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Assessment of agricultural land suitability for cereal crops based on the analysis of soil physico-chemical characteristics

Simeneh Gedefaw Abate^{1*} and Mihret Bizuye Anteneh²

Abstract

This research aimed at evaluation of a given land resource suitable for selected rain fed crops production (malt barley, wheat and teff) in Ambesh watershed. It also quantified suitable land and classified into the land mapping units (LMUs), and presents a land suitability map. Land suitability assessment (LSA) made using climatic condition, topography, soil physical and chemical properties as a major factor integrated with a multi criteria decision making (MCDM) analysis in Ambesh watershed. Fourteen composite soil samples were taken by categorizing the watershed into different land mapping units (LMUs) and analyzed in a soil laboratory. Climatic data, rainfall was obtained from two meteorological stations nearby to the study area. Temperature data derived from Landsat 8 satellite thermal bands data. Data obtained from the soil laboratory and others were finally analyzed using ArcGIS environment and priority estimation tool (PriEst) software's. Weighted Sum Overlay was implemented to investigate the final LSA map of the watershed. Results revealed that LMUs, *VRe-LPq* and *LPK.Pq-FLc* LMUs has higher overall suitability for all the selected rain fed crops. However, LMUs (*VRe-NTu* and *NTu-VRe*) has lower overall suitability values particularly for S_1 suitability class (0.05% and 10.6%, respectively). The least suitable LMU is *VRe-NTu* with 0.05% S_1 suitability class and above 99% of the land laid under the suitability classes of moderately suitable, marginally suitable and not suitable for the selected land utilization types. Moreover, about 219.06 ha (17.76%), 217.6 ha (17.64%), 168.9 ha (13.7%), of land are highly suitable for malt barley, teff and wheat crop production, respectively. In conclusion, during MCDM, classifying the land into closer homogeneities (LMU) an important application of LSA integrated with remote sensing and GIS for a better decision making. Meanwhile, majority (above two third's) of the land in the watershed is under moderate and marginally suitable, it needs intensive land management activities to increase the land qualities and obtain high yields. LSA recommended before land utilization decision has to be made. It is also important to classifying the land into LMUs to make it more homogeneous for sample taking and reducing the prestigious soil laboratory analysis costs.

Keywords LMUs, Land suitability assessment, Malt Barley, RS, Teff, Weighted sum, Wheat

Introduction

The world's population is under very rapid increasing rate and will pass from 7.5 billion by 2020 and projected to reach 9.4 to 10.2 billion by the year 2050 (Lal 2001; He et al. 2016; Boretti and Rosa 2019; Siegel 2021). Thus, global crop demand increased from 100 to 110% by the year 2005 to 2050 (Tilman et al. 2011; Tian et al. 2021). However, the problem is very serious in Africa, which has a negative relationship of the growth rate for cereals

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grain yield (about 1%) and population growth (about 3%) (Carvalho 2006). Moreover, as other studies revealed and has been observed that in the course of the last 35 years, Africa's cereals production per capita has decreased from 150 to 130 kg person⁻¹, however in Asia and Latin America, cereal production increase from 200 to 250 kg person⁻¹ (FAO 2001). Furthermore, the annual cereal deficit in sub-Saharan Africa accounts for 100 million tons and the food scarcity gap (food demand greater than food crop production) is widening. Hence, Food imports increased by about 185% between the year 1974 and 1990 while food aid increased by 295% (Bationo et al. 2007).

In Ethiopia, therefore, low agricultural productivity is characterized by a multitude of factors including human population pressure, which resulted in serious land degradation (WFP 2014). Thus, evaluating land suitability for malt barley, wheat, and teff in Ambesh watershed is very important since the area has a potential to grow the above stated major cereal food and cash crops. It is also important to satisfy the demand of malt barley (malting), teff (staple food supply) and wheat (flour industries) that enhance their efficiency. Ultimately, it can reduce the cost of importing malt for beverage industries in Ethiopia.

Agricultural land suitability assessment (ALSA), the process of assessing land performance used for alternative cropping activities in agriculture (Elsheikh et al. 2013; Akpoti et al. 2019). Therefore, the principal purpose of ALSA is to predict the potential and limitations of a given land for crop production (Ozsahin and Ozdes 2022). Moreover, land suitability also assessed considering rational cropping system, for optimizing the use of a piece of land for a specific use (FAO 1976; Sys et al. 1991). In remote sensing and GIS, "What is to grow or develop where?" can be answered by land suitability analysis with minimum cost and short time (Olusina and Shyllon 2014; Abate et al. 2022). Therefore, higher yield of crop production exists when the sustainability of the land is studied and if the land be categorized and utilized based upon their actual and potential capacity to produce crops (Verheyne et al. 2009; Shah and Wu 2019).

Most LSA has been done with a coarser data analysis of land characteristics mostly without particular soil chemical and physical properties except some researches recently published such as variability modeling and mapping of soil properties (Tiruneh et al. 2023a, b). Moreover, other studies use different methodologies of LSA such as Fuzzy analysis (Ahamed et al. 2000; Prakash 2003; Mokarram et al. 2010; Jamil et al. 2018), GIS and computer based land suitability analysis (Pan and Pan 2012), multi-criteria decision-making approach using GIS (Perveen et al. 2007; Mustafa et al. 2011; Romano et al. 2015; Ostovari et al. 2019), and land suitability analysis (Halder 2013). However, this study used a detail analysis of most

land attributes such as the physical and chemical properties of soil, climatic condition (rainfall and temperature) and topographic factors (altitude and slope). Such land suitability analysis can indicate a better accuracy in finding the best land utilization types input to land policy makers and managerial decisions. Consequently, land use change policy decisions to other economically important land utility can be better and easier.

Crop land suitability mapping and analysis, one of the most important contemporary applications of remote sensing and GIS for planning and decision-making management in developing countries (McHarg 1969; Hopkins 1977; Brail and Klosterman 2001). In Ethiopia, LSA for different purposes can also use the integration of multi-criteria decision making analysis with remote sensing and GIS such as for urban greening site identification and application (Abebe and Megento 2017; Gelan 2021; Anteneh et al. 2023), dam site selection (Karakuş and Yıldız 2022), and solid waste dumping site selection (Gorsevski et al. 2012; Bosompem et al. 2016). The advancement of GIS and Remote sensing technology based land suitability assessment in developing countries, like Ethiopia is limited due to different constraints such as lack of high resolution spatial data and lack of finance to test soil in the laboratory (Yitbarek et al. 2012; Wondrade et al. 2014; Gashayie and Singh 2015; Bhaga et al. 2020).

According to Lakew et al. (2016), inadequate crop production and soil testing based information and knowledge for both malting and food cereal crops such as barley, wheat and teff important for timely operation of farming practices. Therefore, this research aimed at filling the gap by implementing Analytical Hierarchy Process (AHP) integrated with GIS and remote sensing to evaluate the suitability of the land in Ambesh watershed for malt barley, teff, and wheat crops using geospatial soil testing of the soil physical and chemical properties, climate, and topography as limiting factors via MCDM technique. The study can contribute to the global community experiences particularly for those areas not cultivating the selected rain fed cereal crops by reducing the cost, time and labor of soil sampling for laboratory analysis via the application of remote sensing and GIS integrated with LMUs classification (land units having more closely or uniform land characteristics) with Composite Soil Sample (CSS) taking systems. It also investigates the factors that affects crop production, evaluate the suitability of a given land resources (land mapping units) for locally dominant rain fed crops, produce a land suitability map and quantify the land suitable for malt barley, wheat and teff crops in the watershed. This study is important for land use planners to provide decision making and farmers to produce suitable crops based on physical land suitability. It is also very important to malt and wheat

flour industries to target potential malt barley producing areas and can produce higher yields to satisfy their demands.

Research methods

Description of the study area

Ambesh Watershed is located in Aneded District, East Gojjam Administrative Zone (Fig. 1). It is located in between Debre Markos City (North West direction) and Aneded District (Southeast direction), North West direction from the capital city of Ethiopia, Addis Ababa. It is one of the productive watershed to produce cereal crop in Aneded District (Amsalu and Regassa 2022). Ambesh watershed can produce major food crops such as Barley, Wheat and Teff. It is 8 km far from Debre Markos city to the Eastern direction. The altitude of the watershed ranges from 2310 to 2502 m above sea level. It is located between 10°15'00'' N to 10°18'15'' N latitude and 37°47'00'' E to 38°48'00'' E longitude. Ambesh watershed has total area of about 1234 ha of land. The watershed had three major soil types such as Lithosols, Nitosols and Vertisols. It has three major land use systems, cultivation, grassland and plantation (Aneded district SLM project 2014). Slope of the study area ranges from gentle slope (0°) to steep slope (25.45°).

