl digestion procedure, while plant available phosphorus (P) was quantified by Olsen method (Olsen *et al*., 1954). The exchangeable sodium percentage (ESP) was then estimated from the concentrations of the exchangeable Na, and CEC. The analyses were undertaken at Haramaya University Soil Chemistry Laboratory.

The mean weighted value of each determined soil property (V) twas calculated by multiplying the parameter value (Vi) of each horizon by horizon thickness (ti) divided by the total profile depth (T) according to the following equation (Ismail *et al*., 2005):

$$V = \left[\frac{\sum_{i}^{n} = (vi \times ti)}{T} \right] \quad (1)$$

After the final data preparation of the soil morphological, physical and chemical characteristics of representative mapping units, a multilingual SDBm Plus (De la Rosa and Diepen, 2002) was used to store and manipulate the soil data extracted from soil profiles to create information in control section between 0.0 to 100 cm using “File layer generators”to apply in the Almagra model. The soil water retention capacity for all soils was calculated in the vertical control section of soils between 0.0 and 100 cm by the SDBm Plus.

3.4. Land Suitability Assessment

3.4.1. Selection of land utilization types (LUTs)

The aim of this research was to investigate the study area to arrive at the possible LUTs. During the field study, rainfed crop production was considered as the major land use. The rainfed crop production in Legambo Sub- watershed is characterized by low capital, labor intensive and non-mechanized agriculture. The size of farm fields assigned for each farmer is small (less than 1 hectare per household), and their major sources of traction for plowing are oxen, which is largely subsistence-oriented with some amount for marketing. Land utilization types (LUTs) were described according to FAO procedures (FAO, 1983).

The LUTs were evaluated to the suitability of the land against their biophysical requirements, which includes present physical and chemical property of the soils, cropping-system, topography, cultivation practices, crop calendar, market, and land use, and then selection was done through discussion with the informant farmers for the study area. For this study area, the different LUTs (crops) selected for evaluation were sorghum (*Sorghum bicolor* L.), maize (*Zea mays* L.), bread wheat (*Triticum aestivum* L.), sweet potato (*Solanum tuberosum* L.) and soybeans (*Glycine max* L.). Sorghum is already intensely cultivated but the community believes these crops are important for their food security, economy and biofuel issues. Besides, selection of LUTs, the crop environmental requirement and crop altitude adaptability for this study area was considered to define the potential crops to be cultivated in the study area under the changing climate, but also basing on the rigidity of the farmers to the diversification of new crops.

3.4.2. Suitability evaluation

The physical and chemical properties were applied to Almagra Model (Figure 5) available at http://www.evenor-tech.com/microleis/microlei/microlei.aspx (MicroLEIS, 2009) to run the land suitability evaluation for some selected crops: wheat, maize, sweet potato, and soybean as annuals. The crops were evaluated based on available soil conditions of the study area.

This system is not an expert on itself, and therefore, does not provide information, but it's a system that enables one to introduce their own evaluation characteristics; choosing our own LUTs, land qualities (LQs) and land characteristics (LCs). The input for the analysis includes useful effective depth (p), texture (t), drainage (d), carbonate content (c), salinity (s), sodium saturation (a) and degree of profile development (g) (Appendix 2),which were used as diagnostic criteria (Figure 5b). The control or vertical section of soil for measuring texture, carbonates, salinity, and sodium character was established by adapting the criteria developed for the differentiation of families and series in soil taxonomy (USDA, 2014). It refers to between 0.0 and 100 cm in depth, or between 25 cm and the limit of useful depth when the latter is between 0.0 and 100 cm, or in some part of the soil is within the useful depth for perennial crops.

Depending on the gradation considered for each of the criterion that was selected, five relative suitability classes was determined; optimum, highly, moderately, marginally and no suitability, represented as S1, S2, S3, S4 and S5, respectively. Sub classes were indicated by the level that corresponds to the maximum limiting soil factors. The definitions of soil suitability classes, soil limitations and soil factors are presented in Table 1.

Table 1. The definitions of soil suitability classes, soil limitations and soil factors

Soil suitability classes		Limitations		Soil factors	
Symbol	Definition	Symbol	Definition	Symbol	Definition
S1	Highly suitable	1	None	A	Sodium saturation
S2	Suitable	2	Slight	C	Carbonate
S3	Moderately	3	Moderate	D	Drainage
S4	Marginally suitable	4	Severe	G	Profile development
S5	Not suitable	5	Very severe	P	Useful depth
				S	Salinity
				T	Texture

Source: MicroLEIS, 2009.

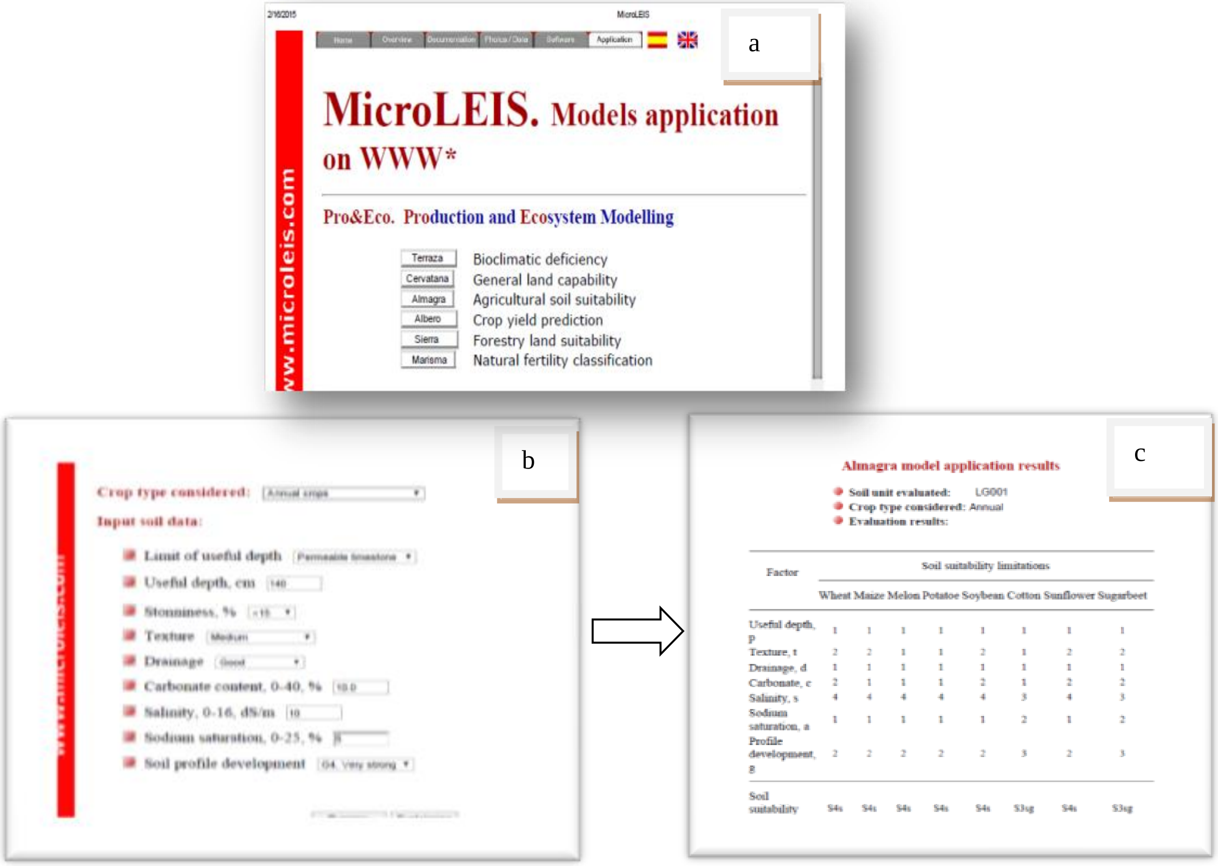

Figure 5. MicroLEIS program (Almagra model); a) the main interface of MicroLEIS throughout you can pick up the model you need, b) the interface to input your own data, and c) the output data for the selected crops (MicroLEIS, 2009).

Once the land unit data is entered, Almagra gives an on-screen evaluation (Figure 5c) based on the criterion of the maximum limitation. The verification of the degree of a single variable is sufficient to classify the soil in the corresponding category. Suitability classes were identified with attention to the land characteristics. In this study, a simple map subsystem (Arc GIS 10.1) was used to show basic data and model results on a map.

Almagra model does not provide land suitability for sorghum, since sorghum is one of the most common crops in the study area. The land suitability was carried out manually by selecting specific criteria (drainage, texture, soil depth, CEC, pH, organic carbon and salinity) according to Sys *et al*. (1993) where four suitability classes were established S1, S2 S3 and N. This is based on the FAO land evaluation framework (1983) for rainfed agriculture. The adopted method consists of matching individual crop requirements as specified in the land evaluation manual (part III) (Sys *et al*., 1993), with the actual land characteristics (Appendix 1). A suitability rating is attributed to each land characteristic.

The crop requirements were further adjusted to suite the conditions of the study area. The soil depth requirement of the crop was chosen according to the usual root depth (in cm) of the crop. This is referred to as the control section in the evaluation process. The specification of the crop that was used in this case study for sorghum is 100cm. The final score was given by multiplying the single parameters. The suitability analysis was done per mapping unit and the results integrated to the Arc GIS and the simple map produced.

In this study, the maximum limitation method in the Almagra model in MicroLEIS system was used to evaluate the physical suitability of rainfed crops for cultivation in a specific land unit in the study area. The Almagra model constituent of MicroLEIS software is an automized application of soil suitability method, which matches the soil characteristics of soil map unit with growth requirements of each particular crop and results in the crop growth limitations being provided by the computer. The suitability method (De la Rosa and Diepen, 2002) was based on an analysis of soil characteristics (edaphic factors), which influence the productive growth of crops. The modeling phase involves the following main stages: and Selection of land attributes: LCs and associated LQs; and Defining of relevant land use requirements or limitations: land use response or degradation level; and Matching of land attributes with land use requirements; and Validation of the developed algorithms in other representative areas (Figure 6). Following the criterion of maximum limitation, each factor has a definite action and the verification of the degree of a single variable is sufficient to classify the soil in the corresponding category (Cardoso 1970).

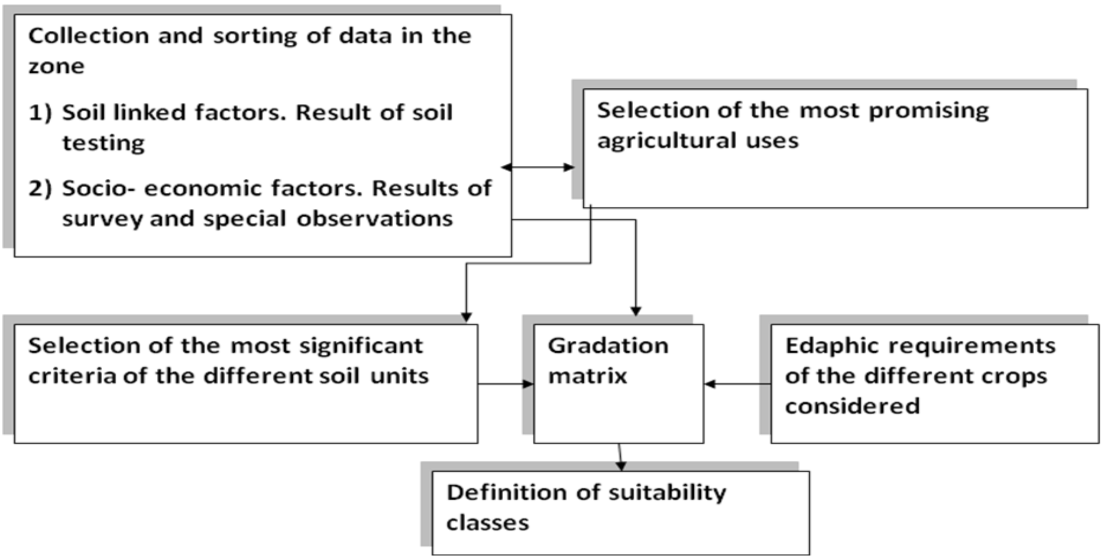

Figure 6. The sequence methodology steps of Almagra model (De la Rosa *et al.*, 2004**)**

3.5. Agro Climatic Data Collection and Analysis

3.5.1. Climate information

Agricultural activities and land use patterns are related closely to the temporal and spatial patterns of climatic elements. The success of land use strongly depends on climatic situation of an area. Rainfall and temperature are the major climatic factors that influence agricultural processes. Therefore, in the land suitability evaluation, climatic variables should be considered as diagnostic land qualities/ or land characteristics.

Climatic data such as mean, maximum and minimum temperatures for each month and total annual precipitation for the last 20 (1995-2014) consecutive years was collected from National Meteorological Agency (NMA), Ethiopia. Mean monthly values of a set of temperature and precipitation variables were stored in a CDBm, which includes software subroutines for calculating climate variables for use in agricultural land evaluation, organization, storage and manipulation of agro-climatic data.

3.5.2. Climate perturbation

The projected temperature increase is widespread over the globe (IPCC, 2013). Therefore, to apply the land suitability evaluation approaches due to climate change and perturbation, two climatic scenarios were constructed. The first scenario was defined by the climate of the current situation, extracted from the climate observations during the last 20 years (1995-2014) for the study area, while the second scenario was based on projected changes in surface air temperature and precipitation for Africa under the highest future emission trajectory (RCP8.5) by 2100 (IPCC, 2013). The IPCC (2013) report on the prediction in changes in mean annual temperature and precipitation (Table 3) compared to the present status (1995-2014) for the study area was used to describe the situation by 2100.

Model projections out to 2100 have become the de facto standard, as in the assessment reports produced by the IPCC. This period is within the planning horizon of many natural resources managers especially for Africa where development rate is slow. Furthermore, the climate change that will occur during this period is not well understood.

3.6. Bioclimatic Deficiency Evaluation

For the calculation of water deficiency and percent yield reduction for the selected crops in the study area, the Terraza model was applied, with following criteria:

The methodology was applied indirectly in which certain properties were assumed for the soil characteristics, such as available water holding capacity and is considered a greater or reduced viability depending on the qualities of the soil. Regarding the available water capacity, it was taken as reference for each existing texture, equal to 100 cm and is calculated to the floor units. This was calculated using the SDBm database. Other parameters such as temperature, precipitation, actual evapotranspiration, potential evapotranspiration, and crop coefficients, monthly coefficient of the crop (K_c) and coefficient of efficiency of the crop (K_y); are in their corresponding estimates as to metric.

3.6.1. Water balance

The calculation of water deficiency and percent yield reduction includes the daily precipitation and temperature compilation on a decadal (10 days) and monthly basis for a period of 20 years (1995-2014). The bioclimatic classification begins by determining the monthly potential evapotranspiration (ET_o), using the method of Thorenthwaite (1948), from the monthly mean temperature (Tm), and the monthly coefficient of light correction (Nm) depending on the site latitude calculated by the CDBm database. Terraza model evaluates the water deficiency of a site mainly from climatic factors and certain others of the plant, so that the evaluation of a single land unit (climate) may differ depending on the current use (crop). In general, the criteria followed are those established by the FAO (1986) with some modifications.

The Thornthwaite (1948), method is calculated as follows:

$$ET_o = 16 \times Nm \left(10 \times Tm / I\right)^a \tag{2}$$

where,

Tm, monthly mean temperature in º C; Nm, monthly coefficient of light correction, depending on the site latitude.

I and a, constants for each site, which are calculated as:

$$I = Sum\left(\frac{Tm}{5}\right)^{1.514} \quad \text{for m = 1, ……………….., 12} \tag{3}$$

$$a = 6.75 \times 10^{-7} \times I^3 - 7.71 \times 10^{-5} \times I^2 + 1.792 \times 10^{-2} \times I + 0.49239 \tag{4}$$

The monthly evapotranspiration of the crop (ET_c) was then calculated from ET_o as follows:

$$ET_c = ET_o \times K_c \qquad (5)$$

where: K_c, monthly coefficient of the crop

Then the monthly real evapotranspiration (ET_a) was given by:

$$ET_a = ET_c - D \qquad (6)$$

where: D, monthly water deficit of the site.

The difference between monthly evapotranspiration and the precipitation at a site can be positive or negative. If positive, this means there is a surplus or excess (S) of water; if negative, there is a deficit or lack (D). During the seasonal period of a crop, this difference was calculated between the precipitation and evapotranspiration of the crop (ET_c).

3.6.2. Crop yield reduction

Prediction of reduction in yield was achieved by employing a simple, linear crop-water production function, shown by equation 7. This formula enables the degree of sensitivity to water to be taken into account in estimating yield reductions for various crops and growth stages based on the soil moisture status. The main indicator of water shortage is actual evapotranspiration (ET_a).

The monthly reduction in crop production (R_y) was calculated using the following formula (FAO, 1986):

$$1 - Y_a/Y_m = K_y(1 - ET_a/ET_c) \qquad (7)$$

Substituting

$$1 - Y_a/Y_m = R_y \qquad (8)$$

we have

$$Ry = K_y(1 - ET_a/ET_c) \times 100 \text{ (expressed as \%)} \qquad (9)$$

Where: Ya, real crop production, Ym, potential crop production, K_y, coefficient of efficiency of the crop.

The annual reduction in crop production (Rys) was calculated as follows:

$$R_y s = K_y s\ (1 - \Sigma ET_a / \Sigma ET_c\ ) \times 100 \qquad (10)$$

Where: K_ys, coefficient of seasonal reduction, ΣET_a, sum of the monthly real evapotranspiration during the phonological period of the crop ΣET_c, sum of the monthly evapotranspiration of the crop during its phenological period.

Crop response factors (K_y) relates the relative yield decrease to the relative evapotranspiration deficit caused by a lack of adequate water. These K_y values are obtained through empirical experiments. K_c and K_y was determined using works of the FAO (1986), which establish the different phenological periods of various crops with different management (extensive, intensive or moderate).

The Terraza model allows a possibility of defining any arbitrary set of climate perturbation(s) as the hypothetical climate change. For example, maximum and minimum temperature (°C) and precipitation (%) are climate related factors which can be manipulated as climate change by adding to the previous figures.

Reduction in yield of sorghum, maize, soybeans, sweet potato and wheat of rainfed conditions were estimated and the results are shown in Figure 15. From the range of annual reduction in crop production (R_ys), four classes of water deficiency were established H1-H4 Table 2.

Table 2. Range of annual reduction in crop production established for each class of water deficiency.

Class	R_ys %
h1	<20
h2	20-40
h3	40-60
h4	>60

Source: (Microleis, 2009)

4. RESULTS AND DISCUSSION

4.1. Analysis of Land Characteristics

4.1.1. Landform

Three landform categories are observed in the study area. The landform is complex, characterized by undulating and rolling topography in the range of 2092 to 2345 m a.s.l, as shown in Figure 7. The dominant landforms in the study area include the plains, hills and a small proportion of high peak hills. The plains are alluvial and are relatively flat, and the hills are high to moderate relief. The landform category with the highest coverage area is the hill (317.84 ha) (69.76%), Meanwhile, landform category with the lowest coverage area is the high peak hills occupying around 1.74 ha (0.38%) which was not evaluated for agricultural production, therefore, will not be discussed here.

4.1.2. Slope gradient

In this very diverse landscape, the slope gradient varies dramatically too. The slope ranges on this study area were grouped into six different classes: 0-2%; 2-4%; 4-7%; 7-14%; 14-32%; and >32%. The slope range with the highest coverage area is the 7-14%; covering 239.25 ha, (52.51%).The spatial distribution of the dominant slope classes is illustrated in Figure 8. The alluvial plains and plateaus are relatively flat, with slope gradients ranging from 0 to 4 %. The steepness of the hills varies from 4 to 14 %, while the landscape of thousand hills is characterized by slopes varying between 7 and 14 %. The high altitude areas of the watershed are steeply sloping, with gradients ranging from 14-32, while the highest points have gradients exceeding 32 %.