Data source

Research data obtained from different primary and secondary data sources (Table 1). Primary data used for the study collected by direct field observation and field survey, taking ground control points (GCPs) using GPS instrument and soil samples collected with soil auger. While, secondary data were obtained from ALOS PALSAR DEM data with 12.5 m spatial resolution, used to calculate the altitude and slope of the watershed. Annual rainfall data were taken from meteorological stations.

Methods

Soil survey methods

The watershed, Ambesh was delineated using DEM data obtained from ALOS PALSAR of 12.5 m spatial resolution (Table 1). Due to the difference in topography (slope and elevation of the land), stratified random soil sampling method was applied to identify and determine the auger points and generate land map units (LMU, having similar property in a single strata) (Smiraglia et al. 2013). This stratified soil sampling technique can maintain to keep the consistency and uniformity of sample taking within the LMUs. LMUs (part of the spatial unit of analysis for land suitability evaluation) refers to internally uniform areas of land with some soil physical characteristics or qualities such as topography of the land and

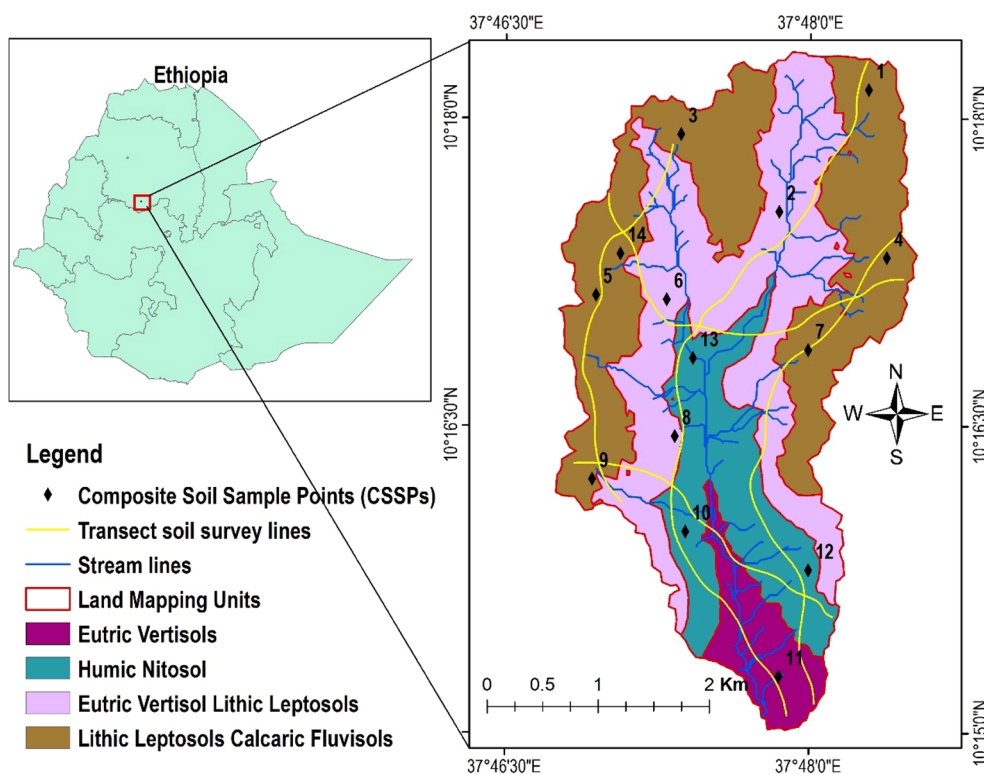


Fig. 1 Location map of Ambesh watershed

Table 1 Data source (primary and secondary data) of the study area

Data type	Data source	Note
DEM(Digital elevation model)	ALOS PALSAR DEM data https://search.asf.alaska.edu/#/	DEM data to delineate and to calculate slope and altitude of the watershed
Other data (major soil types and LUTs)	Amber district Agriculture and Rural Development Office	Major Land Utilization Types in the study area
Altitude/Elevation/slope	ALOS PALSAR DEM data	DEM 12.5 m spatial resolution
Soil properties data	Direct Soil sample collection from Ambesh Watershed	ECe, pH, CEC, OC, N, P, K, CaCO ₃ , Soil texture, soil depth etc
Rainfall and temperature	Ethiopian Meteorological Agency (Bahir dar branch) and www.usgsearthexplorer/ (the 2022 Landsat 8 image data), respectively	Mean Monthly and yearly rainfall and Land surface temperature of Landsat 8

soil color (Mantel and Kauffman 1995). The delineation of LMUs are based on land qualities that have the most influence on the land uses under consideration. Hence, the researcher is free to choose sample points in order to create a systematical model of the soil landscape relationships, draw boundaries, and determine LMU compositions (Fig. 2). As a result, the watershed was divided into four major LMUs based on the soil forming factors of topography (mainly altitude and slope, a re-classification method of natural break of the land) and observed parent materials (FAO 1993; Nachtergaele et al. 2015) (indicated in Table 2). Elevation is the primary determinant

factor of agricultural land use options in Ethiopia due to its influence on temperature and rainfall (Abate 2011). However, other soil forming factors like climate, vegetation and time in the watershed are more or less similar and it was difficult to differentiate the LMUs with these soil-forming factors.

The transect soil survey method was conducted along transects (i.e. following top–bottom of Ambesh watershed landscape) and by using external factors such as variation in topography and land use to decide, profile points (Fig. 2). Soil samples were collected purposively based on the designed LMUs. Therefore, the researchers

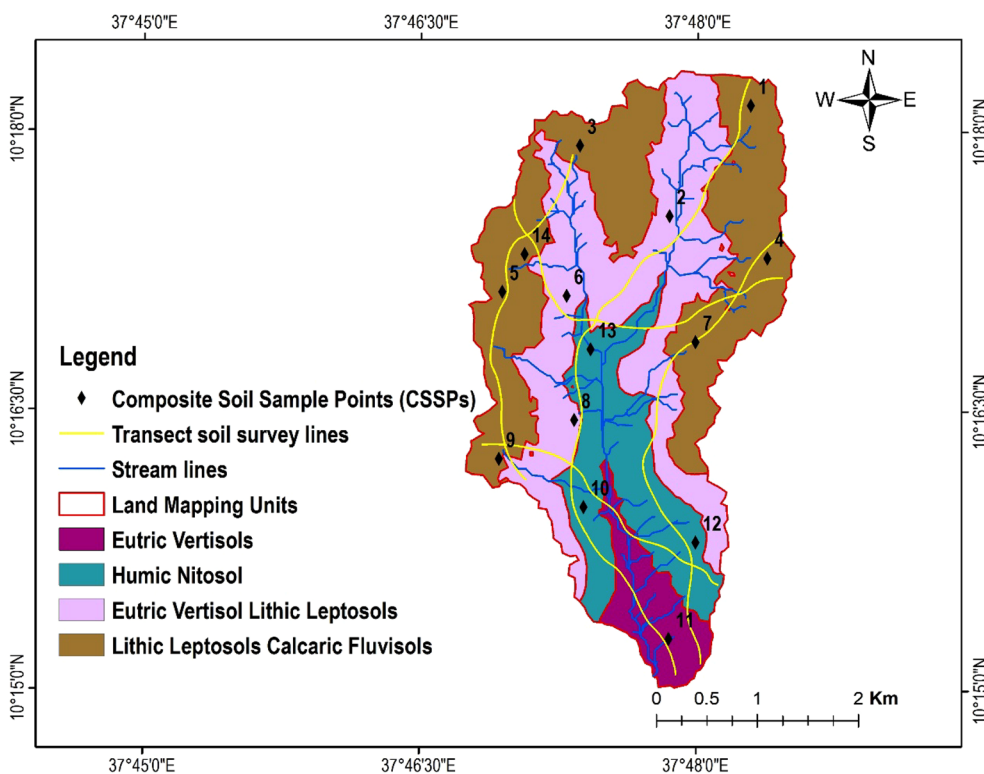


Fig. 2 Land mapping units, transect lines and CSSP during the soil survey in Ambesh watershed