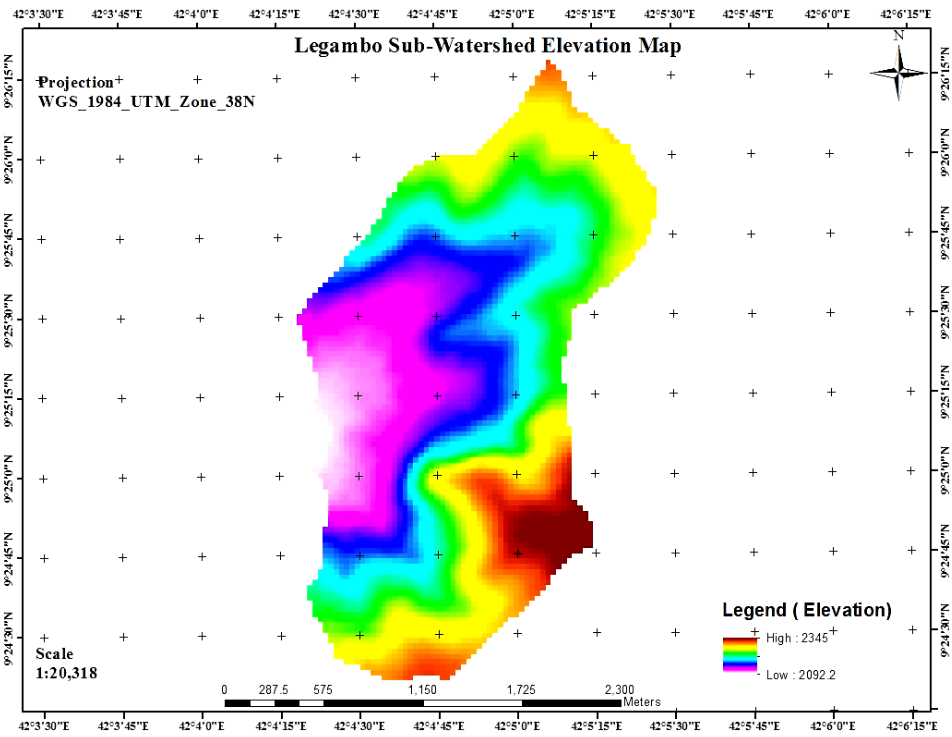

Figure 7. Elevation map of Legambo sub- watershed.

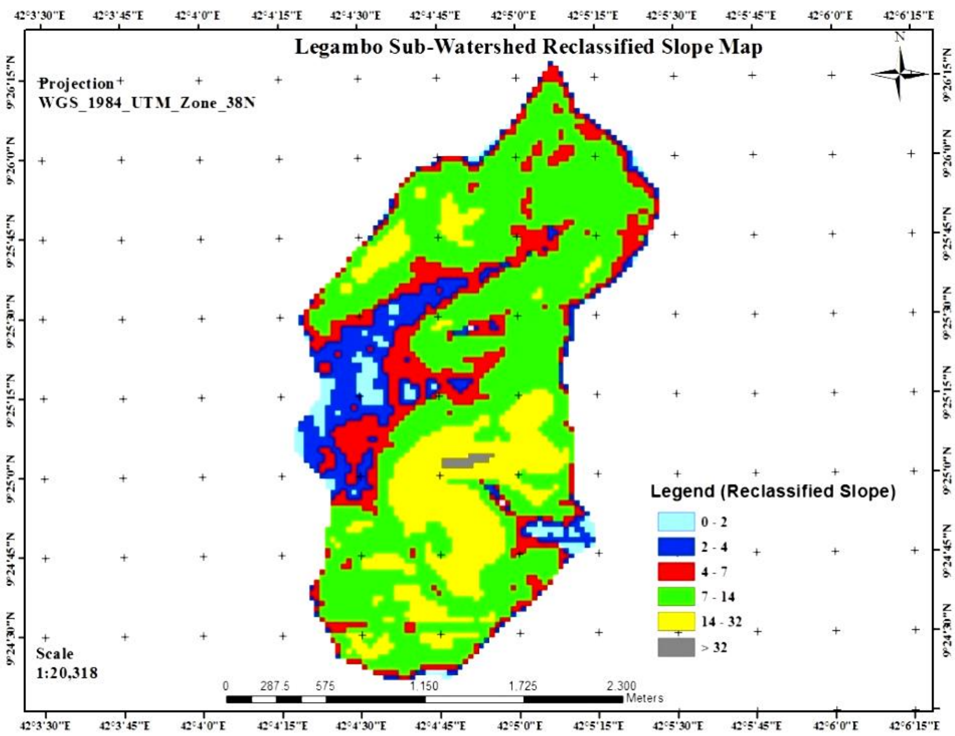

Figure 8. Map of the Slope range of Legambo Sub-watershed.

4.1.3. Physical and chemical properties of soils

This section presents the results obtained from various soil analyses (both physical and chemical parameters).Table 3 and 4 present the mean values of the parameters determined, while Appendix 2 presents the summaries of the major soil variables.

4.1.3.1. Physical properties of the soil

The particle size distribution ranged from 13-38%, 6-12% 50-80% clay, silt and sand, respectively, hence sand particles dominated the soils. The average soil texture for the four soil profile samples was found to range from sandy clay to sandy clay loam (Table 3). This is in accord with what Tadesse and Abdulaziz (2009) found. They found out that most of the soils in Haramaya watershed are sandy-to-sandy loam (the study area inclusive). The soils had high amount of sand and little amount of silt and clay (Table 3).

4.1.3.2. Chemical properties of the soil

According to the soil reaction (pH) rating established by Tekalign and Haque (1991) the results of soil analysis in this study showed that the pH of the soil profile varied from slightly acidic (pH = 6.1) to alkaline (pH = 7.9). Similarly, the mean pH values of soil samples from profiles 2 (6.1) and 4 (6.5) were categorized under the slightly acidic while, the samples from profiles 1 (7.9) and 3 (7.4) were categorized under the slightly to moderate alkaline soil reaction class as per the same rating provided. According to Zewdie (2000), the pH of Vertisols characterized in different parts of the country was within the range of 6.3 to 7.6 on the surface layer. Therefore, the soil pH values from the four profiles soil samples from this study falls within these findings.

The mean organic matter (OM) content of the four profiles (Table 4) had a mean OM contents ranging from 1.4 and 2.6%. According to the rating of soil OM content established by Tekalign and Haque (1991), the soils had low to medium OM contents. The reasons for the low and moderate OM levels in these soils could be due to intensive cultivation of the land, which encourages oxidation reaction, and the total removal of crop residues for animal feed and source of energy. In this study area there is no practice of organic fertilizers addition, such as animal (farmyard) manure and/or green manure that could have contributed to the soil

Table 3. Particle size distribution and textural classes* at the study site.

Profile No	Mapping unit	Clay%	Silt%	Sand%	Textural Class
1	LG001	38	10	52	Sandy clay
2	LG003	13	7	80	Sandy loam
3	LG002	38	12	50	Sandy clay
4	LG004	24	6	70	Sandy clay loam

* Mean value of selected parameters measured in the soil (0–50 cm).

Table 4. Analytical data* per the soil profiles of the study area

Profile No	Mapping unit	pH	OM (%)	$CaCO_3$ (%)	ESP (%)	CEC ($Cmol^{(+)}kg^{-1}$)	ECe (dS/m)	TN (%)	Available P ($Mgkg^{-1}$)	Exchangeable bases ($Cmol^{(+)}kg^{-1}$)			
										K	Na	Ca	Mg
1	LG001	7.9	2.3	15	1.53	3.27	1.11	0.08	10.6	0.06	0.05	2.87	0.29
2	LG003	6.1	2.6	<15	5.17	1.74	0.08	0.11	2.46	0.02	0.09	1.47	0.16
3	LG002	7.4	1.4	Nil	1.58	3.17	1.46	0.03	16.4	0.06	0.05	2.78	0.28
4	LG004	6.5	1.8	Nil	7.43	1.75	3.68	0.06	4.41	0.03	0.13	1.44	0.15

* Mean value of selected parameters measured in the soil (0–50 cm).

OM pool. Variability of soil OM has also been related to land use history and the associated management practices in other soils of Ethiopia (Zewdie, 1999).

The mean total nitrogen (TN) contents of the soil samples from the four profiles varied from 0.03 to 0.1% of soil (Table 4). The mean TN contents of the soil samples from profiles 1 to 4 (0.08, 0.11, 0.03 and 0.06%) are low; this values fell below the critical value (0.2 %) suggested by Landon (1991). This indicate that the soils of the study area are deficient in N to support proper growth and development of crops for expressing their genetic yield potential which suggest that the soils require fertilization with external N inputs and gradual build up of its OM levels to ensure sustainable productivity.

The available phosphorus content of the four profiles ranged from 2.46 to 16.42 $mgkg^{-1}$ (Table 4). According to Landon (1991) rating, the average available P contents fall under the low P status. On the other hand, Tekalign and Haque (1991) reported that 8.5 mg P kg^{-1} of soil was the critical level for some crops such as faba bean on major and/or agriculturally important soils of Ethiopia. Considering these critical levels of soil P, the amount of available P observed in the soils of the present study remains to be low. In general, existence of low contents of available P is a common characteristic of most of the soils in Ethiopia (Negassa and Gebrekidan, 2003) which is similar to the P content observed in the soils of the present study area.

Exchangeable calcium (Ca) followed by magnesium (Mg) was the predominant cation in the exchange sites for all the profiles (Table 4). The mean exchangeable Ca and Mg contents of the soil samples of profiles 1 to 4 ranged from 1.44 to 2.87 and 0.15 to 0.29 $Cmol^{(+)}kg^{-1}$, respectively, while that of exchangeable sodium (Na) and potassium (K) ranged from 0.05 to 0.13 and 0.02 to 0.06 $Cmol^{(+)}kg^{-1}$, respectively. These K values are rated as low to medium according to Landon (1991). Relatively high content of these two cations has been reported in Vertisols of Bichena and Woreta areas (Gebreselassie, 2002).

According to the rating suggested by landon (1991) the cation exchange capacity (CEC) values of the soil profile fall under the very low rate. As indicated in Table 4, the mean CEC values of the soil samples from profiles 1 to 4 ranged from 1.74 to 3.17 $Cmol^{(+)}kg^{-1}$. The low CEC values imply that the soil has low buffering capacity against the induced changes.

4.2. Land Suitability for Crops

The results of land suitability evaluation obtained by applying the Almagra (agricultural soil suitability) model, which is built in MicroLEIS system for agriculture land evaluation, are presented in Table 5. It includes the soil suitability classes for the selected crops and limitations. The results from Almagra were incorporated into the Arc GIS 10.1 and simple maps produced (Figures 9-12).

Out of four investigated mapping units, the map unit LG001 showed high suitability (S2) for maize and sweet potato crops but with texture, drainage and carbonate as limiting factors, nevertheless, it showed moderate suitability (S3) with drainage limitation for the remaining crops. The map unit LG002 showed moderate suitability to all the crops (S3) with texture and drainage constraints. However, LG003 showed no suitability (S5) with texture constraint to all the crops. Partly, map unit LG004 illustrated suitability to sweet potato, with texture, carbonate and salinity constraints and the rest of the crops showed moderate suitability with texture and carbonate as limiting factors (Table 5). The suitability classes were based on maximum limitations factors that cannot be corrected.

The land suitability in the study area for maize cultivation showed that, 14.11 % out of the total area is classified as highly suitable soils (S2) and 68.26% as moderately suitable (S3), while 66.61% is classified as highly suitable for sweet potato production and 15.76% as moderately suitable. On the other hand, 82.37% is classified as moderately suitable for wheat and soybean cultivation; however, 17.25% has no suitability for maize, wheat, sweet potato and soybean (S5) (Table 5)

On the other hand, MicroLEIS model does not include sorghum (*Sorghum bicolor* L.) in the suitability analysis. Due to the dominance of sorghum crop in the study area, soil suitability for sorghum was carried out manually according to the same principles applied in Almagra model and results integrated to Arcview GIS. The result indicated that 29.86% of the study area is highly suitable, 52.51% as moderately suitable while 17.25% as marginally suitable for sorghum cultivation (Figure 13).

The most suitable field crop to grow in the studied area is sweet potato; it is considered the most suitable because S2 percent area was more than 60%, while sorghum and maize are also considered suitable (Table 6). These crops are considered suitable because the (S2) percent area for each single crop represents at least more than 10% of the investigated area that are represented by LG001, LG002, LG003 and LG004 mapping units. With the exception of sweet potato crop, approximately more than 50% of the studied area is considered moderately suitable (S3) for each of the examined crops because of the texture, soil salinity, carbonate and drainage conditions. It is necessary to mention that approximately 17.25% of the investigated area is not suitable (S5) for growing most of the evaluated crops, except sorghum. This is as a result of dominant soil conditions within the study area. The soil texture is the limiting factor that more appears at the evaluation. Drainage, salinity and carbonate are also limiting factors for the cultivation of the selected crops.

Drainage and texture are considerable limiting factors for crop production. However, some crops such as sorghum can withstand short periods of water logging (FAO, 2013). Soil salinity is a considerable limiting parameter for sweet potato cultivation. It is moderately sensitive to soil salinity with yield decrease at different levels of ECe (FAO, 2013). Carbonate on the other hand, is a limiting factor for the growth of maize, sweet potato and soybean. Generally, the two most significant factors controlling crop suitability in this study area are soil texture and drainage in LG001 and LG002, while texture is the major limiting factor in LG003 and LG004.

Table 5. Soil suitability evaluation results from application of the Almagra qualitative model [a] to the study area.

Mapping site				Soil Suitability classes [b]			
Profile No.	Mapping unit	Coverage area (ha)	Coverage area %	Maize	Wheat	Sweet Potato	Soybean
1	LG001	64.28	14.11	S2tdc	S3d	S2tdc	S3d
3	LG002	71.79	15.76	S3t	S3td	S3t	S3td
2	LG003	78.59	17.25	S5t	S5t	S5t	S5t
4	LG004	239.25	52.51	S3t	S3tc	S2tcs	S3tc

[a] Development, inputs and validity of this model are described in De la Rosa *et al*. (1992).

[b] Soil suitability classes: S1, optimum; S2, high; S3, moderate; S4, marginal; S5, not suitable. Soil limitation factors: p, useful depth; t, texture; d, drainage; c, carbonate content; s, salinity; a, sodium saturation; g, profile development

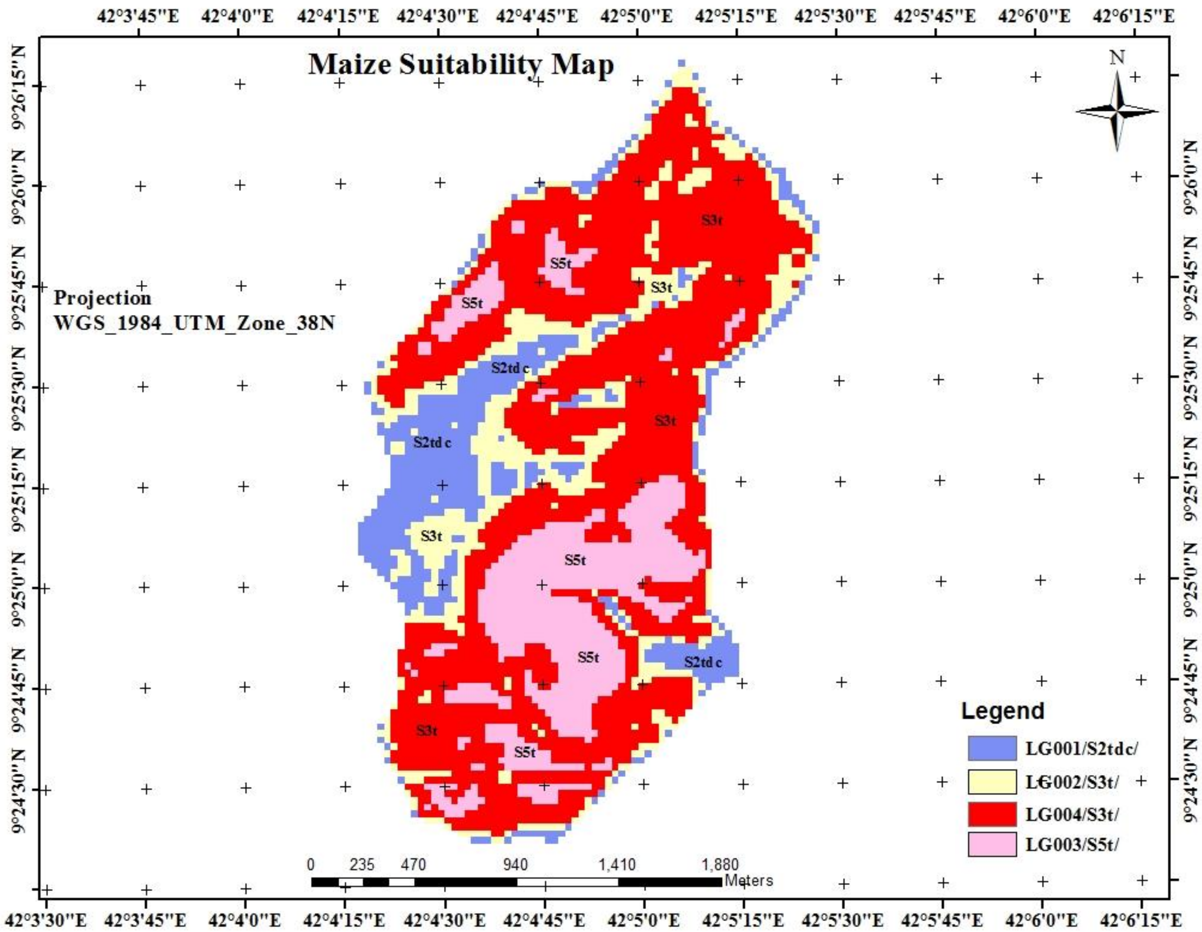

Figure 9. Land suitability map of maize.