Table 2 Land mapping units and their descriptive names of Ambesh watershed

Name of LMUs	LMUs code	Description of LMUs
Eutric vertisol lithic leptosols	VR_e-LP_q	Eutric Vertisol (E_uV_e) Lithic Leptosols (L_{l-pq}) with second level subunit name Lithic ($2L_e$) which is Lithic Leptosols having light clay and clay loam with a deeper soil depth more than 200 cm and its slope ranges from 0 to 4.3 degrees with an altitude range of 2310 to 2365 m.a.s.l
Eutric vertisols	VR_e-NT_u	Eutric Vertisols (E_uV_e) with list of third level Humic Nitosols ($3H_uN_{lu}$) top soil up to 30 cm depth. Soil structure light clay soil. The land unit slope is flat to gentle slope ranges from 0 to 7.8 degrees with an altitude range of 2365 to 2412 m.a.s.l
Humic nitosol	NT_u-VR_e	Humic Nitosol (H_uN_{lu}) with list of third level Eutric Vertisol ($3E_uV_e$) having humic horizon: soil structure light clay loam. The dominant slope range is from 7.8 to 11.8 degree (gentle to steep slope) with an altitude range of 2412 to 2451 m.a.s.l
Lithic leptosols calcaric fluvisols	$LP_kP_q-FL_c$	Rendzic Leptosols (R_{d-l-pq})/Lithic Leptosols Calcaric Fluvisols ($L_{l-p}CF$) with the third level subunit Leptic ($3L_{pq}$) having leptic horizon; associated with loam, clay loam. With a slope dominated by the range of 11.8 to 25.42 degree steep slope with an altitude range of 2451 to 2502 m.a.s.l

Source: Nachtergaele et al. (2015)

can reduce biases and free to choose which, LMUs are to be collected and analyzed (Fig. 3 below). This prevents the sample from being treated in the same way as those samples that are collected by some probabilistic method (Bilonick 1994). Four hundred (400) soil auger samples taken to get fourteen composite soil samples (CSS) CSS requires a very large number of soil sample to make it more precise (Patil 1995; Carter and Gregorich 2007). Each representative CSS contained twenty-five to thirty-three soil auger samples. Seven soil profile pits were digging up with a depth of 60 cm to 200 cm to estimate its soil depth. Fourteen (14) representative CSSs (Fig. 2) with five transects GPS tracks (located on summit, shoulder, foot slope and toe slope) were collected from a depth of 20 cm (Teka et al. 2015).

Soil laboratory analytical methods

The collected CSSs were air dried at room temperature, then ground using mortar and pestle, and sieved to pass through 2 mm sieve soil mesh. Soil textures were analyzed using hydrometer method (Sertsu and Bekele 2000). Soil textural class was determined by using soil textural triangle calculator giving the percentage of each

texture clay, silt and sand obtained from the laboratory soil test results. Once the percentage of sand, silt, and clay determined, the soil textural class was assigned using the USDA textural triangle. Soil pH was measured by water (1:2.5 ratio) using glass electrode pH meter. $CaCO_3$ in the sample was dissolved in excess hydrochloric acid (HCl). The remainder of the acid is titrated against sodium hydroxide (NaOH). Soil OC was determined using wet digestion method by Walkley and Black (Sertsu and Bekele 2000). After obtained the soil organic carbon content of the soil, organic matter content was computed from it by multiplying its value with a constant number 1.724 (Sertsu and Bekele 2000). Total N measured after wet digestion using the renown Kjeldahl procedure. Soil phosphorous (P) content was determined using Olsen’s method by the sodium bicarbonate ($NaHCO_3$) (Olsen 1954). Potassium (K) was measured by the flame photometer. Soil salinity is the concentration of soluble inorganic salts in the soil (Rhoades 1996). It is measured by extracting the soil sample with water (1:1 or 1:5 soil: water ratio, w/v) or in an extract saturated paste. With such rapid extract, salinity is measured by electrical conductivity meter (ECe meter).



Fig. 3 Collected composite soil samples (CSSs)

Rainfall and temperature analysis

Rainfall variability of the watershed were calculated by the annual (yearly) rainfall amount of the nearby meteorological stations, then interpolating (IDW interpolation method) the rainfall data of Debre Markos (located north western direction of the watershed) and Amber station (located south eastern direction of the watershed). The rainfall amount of Ambesh watershed determined by the data obtained from Ethiopian meteorological agency (Bahir Dar branch). It was interpolated and then clipping with the study area shape.

An average yearly four seasons (four representative months) namely; summer (July), autumn (October), spring (April) and winter (January) land surface temperature of the area was computed with Landsat 8 (2022) satellite data. Top of the atmosphere (TOA) radiance calculated by using radiance rescaling factor, thermal infrared digital numbers that are converted into TOA spectral radiance (Rajeshwari and Mani 2014) as follows:

$$L\lambda = RaMb * Qcal + RAb, \tag{1}$$

where $L\lambda$ —TOA spectral radiance (watts m^{-1}), $RaMb$ —radiance multiplicative band (Band number), RAb —radiance add band (Band number), Q_{cal} —quantized and calibrated standard product pixel values (DN).

Secondly, TOA brightness temperature was calculated with spectral radiance data that can be converted to top of atmosphere brightness temperature using the thermal constant values from the meta data file of Landsat 8 data (Latif 2014).

$$Bt = \frac{K2}{\ln\left(\frac{K1}{L\lambda} + 1\right) - 273.15}, \tag{2}$$

where: Bt —top of atmosphere’s brightness temperature ($^{\circ}C$), $L\lambda$ —TOA spectral radiance (watts m^{-1}), $K1$ — $K1$ constant band from the meta data (no.), $K2$ — $K2$ constant band from meta data (no.).

Thirdly, a standardized vegetation index (normalized vegetation index, NDVI) calculated using the near infrared band (B5, DN value from the infrared band) and red band (B4, DN value from the red band).

$$NDVI = \frac{NIR(B5) - Red(B4)}{NIR(B5) + Red(B4)}. \tag{3}$$

On the fourth stage, the land surface emissivity (PV), an average emissivity value of an element of the surface of the earth calculated from the NDVI.

$$PV = [(NDVI - NDVImin)/(NDVImax + NDVImin)]^2 \tag{4}$$

where PV—proportion of vegetation, NDVI—DN values from NDVI image, NDVI min—minimum DN values from NDVI image, NDVI max—maximum DN values from NDVI image.

$$E = 0.004 * PV + 0.986, \tag{5}$$

where E —LSE, PV—proportion of vegetation.

Finally, the land surface temperature (LST) of the earth calculated as the radiative temperature using top of atmosphere brightness temperature, wavelength of emitted radiance and LSE (Dash et al. 2002) as follows.

$$LST = \left(\frac{BT}{1}\right) + W * \left(\frac{BT}{14380}\right) * \ln(E), \tag{6}$$

where BT —top of atmosphere brightness temperature ($^{\circ}C$), W —wave length of emitted radiance, E —land surface emissivity

Kriging interpolation

Kriging estimates the unsampled locations in the spatial field because of its advancement, successful prediction and description of geostatistical spatial variability performance in digital soil mapping (Martín et al. 2016; Guan et al. 2017; Dong et al. 2021), isopleth development, and evaluation of the spatial distribution of soil and waste properties. Thus, the nature of the kriging equations has important implications for the design of soil survey (Burgess and Webster 2019). Its primary purpose for utilization is within the system of samples. It should not be used to extrapolate outside of the boundaries of the sampling area (Barth and Mason 1984).

$$Z(S_o) = \sum_{i=1}^N \lambda_k Z(S_k), \tag{7}$$

where: $Z(s_k)$ = the measured value at the k th location, λ_k = an unknown weight for the measured value at the k th location, s_o = the prediction location, N = the number of measured values.

According to Burgess and Webster (2019) the results of kriging “...depend to some extent upon the tools and methods that happen to be convenient for sampling”, most appropriate when there is a spatially correlated distance or directional bias in the data and often used in soil science and geology. While, in Inverse Distance Weight (IDW) interpolation method, the weight, λ_k , depends solely on the distance to the prediction location. However, with the kriging method, the weights based not only on the distance between the measured points and the prediction location but also the overall

spatial arrangement of the measured points. To use the spatial arrangement in the weights, the spatial autocorrelation has to be quantified. Thus, in ordinary kriging, the weight, λ_k , depends on a fitted model to the measured points, the distance to the prediction location, and the spatial relationships among the measured values around the prediction location. However, according to Tiruneh et al. 2021, the inverse distance weighting (IDW) and ordinary kriging (OK) models well described the variation of all soil fertility parameters except OC and available phosphorus.

Selection of land utilization types (LUTs) and land use requirements, (LURs)

Land resources in Ambesh watershed allow the cultivation of different food and cash crops. However, the farmers in the watershed are striving to be self-sufficient in food crops production rather than producing cash crops like malt barley. They produce major food crops of like teff, wheat, engdo (barley *spp.*), barley, and maize. Therefore, producing cash crops required for malting, a raw material for beverage factories of malt barley (*Hordeum distichum* L.) is very important source of income for the farmers. Teff (*Eragrostis teff*) and wheat (*Triticum aestivum*) also other major food crops produced in the watershed for consumption as well as for sale to flour industries and food complex factories.