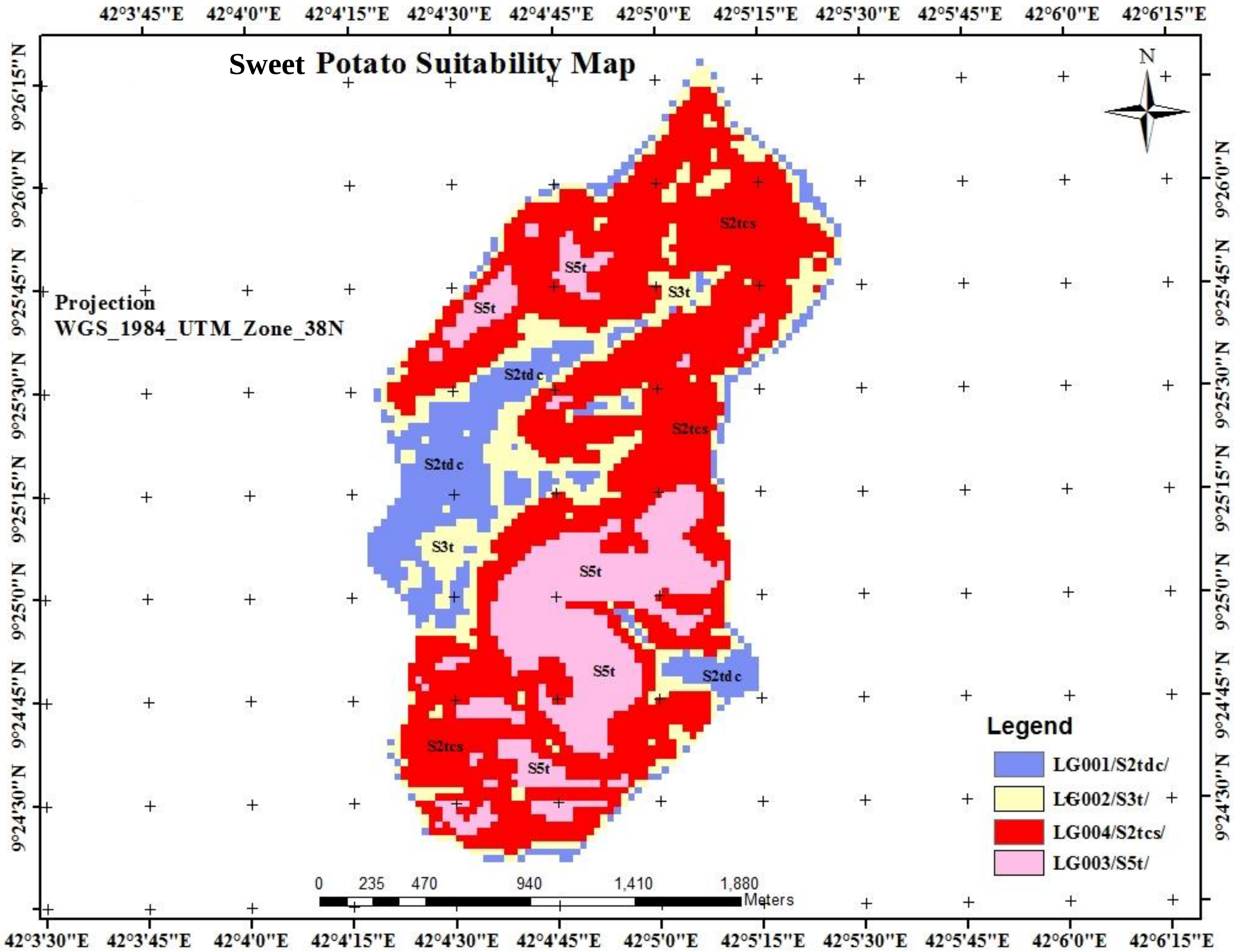

Figure 10. Land suitability map of sweet potato.

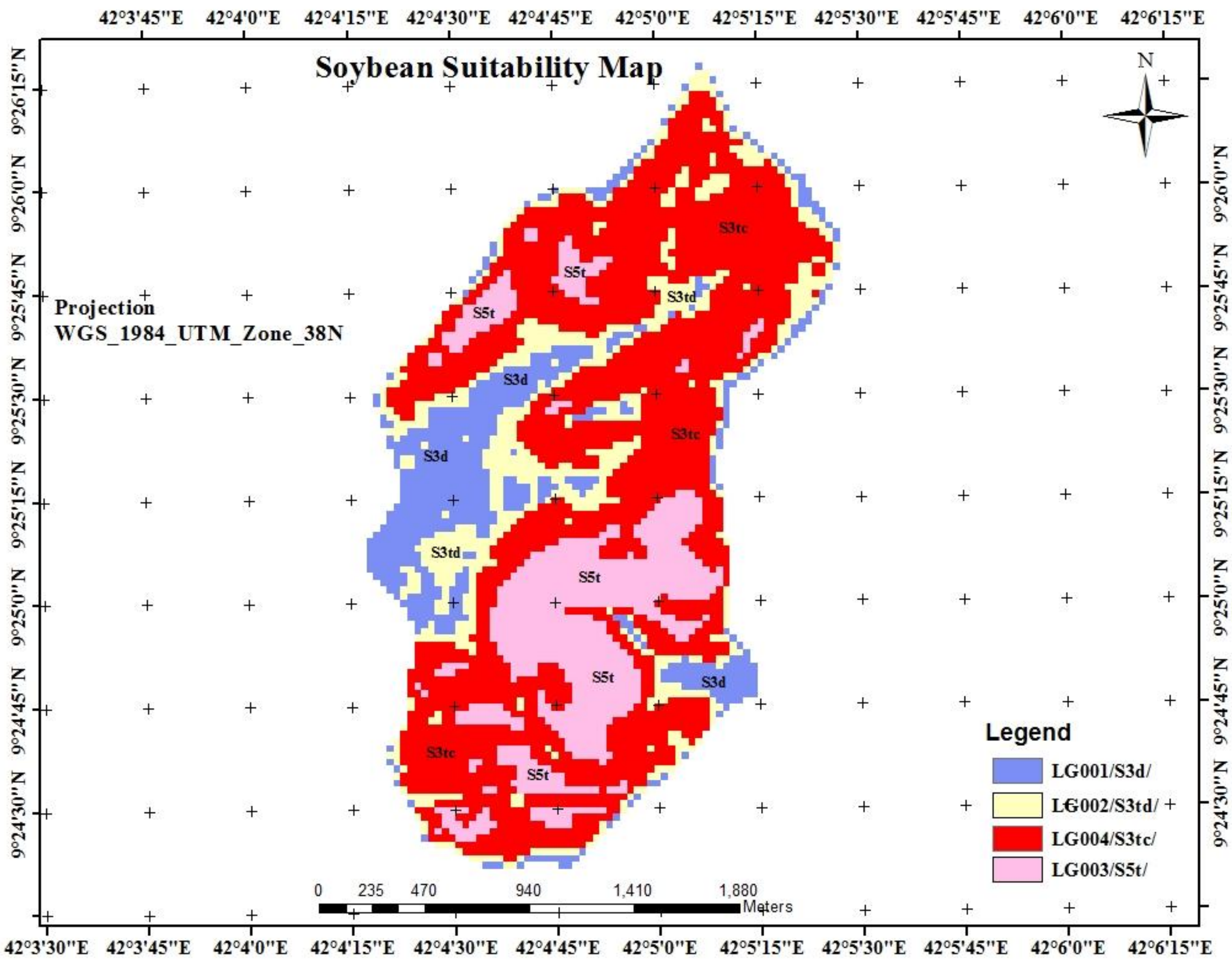

Figure 11. Land suitability map of Soybean.

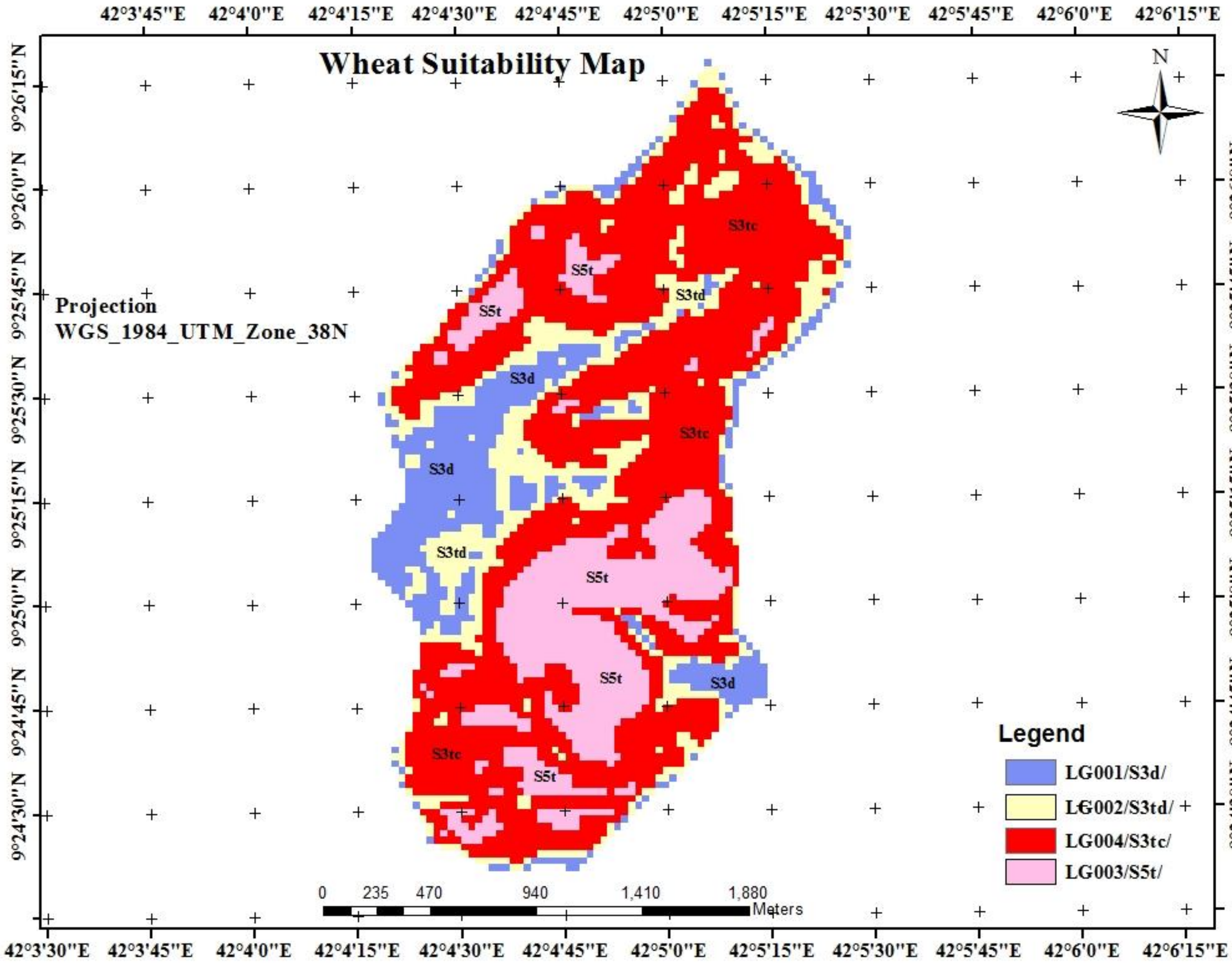

Figure 12. Land suitability map of wheat.

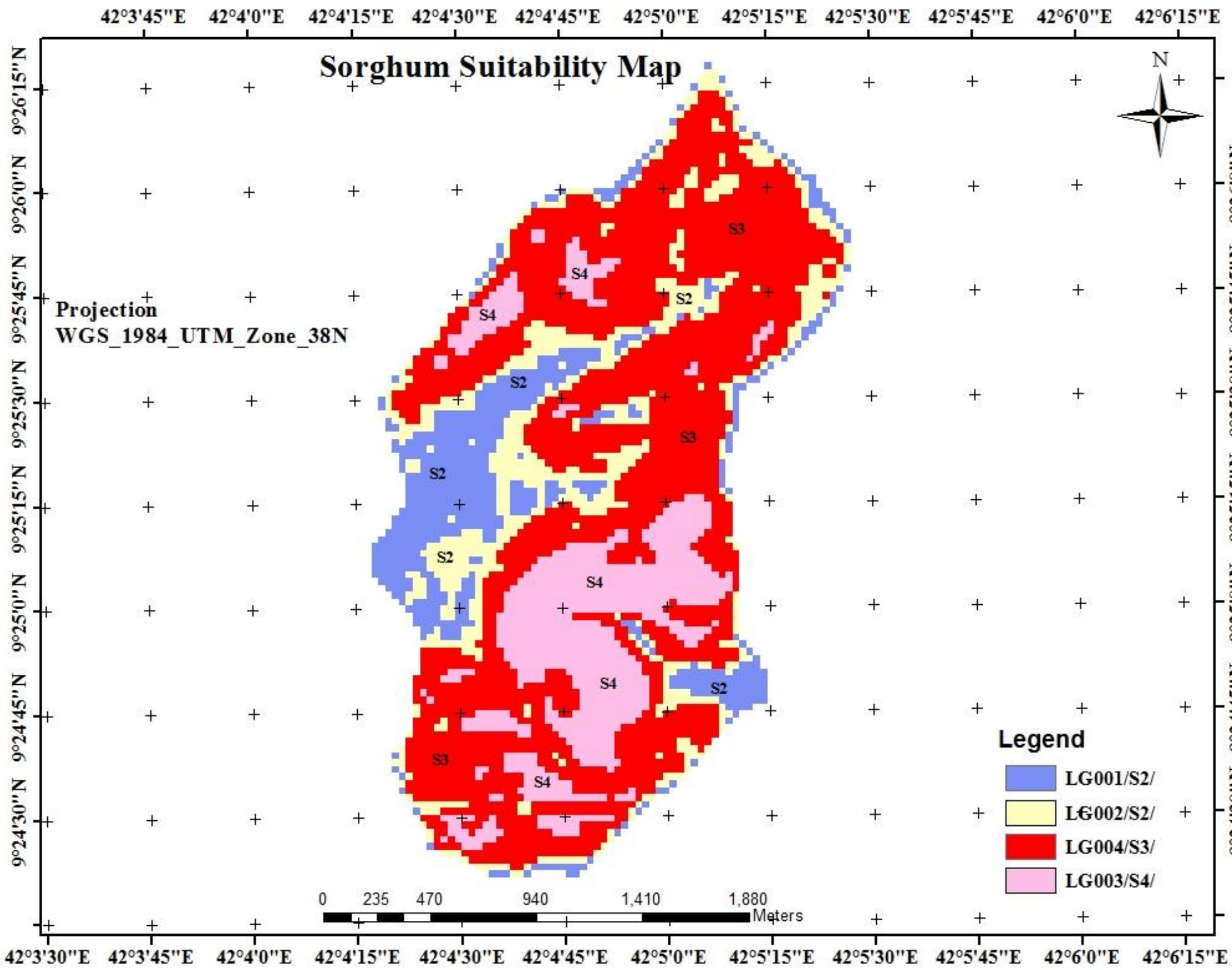

Figure 13. Land suitability map of sorghum.

Mapping units LG001 and LG002 have a fine texture, which shows a problem of drainage, and may lead to salt problems. This is due to high clay content and low infiltration capacity of water in these soils. Soil compaction could also be a problem and its one of the primary factors limiting plant growth in poorly drained land. This soils lack large pores, thus restricting both water and air movement, therefore, easily water logged. Therefore, management practices need to be adapted to improve the soils. Mapping unit LG003 and LG004 have coarse and medium texture, respectively, this in turn can be a problem with water holding capacity of the soil, and therefore, the plants may suffer from water deficit during growth, due to excessive drainage, this is seen from the texture characteristics; the plants therefore, might be subjected to frequent water stress.

Therefore, considering the suitability classification of sorghum, the arrangement of priority agricultural utilization or crop diversification according to their soil suitability classes in this area is as follows: sweet potato, sorghum, maize, soybean and wheat in respect of that order. The result of crop diversification is shown in Table 6.

The possible loss of currently suitable areas for any given crop such as land mapping unit LG003 that showed no suitability to majority of the crops, is especially important for smallholder farmers who are growing those crops in that area, points to the strong possibility that they will need to adapt to climate change. Jones and Thornton (2009) suggested that there will be places where livelihood strategies of rural people may need to change in order to preserve food security and provide income generating options.

Table 6. Summary of land suitability classification (% of the total area)

Suitability classes	Sweet potato	Sorghum	Maize	Soybean	Wheat
S2	66.61	29.86	14.11	-	-
S3	15.76	52.51	68.26	82.37	82.37
S4	-	17.25	-	-	-
S5	17.25	0	17.25	17.25	17.25
Total	99.62	99.62	99.62	99.62	99.62

* The remaining 0.38% of total area is occupied by Mountainous region.

4.3. Impact of Climate Perturbation

4.3.1. Water balance

Predictions for East Africa by 2100 under the RCP8.5 scenario indicate that the mean temperature will increase by 3.5º C in all four season, in the future scenario and at the study area with respect to present day (1995-2014). The total precipitation projected is variable where the spring and summer season will increase by 10 percent, and 20 and 50 percent in autumn and winter, respectively (Table 7). In the study area, climate change will not cause severe water stress in the 21st century, because of the increase in precipitation.

Table 7. Mean annual temperature and precipitation predicted.

Scenario (years)	Annual temperature,°C				Annual precipitation, %			
	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON
Future scenario (RCP8.5, 2100)	+3.5	+3.5	+3.5	+3.5	+50	+10	+10	+20

Source: IPCC, 2013.

Using the RCP8.5 scenario (highest future emission trajectory) for 2100s, the basic necessary data of CDBm program such as mean, maximum and minimum temperatures, as well as total annual precipitation were calculated. Results pertaining to CDBm program calculations for climate change perturbation are shown in Appendix 3 and 4. Summaries of water balance components calculated through CDBm program of MicroLEIS for current scenarios and future for Haramaya station are graphically shown in (Figure 14).

Through climate change in the long term; annual average temperature, precipitation, and evapotranspiration will be increased by 3.5 °C, 61.5 and 22.7%, respectively. Although precipitation increases are anticipated, it is important to note this does not necessarily translate into more available moisture for crop production. Higher temperatures increase evapotranspirative losses to the atmosphere, and the relative balance of the two factors may lead to less moisture in soils and surface waters for crop to utilize both now and in the future (quote). This means that in the distant future, in spite of increase in rainfall in the study area; the main problem confronting agricultural land use might be flooding and probably post harvest losses, due to high humidity during harvest period. FAO (2010) stated that, areas such as in East Africa and the Ethiopian highlands, rainfall and runoff are expected to increase with climate change, and more extensive and severe flooding is anticipated.

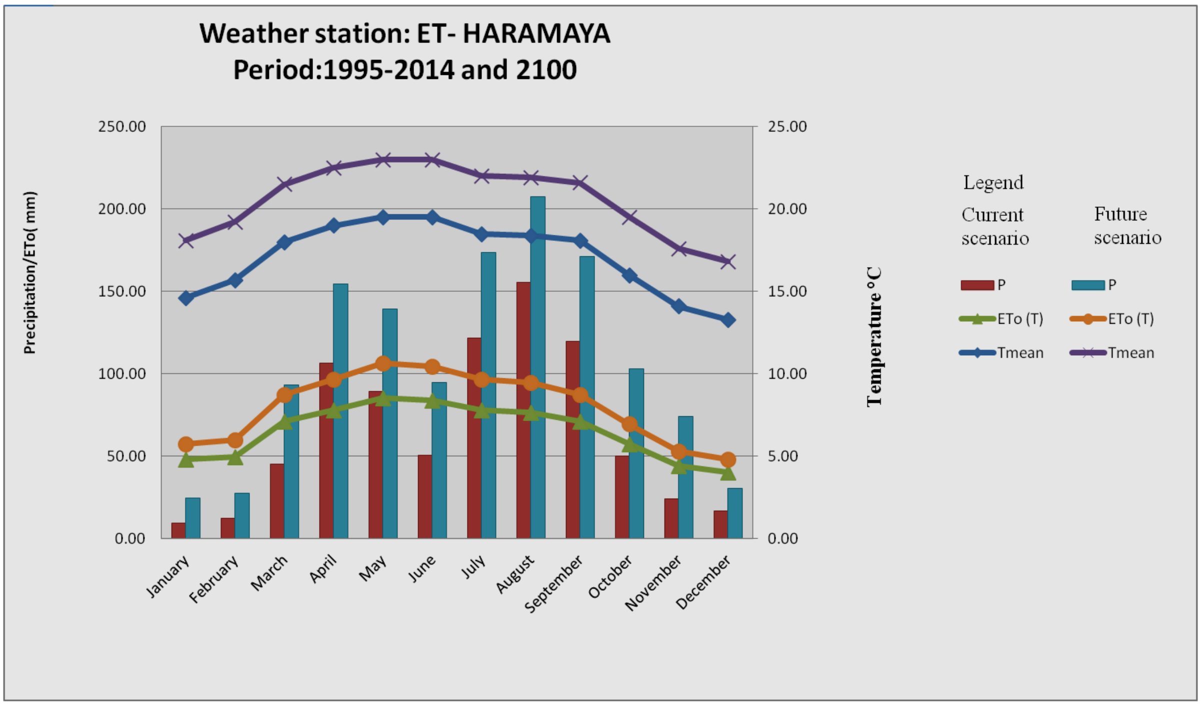

Figure 14. Climate graphical representation of the study area (current and future scenario)

From the analysis of the future climate, it shows that there would be an increase in precipitation in the study area, which is coherent with other projection. For example, FEWS NET, (2011) stated that several areas of Ethiopia might maintain moist climate conditions and agricultural development could help offset the impacts of declining rainfall in other parts. However, not all changes in climate and climate variability will be negative, as agriculture and the growing seasons in certain areas may lengthen under climate change, due to a combination of increased temperature and rainfall changes (Thornton *et al*., 2006). It is important to note that many areas of Ethiopia appear climatically secure, and appear likely to continue to receive more than 800 millimeters of precipitation during the *Kiremt* season. This is true for large areas of Ethiopia, during both the *Belg* and *Kiremt* seasons. Ethiopia, therefore, does not face a catastrophic national failure of rainfall, but rather regional hot spots with a tendency towards more frequent droughts (FEWS NET, 2012).