The LURs are measurable factors on which decisions about land quality and its suitability for a specified land use can be made (Eastman 1999). After the determination of the problem, the set of evaluation criteria, which includes attributes and objectives, should be designated (Jankowski 1995). It involves specifying a comprehensive set of objectives that reflects all concerns relevant to the decision problem and measures for achieving those objectives, which were defined as attributes. Because the land use requirements are related to geographical entities and the relationships between them, they can be represented in the form of maps referred as attribute maps.

Rationally, criteria identification can be done using the participatory approach by a group of experts from various concerned disciplines. However, based on the crop requirements for specific soil parameters, climate and topographic data, FAO (1976) has given a framework for ALSA as highly suitable (S_1), moderately suitable (S_2), marginally suitable (S_3) and not suitable (N). In this study, criteria identification was done based on various literatures and guidelines and data availability of the watershed (Sys et al. 1993; Landon 2014). Hence, the following evaluation criteria were considered to address the suitability of the land for agricultural crops such as soil physical properties (soil texture, soil structure, soil depth). Among the soil chemical properties, Electrical

Conductivity (ECe), soil pH, Organic Carbon (OC), Cation Exchange Capacity (CEC), total Nitrogen (TN), available Phosphorous (P_2O_5), available potassium (K_2O), and $CaCO_3$) were selected. Others climatic factors (temperature and rainfall), and topographic factor (altitude and slope).

Multi criteria decision analysis

Multi criteria decision analysis (MCDA) can provide to do the LSA with a multi or numerous criteria be identified on the field based on land qualities. Here, since the study area is at watershed level, the soil physical and chemical properties are the basic land qualities to investigate the analysis. As a rational decision maker is an individual who maximizes profits and/or minimizes losses (Gabor and Meunier 1993). The ultimate aim of remote sensing and GIS is to provide support for making spatial decisions (Malczewski 2004). The integration of MCDA in GIS provides a powerful spatial decision support system, which offers the opportunity to produce land suitability maps efficiently (Mendas and Delali 2012). Therefore, MCDA also aids decision makers in analyzing potential actions or alternatives based on multiple incommensurable factors/criteria, using decision rules to aggregate those criteria to rate or rank the alternatives (Greene et al. 2011).

Analytical hierarchy process (AHP)

During the application of AHP an inconsistency can occur due to improper computation (Belton and Gear 1983). AHP helps to capture both subjective and objective evaluation measures, providing a useful mechanism for checking the consistency of the evaluations thus reducing bias in decision-making (Ishizaka and Lusti 2006). AHP uses pairwise comparisons to derive the relative importance (Table 3) of the decision factors. It involves three steps: development of a comparison matrix at each level of the hierarchy, beginning at the top, computation of relative importance or weights for each element in the hierarchy, and estimation of consistency ratio (C.R).

Consistency ratio (C.R)

C.R. is a measure of how far a matrix from consistency. Therefore, it can reduce or evaluate inconsistency of judgments in criteria weighting through pairwise comparison. A matrix "a" is consistent if and only if $a_{ik} a_{kj} = a_{ij}$ at which a_{ij} is the ij th element of the matrix (Buckley 1985). In practice, however, it is unrealistic to expect that decision-makers provide exact consistent pairwise comparison matrices especially in the cases with a large number of alternatives. As a general rule of thumb, a

Table 3 The fundamental scale of absolute numbers in AHP

Power of importance	Description
1	Equally important
3	Moderately important
5	Strongly important
7	Very strongly important
9	Extremely important
Reciprocals importance values of the above numbers	If criteria <i>i</i> has one of the above non-zero numbers assigned to it as compared with activity <i>j</i> , then <i>j</i> has the reciprocal importance value as compared with <i>i</i>
1.1–1.9	If the criteria's have very closely important to each other

Source: Rating scale of Saaty (2008)

C.R. value of 10% (0.1) or less is considered as acceptable (Zeshui and Cuiping 1999).

Consistency Index (C.I.) is calculated as:

$$C.I = \frac{\lambda_{max} - n}{n - 1} \tag{8}$$

C.R. for each matrix in the hierarchy was computed by using the following formula:

$$C.R = \frac{C.I}{R.I} * 100 \tag{9}$$

where, *n* is the number of criteria, *R.I* is the Random Index, and λ_{max} is the biggest eigenvalue. Random Index is the average consistency index of randomly generated comparison matrix (Table 4).

Weighted sum overlay analysis (WSO)

The GIS software, computer assisted overlay techniques were developed as a response to the manual method's limitations of mapping and combining large datasets (MacDougall 1975; Steinitz 1976). Weighted overlay is a technique for applying a common scale of values to diverse and dissimilar inputs to create an integrated analysis (Malczewski 1996, 2004). WSO analysis can overlay several raster multiplying each by their given weight and summing them together. The WSO tool provides the ability to weight and combine multiple inputs to create an integrated analysis. The WSO tool does not rescale the reclassified values back to an evaluation scale and it allows floating-point and integer values. In WS decision and weight matrixes the decision

maker assigns a set of importance weights to the criteria as $W = (W_1, W_2, \dots, W_n)$. The weights W_j was normalized:

$$\sum_{j=1}^n W_j = 1 \tag{10}$$

Then, assign the value for each factor or criteria and weight to each factor (Eq. 10). Thus, the weighted value of the watershed suitability was obtained for Ambesh watershed land suitability.

$$CrLSi = \sum W_j X_{ij} \tag{11}$$

where, C_rLSi = Crop land suitability value of *i* in Ambesh watershed, W_j =is the weight of the factor *j*. X_{ij} =the reclassified value of factor '*j*' in the area '*i*'

Conceptual framework

The study area has a conceptual workflow (framework) as indicated in Fig. 4 below. It has contents in the left side as setting objectives, determination of LURs (main criteria and sub criteria), standardization of scores and suitability rating of main and sub criteria's (as S_1, S_2, S_3 and N), WSO and ALSA.

Results and discussion

Soil physical properties

Soil physical properties such as soil texture, soil depth and soil structure are particularly important for teff, the major food cereal crops production (Demelash 2017). Owing to its grain size, germination and root support for stand from the soil teff crop needs very compacted soil and

Table 4 RI value of consistency index for various number of input factor (F) used developed by (Saaty 2008)

F	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0	0	0.58	0.89	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.58