The average temperature and precipitation are not the only factors that affect crop production. Extreme climate conditions, such as droughts, heavy rainfall, snow events, and heat waves affect crops in different ways, depending on the crop tolerance. Change in the incidence of extreme events could thus have major impacts on the study area, rainfed crop production and must be considered when assessing vulnerability to and impacts of climate change.

The increased temperature on the other hand is good for the study area. With an annual average temperature of 20.56 °C yields are unlikely to be affected by temperature because it's within the optimum range for all the crops studied. Moreover, it will improve the growth rate of the plants.

4.3.2. Crop yield reduction

The bioclimatic deficiency was calculated by the application of the Terraza model, for the major crops, sorghum, maize, soybean, sweet potato and wheat. In the current scenario, the Terraza modelling approach predicts that, all the crops are suitable for the production. Wheat has 0% (H1 class) of yield reduction, currently maize, sorghum soybean and sweet potato have 9.68, 13.97, 7.06 and 10.99% (H1 class) yield reduction, while this reduction will decrease to 1.11, 6.31, 4.58 and 0%, respectively, in the future scenario (Figure 15).

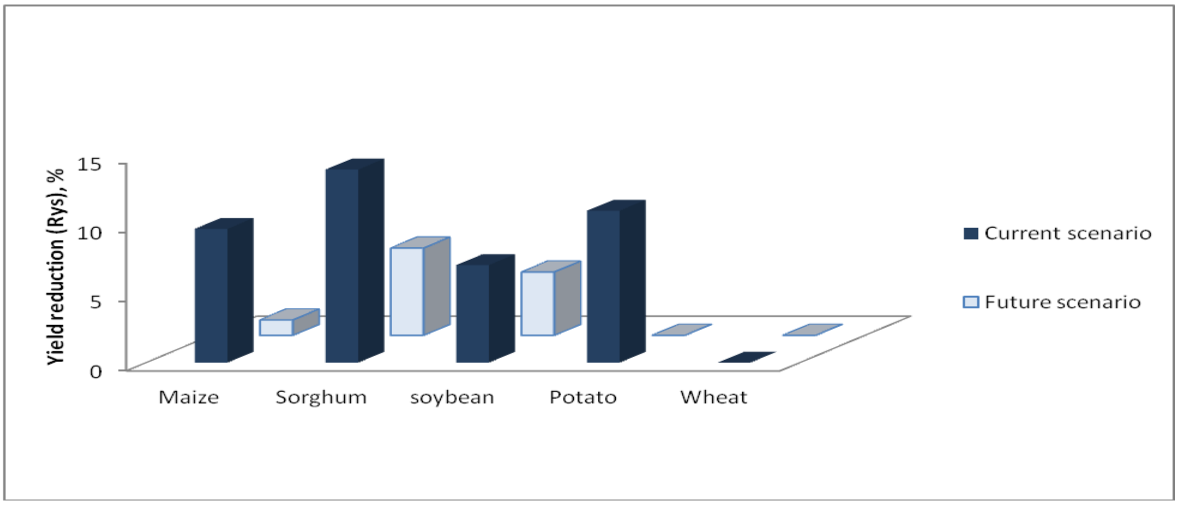

Figure 15. Annual yield reduction under rainfed conditions comparing two scenarios.

The results showed that, the current water deficit in the study area will be reduced as a result of climate change by the 2100 for all the crops except wheat. Sorghum has the highest percentage yield reduction, this can be attributed to the high demand of water during the mid-stage of growth. All the crops that showed yield reduction either in the current or future scenario, there are possible explanations to this distinct behavior. One could be sorghum, sweet potato, soybean and maize have there phenological period that covers from March/April to August/September which coincides with the climatic conditions of maximum reduced precipitation and increased evapotranspiration in the month of June. For all the crops monthly yield reduction (R_y %) was experienced in June except sweet potato that was in May and June. From the climate data, the precipitation reduces in June and picks up again in July. This shows that the greatest reduction in available precipitation is encountered when the crops are planted early rather than late, and the same scenario will be experienced in the future. Wheat is planted in July, and this clearly shows why there is no yield reduction because the crop receives maximum precipitation throughout its growth period. Water availability and quality, and timing of rains for initial sowing during the growth cycle and at harvesting can have significant impacts on yields (FAO, 2011b). Therefore, planting dates changed for a better match with season length and productivity in relation to temperature, water availability and rainfall.

It should be noted that this assessment of bioclimatic crop suitability does not take into account possible positive or negative interactions between bioclimatic and soil type, crop management, and pest and disease incidence, which can have strong mitigating effects. In addition, the crop parameters used are for a species mean, not for varieties that are specifically adapted to more extreme climates. The use of well-adapted varieties may thus increase suitability, while that of less well-adapted varieties may reduce suitability.

4.4. Land Suitability to Climate Change

Agriculture has always been dependent on the variability of the climate for the growing season and the state of the land at the start of the growing season. The key for adaptation for crop production to climate change is the predictability of the conditions. What is required is an understanding of the effect of the changing climate on land, water and temperature. The bioclimatic suitability of a range of crops were assessed against the current and future climate scenario for rainfed crop production.

All the evaluated crops showed no response to climate change concerning to constant bioclimatic deficiency class (H1), so more than 50% of the study area was considered moderately suitable for all the crops. The major limitation factors in classifying the suitability of the area were texture and drainage, which were constant with climate change**.** The results showed that bioclimatic deficiency in this case does not affect the suitability of the crops in this study area for rainfed cultivation in both hypothetical scenarios (the current situation and the future). Therefore, the suitability classes will not be changed in the long-term scenario. This is because of increased precipitation and temperature, which offers a good environmental condition for the growth of the crops. The reduction in percent yield observed in most of the crops is due to precipitation decrease during the mid stage growth period. Therefore, the planting dates can be changed from April/May to June, since at the beginning the demand for water by the plants is lower. This will not affect the growing period in general, because of the increased precipitation during short rains towards the end of the growth period, in turn, it will help the crops to coincide with less precipitation during harvest period, and thereby reducing post harvest loses.

For the investigation of future agricultural suitability for the time-period 2100 under RCP8.5 scenario, we assumed no changes in soil properties, terrain or any adaptations, such as crop breeding. With climate change, no land will be changed from its current suitability status, looking at the percent yield reduction; therefore, bioclimatic deficiency is not a limiting factor. However, there might be increased limitations, such as drainage and erosion. This is true especially for LG001 and LG002 mapping units due to the poor drainage soils in that area characterized with fine texture soils in lowland landscape. The excess water may limit the production of specified crops. This excess water may result due to a high water table or inadequate soil drainage. Meanwhile the mapping units LG003 and LG004 might experience soil erosion due to the nature of the soils, characterized by moderate to coarse texture and steep landscape. The landscapes on the steep slopes may incur the risk of water erosion and may limit cultivation leading to loss of land for agriculture.

Future agroclimatic change in this study area is positive, although, future changes in climate could affect crop production directly by impacting on plant growth and indirectly by influencing land management practices, including trafficability and workability and the planting and harvesting dates (Daccache *et al*., 2012) and by providing a more favourable environment for new or existing pests and plant diseases. Warmer temperatures and elevated CO_2 levels are expected to result in more favorable growing conditions for most crops grown in this study area although, of course, there will also be some negative consequences, which will vary spatially and temporally. If food security is less pressing in this area, increased water availability may justify and facilitate diversification into cash cropping.

This work may overlook possible damages to land quality from extreme events such as floods. The increasing precipitation rates projected may lead to the expansion of floodplain, and as a result, the reduction of existing croplands. Moreover, the influences of intra-year climate variability also affect agricultural land use. Rainfed crop production will be particularly sensitive, both directly from changes in rainfall and temperature but also indirectly, since any changes will also impact on the agricultural potential of soils by modifying soil water balances, with consequences for land management. In this study area, climate change will impact on land suitability through the viability of rainfed production, and hence demand for drainage and erosion management strategies to reduce the impacts.

4.5. Methodological Limitations

The concept of land suitability for a particular crop is complex. The method adopted for this study assumes good management practices such as fertilizer application, cultivars, crop protection etc. The suitability is assessed for a sustained production for crop diversification, hence the MicroLEIS model has no capacity to take into account these factors and other factors such as social and economics. Land suitability is affected in many ways by these factors, such as the differences in farm size and layout can affect cropping preferences and override intrinsic land suitability. Furthermore, competition between land uses has not been taken into account, in this study area the major portion of land is allocated to *Khat* (*Catha edulis* L.) production due to the cash it fetches.

The land suitability was based on the average climate for the period 1995-2014 and average soil data. The results must therefore, be interpreted with these limitations in mind. Projection of land suitability is spatially resolved to 100 m. The role of sharp mountain range slopes, such as the Great Rift Valley in Ethiopia, can greatly affect local climate. The IPCC GCMs are based on a large grid resolution (200 x 200 km^2) and do not include modifications for altitude. GCM projections are valuable projections on the large scale, as long as they are interpreted with caution, particularly when large contrasts in altitude exist over short distances like in Ethiopia.

The climate change impacts were based on the IPCC projections for Africa under the RCP 8.5 scenario to project the future suitability of the study area. Therefore, undertaking future land suitability for the study area based on the site climate projections, the outcome might not necessarily happen together. The future climate data and modelling contains high degree of uncertainty (particularly by the 2100), therefore, it is not necessarily that the outcome will be between these. However, the model provides the objective assessment of land suitability based on the standard data sets and gives an idea of the impacts of climate change for future scenario.

5. SUMMARY AND CONCLUSIONS

Climate change is rapidly emerging as a serious threat worldwide. No country is immune from its impacts. In Ethiopia, climate change poses the risk to the suitability of land in this region, which depends predominantly on agrarian economy, which is rainfed and small-scale farming. Significantly degraded lands, high rural population and utilization of lands regardless of its suitability points to a need to evaluate the impacts of climate change on land suitability.