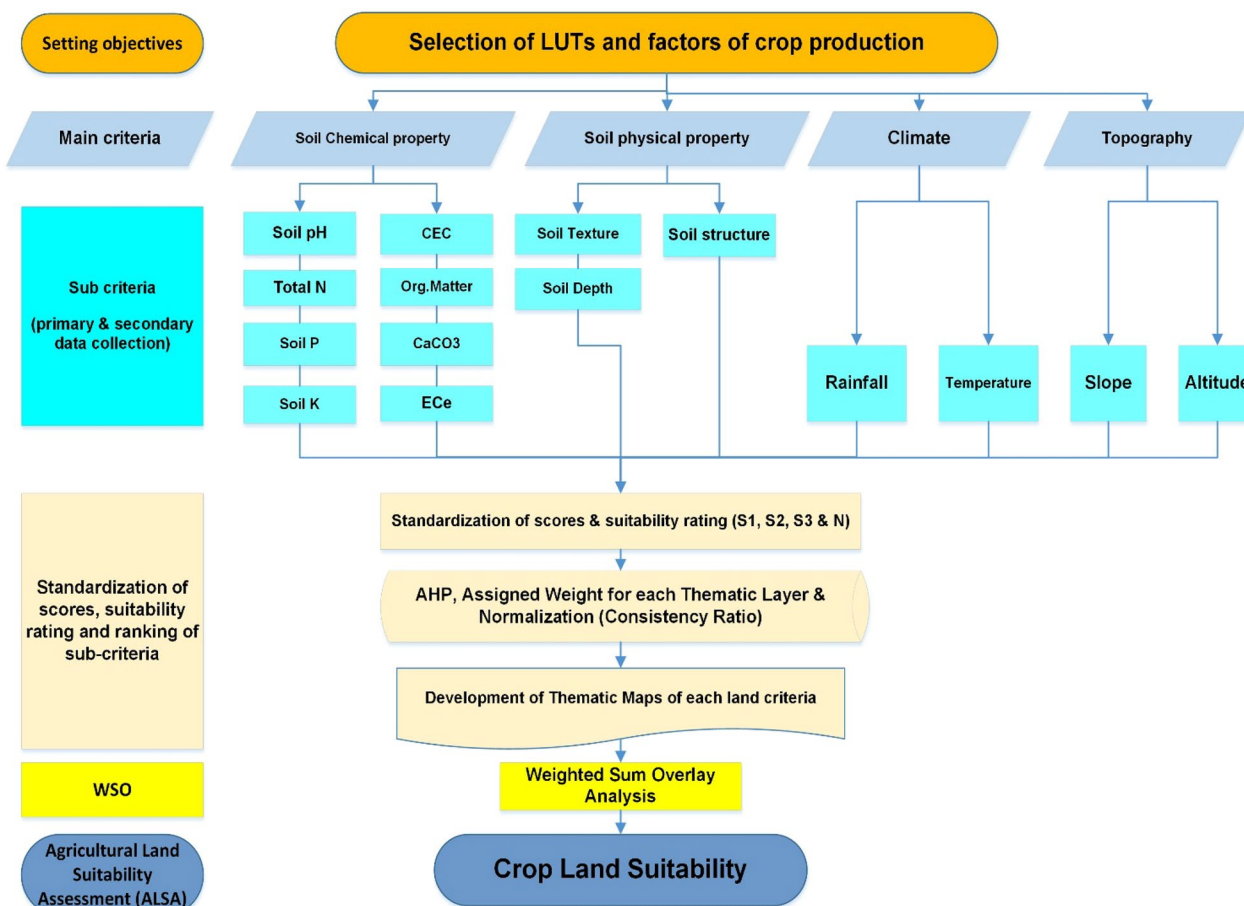


Fig. 4 Conceptual frame work

planting applied on it (Gelaw et al. 2013). Therefore, for teff crop, among those properties soil structure ranks first (criteria weight of 0.488). Soil texture ranks second with a weight of 0.357 and soil depth ranks the third by weight of 0.155. It has a CR of 0.001 (Table 5). Altitude and slope of the study area has also an influence in the production of teff crop. Therefore, altitude ranks first (weight of 0.524) and slope ranks second (weight of 0.476) (Table 5). However, malt barley and wheat crop requires `same pairwise

comparison matrixes of soil physical properties soil texture (ranks 1st), soil structure (ranks 2nd), and soil depth (ranks 3rd) as shown in Table 5 below. Soil texture is an important parameter affecting the suitability of wheat and malt barely; therefore, the weight of texture was calculated as 0.423 (Mandal et al. 2020). However, soil structure and soil depth ranks second and third with a criteria weight of 0.335 and 0.242, respectively for wheat and malt barley crop (Table 5).

Table 5 Physical soil property PWCM for malt barley, wheat and teff crops

	Malt barley and wheat crops					Teff crop					
	S_txr	S_depth	S_str	CWt	Rank	S_txr	S_depth	S_str	CWt	Rank	
S_txr	1	1.7	1.3	0.423	1	S_txr	1	2.25	0.75	0.357	2
S_depth		1	0.7	0.242	3	S_depth		1	0.31	0.155	3
S_str			1	0.335	2	S_str			1	0.488	1
CR=0.001						CR=0.001					

Soil texture

Soil texture, soil structure and soil depth are soil physical properties considered to analyze ALSA in the watershed. Soil texture is the classification of the proportion or the percentage of clay, silt and sand in the soil (Ritchey et al. 2015). Therefore, the soil textural class of the study area clay and clay loam soil (Table 6). However, clay soil texture is the dominant one. Soil structure is classifying the soil structural classes into very fine, fine, medium, coarse, very coarse (Thomasson, 1978). Accordingly, very fine, fine and medium structure soils were present in the study area. The depth of the soil ranges from very deep soil greater than 200 cm to shallow soil depth 60 cm (Table 7). Results obtained shows that soil textural classes of the study area are of two types. These are clay loam and clay texture. This is because the proportion of clay in most samples is greater than silt and sand (Table 6).

Soil structure and soil depth

Soil structures in the study area are classified in to three. These are very fine (VF), fine (F) and medium (M) structured soil. It is very important soil physical characteristic especially for teff crop production (Gebretsadik et al. 2009; Mihretie et al. 2021; Barretto et al. 2021). Soil depth is an important crop factor for effective rooting condition of crop growth and development. Depth of the soil in the study area ranged from 60 to 200 cm depth. The spatial variability of soil depth in the study area is shown below in Fig. 5b.

Soil chemical properties

Eight major chemical properties of the soil were analyzed in the laboratory namely; electrical conductivity (ECe), organic matter (OM), soil pH, cation exchange capacity (CEC), total nitrogen (TN), phosphorus (P), potassium (K) and calcium carbonate (CaCO₃) content of the soil.

Table 6 Soil texture class

CSS	%clay	%silt	%sand	Textural class	CSS	%clay	%silt	%sand	Textural class
1	48	29	23	Clay	8	44	29	27	Clay
2	39	30	31	Clay loam	9	52	25	23	Clay
3	30	33	37	Clay loam	10	54	25	21	Clay
4	50	25	25	Clay	11	46	27	27	Clay
5	48	31	21	Clay	12	44	27	29	Clay
6	50	23	27	Clay	13	48	29	23	Clay
7	44	27	29	Clay	14	46	29	25	Clay

Table 7 Soil properties data (physical and chemical soil properties laboratory and field observation result)

CSS	Soil structure	Depth (cm)	Soil texture	Soil pH (H ₂ O)	OC (%)	OM (%)	ECe (µs/cm)	CEC (meq/100 g)	Total N (%)	P (ppm)	K (ppm)	CaCO ₃ (%)
1	F	150	C	5.01	1.64	2.82	35.22	28.52	0.152	13.06	0.57	23.1
2	M	100	CL	5.15	1.72	2.96	24.55	28.81	0.158	13.15	0.58	21.94
3	M	200	CL	4.6	2.97	5.13	72.12	29.69	0.285	13.46	0.57	21.44
4	VF	100	C	5.13	1.72	2.97	22.3	27.36	0.166	13.49	0.58	21.84
5	F	80	C	5.24	1.42	2.46	21.22	28.75	0.132	12.71	0.56	22.34
6	VF	100	C	5.53	1.35	2.34	14.6	29.09	0.125	12.88	0.57	22.75
7	M	75	C	5.34	1.97	3.39	19.94	31.56	0.166	12.85	0.56	22.26
8	F	100	C	5.57	1.95	3.36	28.67	32.63	0.172	12.52	0.59	20.32
9	VF	100	C	5.04	1.40	2.41	15.33	28.75	0.11	12.72	0.56	23.97
10	VF	150	C	5.46	1.32	2.27	17.38	28.20	0.12	12.51	0.57	22.09
11	M	200	C	5.46	1.49	2.56	22.22	31.24	0.132	13.09	0.58	24.14
12	M	60	C	5.57	0.88	1.52	20.37	32.81	0.085	12.8	0.58	22.03
13	F	200	C	5.45	1.82	3.14	24.68	30.34	0.178	12.68	0.59	22.18
14	M	150	C	5	1.83	3.15	28.2	28.11	0.149	12.9	0.57	21.08

CSS—composite soil sample, soil structure (VF—very fine, F—is fine and M—medium structure) and soil texture (C—is clay and CL—clay loam)

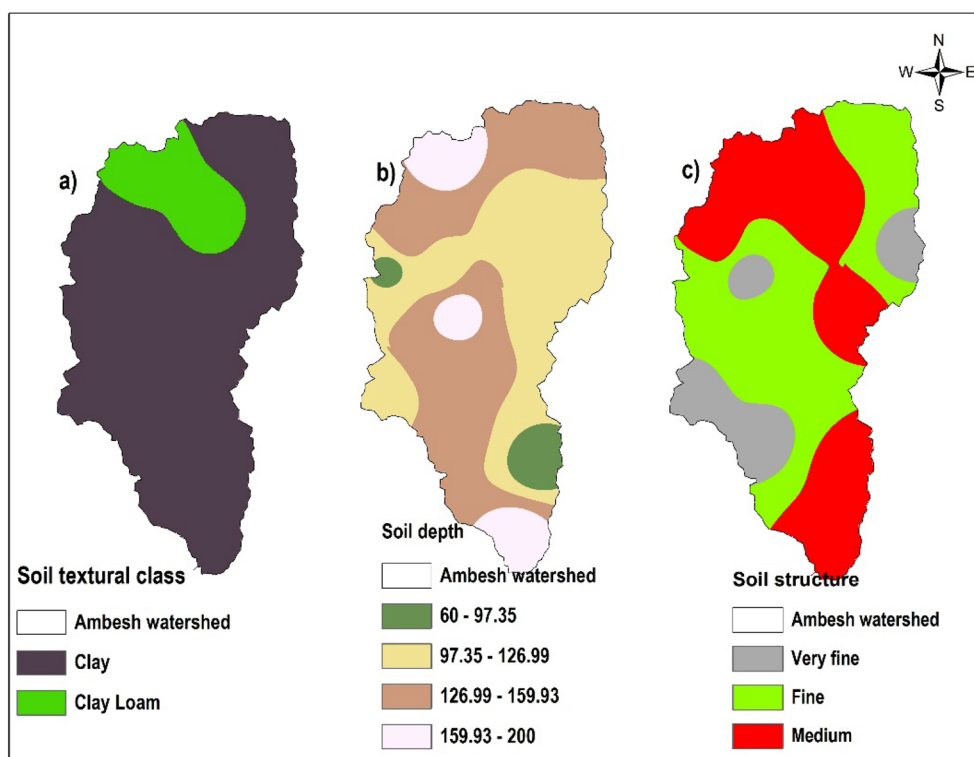


Fig. 5 Spatial variability (a) soil texture (b) soil depth (c) soil structure

Spatial variability of nitrogen (N), phosphorous (P) and potassium (K)

Nitrogen is most important nutrient in agricultural activity. It is a major essential nutrient and component of chlorophyll for the growth of plants (Bojović and Marković 2009; Ohyaama 2010; Clevers and Gitelson 2013). The amount of total nitrogen in the soil has great advantage to increase the yield of cereal crops such as wheat, teff and malt barley (Ladha et al. 2016; Zörb et al. 2018). However, it should not be underestimate to monitor N fertilizer dynamics in soils because of its importance from the environmental protection perspective, as Nitrate (NO_3^-) is the major pollutants of groundwater, rivers, water and lakes (Liu et al. 2005). Consequently, these accumulations of nitrogen, phosphorous and potassium fertilizers enhance the challenges of eutrophication in water bodies, which will create favorable condition for the growth of invasive weeds such as water hyacinth (Schindler 2006).

The phosphorous (P) content of Ambesh watershed ranges from 12.51 to 13.48 ppm (3.4 to 3.75 mg kg^{-1}). According to Olsen phosphorous nutrient level, indicated that its level is very low if it is less than 5 mg kg^{-1} (Olsen 1954). Crop production relies on continuous input of large amounts of phosphorus (P) however; the spatial variability of the soil is the determinant factor for

the application of P fertilizer (Manschadi et al. 2014). In association with soil N and soil P, soil K also a macronutrient demanded by plants for rising crop production and productivity per unit of land. Most soils contain relatively large amounts of total potassium (1–2%) as components of relatively insoluble minerals. However, only a small fraction (about 1%) presented in available form to plants (water-soluble and Exchangeable-K). In tropical regions (highly weathered acid soils) are more frequently deficient in plant available K, whereas soils in arid and semi-arid areas well supplied with soil K (Ryan et al. 2001). As results revealed that the availability of soil K in the study area is lower, ranges from 0.56 to 0.59 ppm (Fig. 6c).

Spatial variability of organic matter (OM), cation exchange capacity (CEC) and soil pH

Organic matter, also known as humus. Based on climate and drainage condition of a given soil type, the OM content of the surface layer varies from the range of 1 to 10% (Woldegiorgis 2007). The range of most mineral soils generally have OM content of 0.5% and 6% (Gao et al. 2020). Very low OM is usually found in the soils of arid climate and higher content in soils of cool climate (Franzuebbers 2002) and requires remedial soil OC management strategies (Tiruneh et al. 2023a; b).

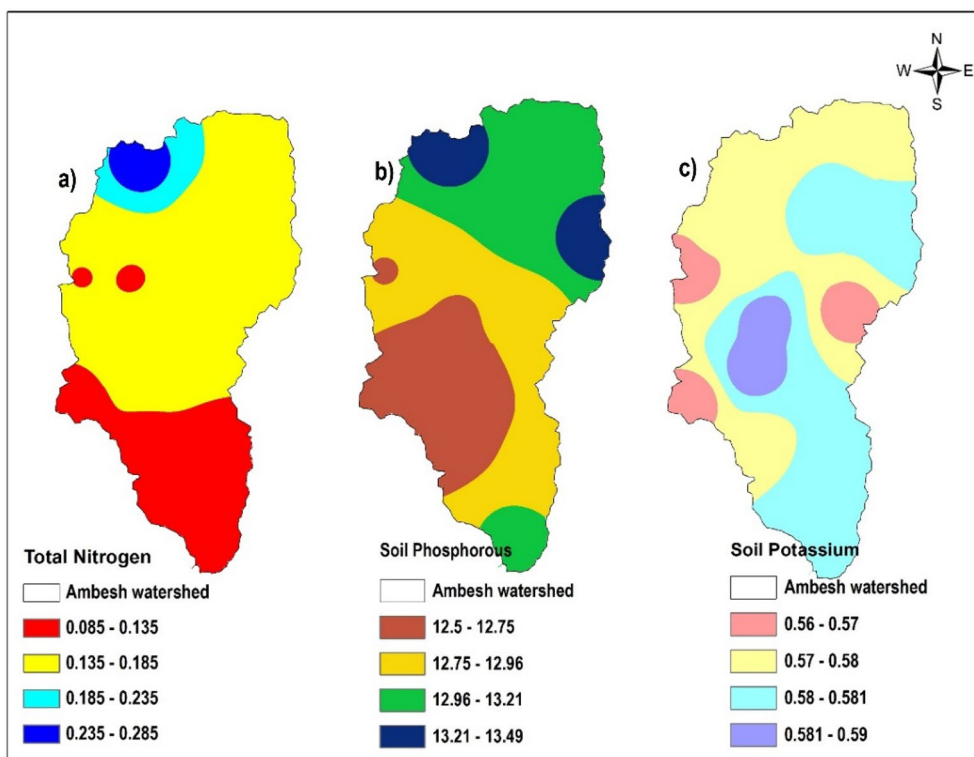


Fig. 6 Spatial variability (a) total nitrogen (b) soil phosphorous (c) soil potassium content of the study area

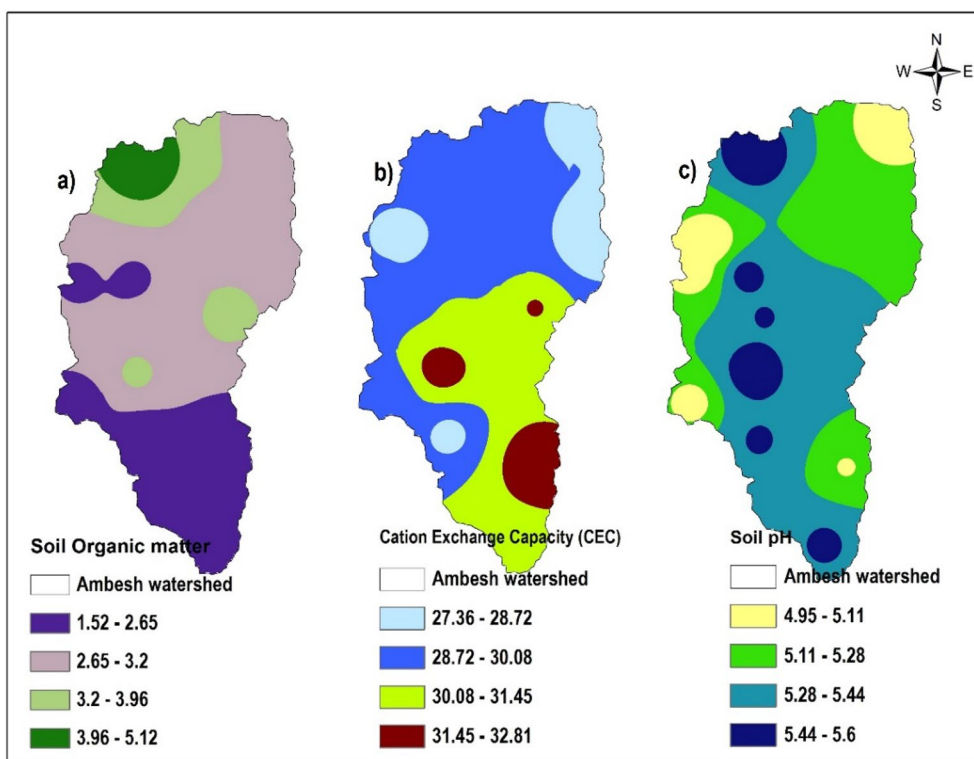


Fig. 7 Spatial variability (a) soil OM content, (b) CEC and (c) Soil pH

Soil CEC, the sum of exchangeable cation soils can absorb (Chapman 1965). It is a measure of the quantity of cations (negatively charged sites) adsorbed and held by the soil (the surfaces of clay and humus, called soil colloids) (Rhoades 1983). CEC also an indicator of the type of clay mineral present in the soil and its capacity to retain nutrients against leaching (Sertsu and Bekele 2000). Soil analysis results revealed that CEC in Ambesh watershed is high (27 to 31 meq/100 g) (Fig. 7b). Therefore, higher CEC values reflect the dominance of 2:1 clay minerals, and lower values reflect the presence of 1:1 clay minerals. With a consideration of CEC class, soils that have less than 10 meq/100 g has low CEC, ranges from 10 to 25 meq/100 g has medium CEC and those having greater than 25 meq/100 g has high CEC capacity (Burrow 2023).