Evaluation of the impacts of climate change on land suitability for rainfed crop production to achieve sustainable agriculture was the main objective of this study. The specific objectives were to identify potential land suitability for specific crops for diversification and to estimate yield reduction in rainfed condition with special attention to the influence of climate change. The study was conducted in Legambo sub-watershed. MicroLEIS DSS using the Almagra and Terraza model was used to assess the suitability of land to specific crops and to predict the bioclimatic deficiency, respectively. Land utilization types (LUTs) selected for this study were, sorghum (Sorghum bicolor L.), maize (*Zea mays* L.), bread wheat (*Triticum aestivum* L.), sweet potato (*Solanum tuberosum* L.) and soybean (*Glycine max* L.).

Primary data was collected from the field through soil survey and representative soil profiles described and further soil samples collected for laboratory analysis. The climate data was collected from NMA that is temperature and precipitation for 20 consecutive years (1995-2014). Two scenarios were constructed, current scenario (1995-2014) and future scenario (projected changes RCP8.5 for Africa by 2100) for the evaluation of the land suitability due to climate change perturbation.

The results showed variation in land suitability for different crops. In general, 82.35% of the study area is highly suitable to moderately suitable, while 17.25% of the study area was not suitable for rainfed agriculture. Both the classes S2 and S3 (highly suitable to moderately suitable) and S4 and S5 (marginally suitable and non-suitable) were the most representative classes for the crops. Mapping unit LG003 with 78.59 ha extension are not suitable for agricultural uses. Mapping units LG001, LG002 and LG004 with 375.32 ha extension are suitable and moderately suitable. Generally speaking, the main restricting factors for good land suitability in this study area were, texture and drainage. The arrangement of priority agricultural utilization or crop diversification was selected as sweet potato> sorghum > maize > soybean > wheat in that order.

Bioclimatic deficiency on the other hand, is the most-sensitive factor affected by climate change. For rainfed conditions, the percent yield reduction decreases with climate change for all the studied crops, as follows: wheat < sweet potato < soybean < maize < sorghum. Climate perturbation effects on rainfed conditions showed a positive impact on all the crops. The percent yield reduction will reduce in the future scenario, although, the general classification remains constant, and with special reference to the wheat crop, is constant in the two comparable scenarios with 0% yield reduction. The climate change will not change the suitability status of the agricultural lands in all mapping units of the study area due to bioclimatic deficiency for the future scenario (RCP 8.5). Therefore, the only concern will be to deal with the limitation factors that might indirectly arise due to climate change in the study area.

The main conclusion from this study is that, 80% of the land is moderately suited for rainfed production of the crops studied and the land suitability is projected to remain the same under climate change. Current crop suitability matches current cropping patterns for almost all the crops. The change in bioclimatic suitability for the predicted 2100 climate was positive for all crops (maize, sorghum, wheat, sweet potato and soybean). The suitability assessment result showed that although, agroclimatic conditions were optimum for rainfed cultivation of all the crops, there was no optimum suitability (S1) land for the cultivation of any crop in the area. The area was highly suitable to moderately suitable (S2 to S3), marginally suitable (S4) and currently non-suitable (S5) for the evaluated crop production.

In order to raise the productivity level of the land to optimum performance for production, the management techniques should enhance the nutrient and moisture holding capacity of the soil. Such techniques should include; putting up appropriate drainage facilities in place to take care of the poorly drained area of the land while using organic manure in the excessively drained land to improve the water holding capacity of the soils.

The marginally suitable areas for the major staple crops such as sorghum and maize are encouraging, in general, those crops can continue to be grown where they are currently grown because climate change provides better opportunity in terms of increased precipitation and temperature to which from the results is not likely to affect growth and yield. The net effect of climate change on land suitability is positive and therefore, this study area would take advantage and improve the lands that showed low suitability due to limitation factors that its effects can be manageable, such as texture and drainage through good agricultural practices.

It must be noted that each application of MicroLEIS models does not necessarily reflect the land properties of the whole of Haramaya watershed. Although typical soils were selected because they occupy large proportions of the area, soils are significantly different in this area. Therefore, the results of this study area, analysis of soil, use and management must not be extrapolated to a large geographical area without additional studies. Soil or land use planning, relating major land use for each particular site, is considered the first objective in achieving environmental sustainability. Therefore, any kind of agricultural management system will have a negative environmental impact when applied on land with very low suitability for agricultural uses. In the study area, for example, marginal agricultural land under any kind of farming system is the ideal scenario for soil erosion. Therefore, land with no suitability to the crops will need to adapt to climate change by changing their choice of crop or even their activity. Soil conservation technologies have to be adopted in this area in order to improve the suitability of land.

These outputs are very valuable starting point for planners, land mangers and all the stakeholders regarding adaptation and mitigation options for rainfed crop production. Shifts in land use potential have serious implications for strategic land resource planning and food security.

The use of other robust models that can accommodate limitations of the present model can be used for further studies. To accommodate the social and economic factors in land suitability evaluation, gives a good idea especially when recommending the farmers to reallocate lands for each land use type.

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7. APPENDIX

Appendix 1. Topographical and soil requirement for sorghum crop.

Landscape and soil characteristics for sorghum	Class, degree of limitation and rating scale					
	S1			S2	S3	N
	0	1		2	3	4
Soil Depth	100	95	85	60	40	25
Topography (t)						
Slope (%)						
High level management	0	1.3	3.8	10.0	15.0	19.0+
Low level management	0	2.5	7.5	20.0	30.0	38.0+
Wetness (w)						
Flooding	F0	-	-	F1	-	F2+
Drainage	good imperfect	moderate moderate	imperfect good	poor and aeric	poor, but drainable	poor, not drainable
Clayey and loamy s.	g	m	i	pa	p	vp
Sandy soils	i	m	g	pa	p	vp

Physical soil characteristics (s)						
Texture/ structure	C-s Co,CL, SiCs, SiCL, SiL, Si	C+s C-v SC SCL L	C+v SL LS	LcS fS		Cm, S
Coarse fragm.(vol%)						
Quartz	0	0	11	38	59	
Iron oxides	0	5	16	43	35	
Rock fragments	10-	15	25	50	70	
Soil depth (cm)	100+	93	80	47	20	
CaCO3(%)	5-	8	15	23	30	35
Gypsum (%)	0	2	5	13	20	25

Topographical and soil requirement for sorghum crop (Continuation).

Soil fertility characteristics (f)						
Apparent CEC (cmol(+)/kg clay)	24+	21	16(-)	16(+)	1.5	
Sum of basic cations (cmol(+)/kg clay)	6+	5.6	4.9	3.0		
Base saturation (%)	>80	80-50	50-35	35-20	<20	-
pH (H2O) (0-25 cm)	5.8-6.5	6.7 5.7	7.1 5.6	8.2 5.2	9.7 4.7	
Organic carbon (%) (0-25cm) Kaolinitic material Calcareous material Other material	2.0+ 0.8+ 1.2+	1.9 0.7 1.1	1.6 0.6 1.0	1.0- 0.4- 0.6-		
Salinity and Alkalinity (n)						
Ece (mmhos/cm) mean 0-100cm	1.7-	2.1	3.0	5.0	6.7	8.0
ESP (%) Ma.0-100 cm	0	5	15	20	25	

Source. (Sys *et al*.1993)

Appendix 2. Summary of major soil variables in different soil mapping units

Profile No	Mapping Unit	Area extn (ha)	Limit of useful Depth	Useful depth (cm)	Drainage (Class)	Soil profile development
1	LG001	64.28	Permeable limestone	100	Poor	Incipient
2	LG003	78.59	Gravel or sand	75	Excessive	Moderately strong
3	LG002	71.79	Permeable limestone	90	Poor	Incipient
4	LG004	239.25	Permeable limestone	120	Good	Strong

Source. Author.

Appendix 3. Summary of agro-meteorological data Result for Haramaya (ET-HA) station data (1995-2014) generated by the CDBm database

Months	T_{mean} (°C)	T_{max} (°C)	T_{min} (°C)	P (mm)	ET_o (T) (mm)	GS
January	14.60	23.10	5.90	9.40	47.98	
February	15.70	24.70	6.70	12.20	49.51	
March	18.00	25.70	10.20	45.10	71.00	
April	19.00	25.40	12.70	106.60	77.96	
May	19.50	25.60	13.50	89.40	85.51	
June	19.50	25.10	14.10	50.50	83.92	
July	18.50	23.60	13.40	121.40	78.06	
August	18.40	23.40	13.40	155.60	76.62	
September	18.10	23.70	12.40	119.80	70.99	
October	16.00	24.10	7.80	50.00	57.35	
November	14.10	23.40	4.60	24.30	44.27	
December	13.30	22.40	4.10	16.60	40.43	
Total	17.06	24.18	9.90	800.90	783.61	12

Tm – mean temperature, Tmax – maximum temperature, Tmin – minimum temperature, P – precipitation, ET_o (T) – Evapotranspiration calculated by Thornthwaite method; GS–Growing season.

Appendix 4. Summary of agro-meteorological data from Haramaya (ET-HA) station, considering the climate change perturbation for 2100, as generated by the CDBm database

Months	T_m (°C)	T_{max} (°C)	T_{min} (°C)	P (mm)	ET_o (T) (mm)	GS
January	18.10	26.60	9.40	24.60	57.40	
February	19.20	28.20	10.20	27.60	59.81	
March	21.50	29.20	13.70	93.40	87.32	
April	22.50	28.90	16.20	154.40	96.72	
May	23.00	29.10	17.00	139.40	106.56	
June	23.00	28.60	17.60	94.50	104.59	
July	22.00	27.10	16.90	173.50	96.42	
August	21.90	26.90	16.90	207.50	94.55	
September	21.60	27.20	15.90	171.10	87.38	
October	19.50	27.60	11.30	103.10	69.42	
November	17.60	26.90	8.10	74.10	52.95	
December	16.80	25.90	7.60	30.60	48.18	
Total	20.56	27.68	13.40	1293.80	961.28	12

T_m – mean temperature, T_{max} – maximum temperature, T_{min} – minimum temperature, P – precipitation, ET_o (T) – Evapotranspiration calculated by Thornthwaite method; GS–Growing season.