Soil pH is one of the most important attributes of a soil. It can help to determine whether a soil is acidic, neutral or basic. Under normal soil circumstance, the agricultural soil pH range varies from 4 to 10. Soil pH lowers with continuous cultivation and excessive application of inorganic fertilizers for longer period (Mokwunye and Bationo 2001). However, the soil pH found in the study area ranges from 4.6 to 5.57. It indicates that the soil is strongly acidic to moderately or slightly acidic soil. Soil pH ranges 5.5–6.5 is lime free and satisfactory for most

crops, however, it should be monitored closely (Estefan 2013).

Spatial variability of electrical conductivity (ECe) and calcium carbonate (CaCO₃)

ECe of the study area ranges from 14 to 72 μS/cm (spatial variability of ECe shown below in Fig. 8a). Based on saturation extract, values of 0 to 2 dS/m are good for all crops; yields of very sensitive crops are affected between 2 to 4 dS/m; most crops are affected between 4 and 8 dS/m; while only tolerant crops grow reasonably well above 8dS/m.

CaCO₃ content in Ambesh watershed ranges from 20 to 24 percent as shown in Fig. 8b. Inorganic carbonate, either as calcium (calcite) or magnesium (dolomite) carbonate or a mixture of both, occurs in soils as a result of weathering, or is inherited from the parent material. Most soils found in arid and semi-arid regions are calcareous soils.

Topography of the land

Altitude and slope classification

Results indicated based on the altitudinal classification, Ambesh watershed is highly suitable for most selected LUTs of crops (malt barley and wheat crops). However, teff crop is out of the range of optimum altitude of 1700

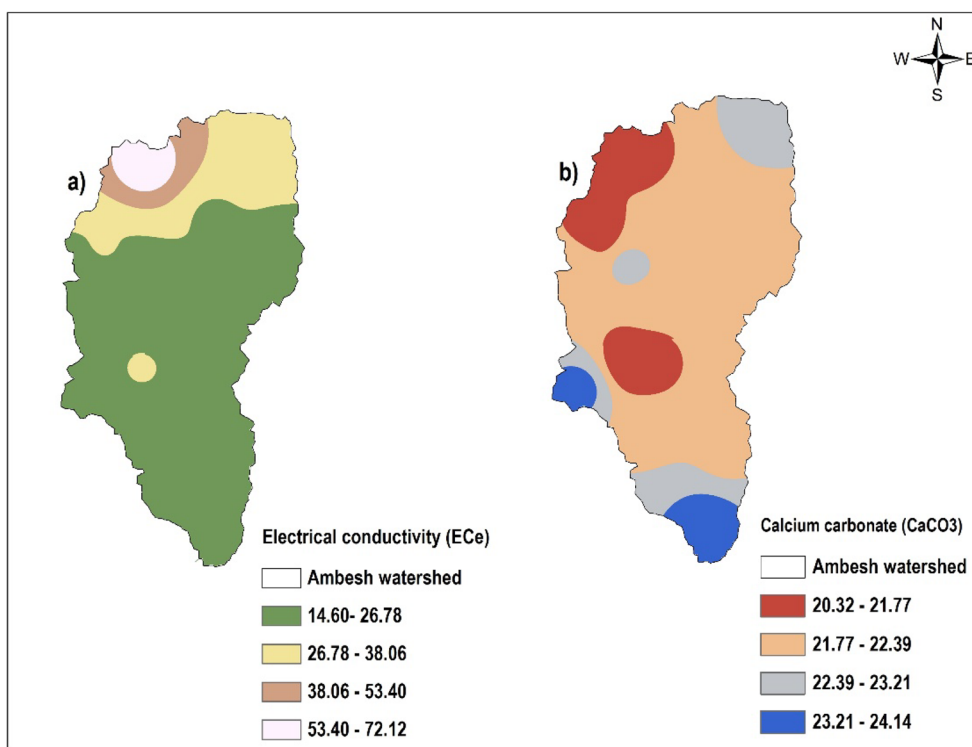


Fig. 8 Spatial variability of (a) soil ECe and (b) soil CaCO₃

to 2200 m and the study area is marginally suitable for it because of few varieties grow above the range of the altitude, 2200 m. Generally, slope ranges (in degrees) from 0 to 4.3 highly suitable, 4.3 to 7.6 is moderately suitable, 7.6 to 11.7 marginally suitable, and 11.7 to 25.42 not suitable for the selected crops. As the slope range value increases, soil depth became shallower, exposure for flooding (run-off) also increases, nutrient availability will decrease and soils are unweather (Wohl 2000; Mensah 2015).

Topography (altitude and slope of the land) and climatic factor, another major criterion for ALSA. In Ambesh watershed, the weight of altitude ranks first (CWt. of 0.64, 0.6 and 0.524) and slope ranks second (CWt. of 0.36, 0.4 and 0.476) for malt barley, wheat and teff crops, respectively (Fig. 9, Table 8).

Climate temperature (t) and rainfall (R_f)

Temperature depends on the value of altitude and slope aspect (Tiruneh et al. 2023a, b), and altitude have inverse relationship, as the altitude of the area increase the temperature decrease and vice versa Ohmura 2012). According to Braak (1928) as the higher the elevation or altitude of the area, the lower is the air temperature as cited in (Widiatmaka 2016) and the temperature of Ambesh watershed is from 3.373 °C (minimum temperature) to 28.778 °C (maximum temperature) Fig. 10b. Results revealed that, rainfall variability of the study area ranged from 1254.15 mm to 1302.52 mm, as indicated below in Fig. 10a.

Climatic condition of the study area has its own influence by providing the fundamental plant growth and development factors such as water (rainfall) and temperature to the selected LUTs. Among the selected sub

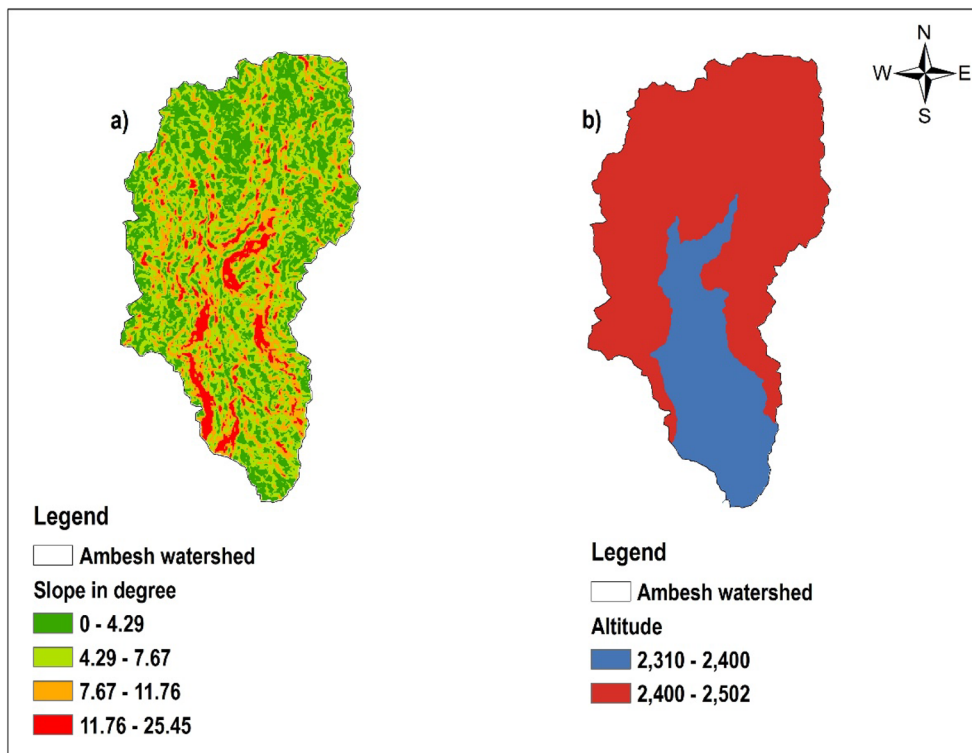


Fig. 9 Spatial variability of slope (a) and altitude (b)

Table 8 PWCM of topographic factors for malt barley, wheat and teff

	Malt barley				Wheat				Teff			
	alt	sl	Wt	Rank	alt	sl	Wt	Rank	alt	sl	Wt	Rank
alt	1	1.78	0.64	1	alt	1	1.5	1	alt	1	1.1	1
sl		1	0.36	2	sl		1	2	sl		1	2

CR value does not compute since the factors are two and its RI value is 0 (Table 4 above)

criteria’s rainfall ranks first having a greater weight that is 0.549, 0.64 and 0.629 followed by temperature, which accounts 0.451, 0.563 and 0.371, for malt barley, wheat and teff crops, respectively (Table 9).

Standardization of factors/criteria of crop production

Soil chemical and physical properties are the basic nutrient supplier for cereal crop production. The main criteria’s rank soil chemical properties, soil physical properties, climate and topographic factors first,

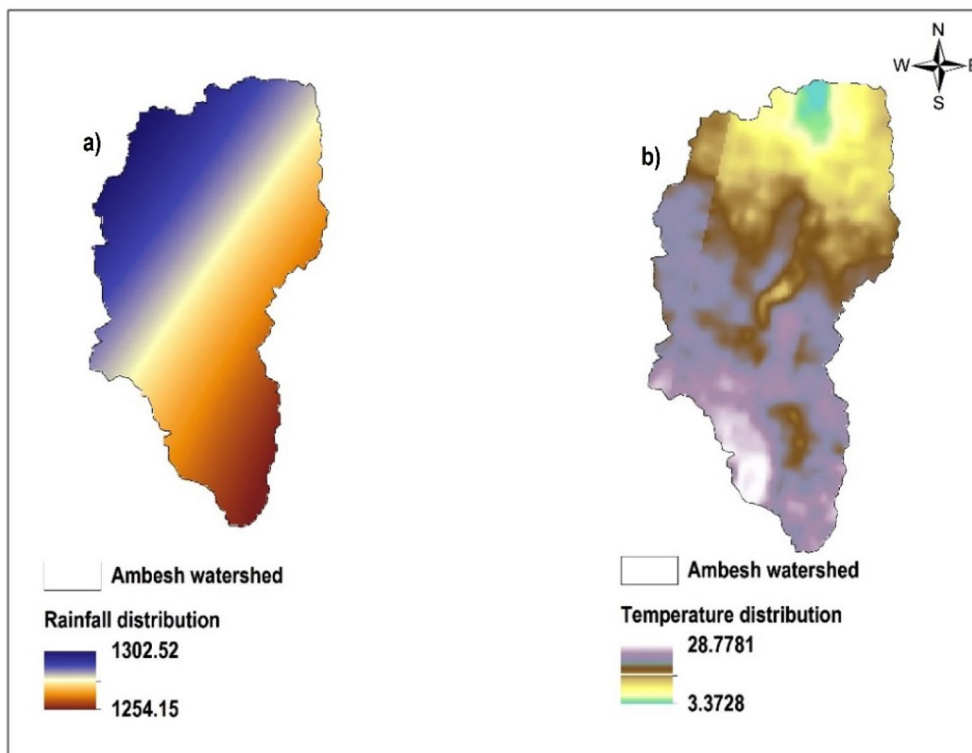


Fig. 10 Rainfall (a) and temperature (b) distribution map

Table 9 PWCM of climatic factors for malt barley, wheat and teff

	Malt barley				Wheat				Teff					
	Temp	R _f	Wt	Rank	Temp	R _f	Wt	Rank	Temp	R _f	Wt	Rank		
Temp	1	0.82	0.451	2	Temp	1	0.563	0.36	2	Temp	1	0.59	0.371	2
R _f		1	0.549	1	R _f		1	0.64	1	R _f		1	0.629	1

CR value does not compute since the factors are two and its RI value is 0 (Table 4 above)

Table 10 Pairwise comparison matrix (PWCM) of main criteria of LSA for all the selected LUTs

Main criteria	Chemical property	Physical property	Climate	Topography	Weight	Rank
Soil chemical property	1	2	5	7	0.542	1
Soil physical property		1	2	4	0.264	2
Climate			1	2	0.125	3
Topography				1	0.068	4
	CR=0.005				Sum=1	

agricultural land suitability (reclassification) requirement of malt barley has been shown in Table 11.

OM content of the soil in Ambesh watershed ranks first for the production of malt barley (Table 12). CR value for malt barley is 0.003. Therefore, OM content of the soil in Ambesh watershed is very important factor for the production of malt barely followed by CEC and total nitrogen. However, the least factors of production for malt barley production are ECe and CaCO₃ of the soil chemical properties, respectively. Among the physical properties of the soil characteristics, soil texture ranks first (with a weight of 0.423), soil structure ranks second (weights of 0.335) and soil depth ranks third (having weights of 0.242). Soil texture is most important factor of physical soil properties for malt barley production. However, soil depth is the least of all the physical soil properties due to its shallow and fibrous root system (Bodner et al. 2021). The CR value of the physical properties is 0.001 (less than 0.1) and is acceptable.

Land suitability for Teff

Teff (*a gluten-free small sized grain crop*) is a cool weather crop grown predominantly in Ethiopian highlands at optimum altitude range of 1800–2200 m (Dereje and Eshetu 2011). Maximum yield for teff production occurs at altitudes of 1800–2100 m, with a growing season minimum rainfall of 450–550 mm, and a temperature range of 10–27°C (Gorfu and Ahmed 2012). However, a very good result can also be obtained at an altitude range of 1700–2200 m and growing season minimum rainfall amount of 300 mm (<http://www.worldbank.org>). Teff can also grow above 2200 m altitude up to 2600 m for some varieties like *DZ-CR387* and *DZ-01-1868* (Belay and Wondie 2022; Abew et al. 2020). It is cultivated in soils with pH up to 8.5, but pH value of below 5.0 is not suitable (Bahir et al. 2015).

According to Table 13, CEC of the soil in the study area is the first chemical soil property for a better production

of teff crop followed by P and OM content of the soil. For teff crop production, ECe is the least important factor of production. The CR value of the chemical properties of a soil for teff crop production is 0.002, which is less than the acceptable range of CR 0.1 (Table 14).

Land suitability for wheat

Wheat in Ethiopia is grown from 1500 m and 3300 m.a.s.l. However, it yields satisfactorily between 2000 and 2600 m altitudes (FAO/UNDP 1987a cited in Abate 2011). On an average temperature of 15–25 °C and an average rainfall of 400–1200 mm is required. The distribution of rainfall throughout the crop growth period is very important. Wheat can be produced on different soil types such as black clay soils, red and brown soils. Sandy soils and soils with problems of waterlogging are unsuitable for wheat production. It requires a high soil fertility, particularly nitrogen and phosphorus, and moderate salinity tolerance (Acevedo et al. 2002; EL Sabagh et al. 2021; Syers et al. 2008). Suitable soil pH for wheat ranges from 5.5 to 8.0 (Garrett 1936). It also requires 184 Nitrogen and 92 P₂O₅ ha⁻¹ fertilizer to get maximum yield of wheat in the surrounding areas of Ambesh watershed (Assefa et al. 2023).

As indicated in Table 15, among the soil chemical properties, OM content of the soil is the most important factor of production for wheat crop followed by CEC and P content. The least important factors for wheat crop production are CaCO₃ and ECe with Consistency Ratio (CR) value of 0.011. For example, OM is 1.5 times and twice more important than pH and K (Table 16).

Overall suitability of LMUs for selected LUTs in Ambesh watershed

Overall suitability is the total land suitability of each LMU with respected to its selected LUTs. It indicated that which LMU has large suitability coverage (S₁, S₂, S₃ and N) for the selected cereal crops. Overall suitability

Table 13 Chemical properties of a soil PWCM of Teff

Soils Chemical properties	OM	pH	CEC	TN	P	K	CaCO ₃	ECe	Weight	Rank
OM	1	1.54	0.94	1.42	0.94	1.42	2.43	3.4	0.17	3
pH		1	0.61	0.92	0.61	0.92	1.6	2.2	0.111	6
CEC			1	1.5	1	1.5	2.6	3.6	0.181	1
TN				1	0.66	1	1.71	2.4	0.121	4
P					1	1.5	1.71	3.6	0.173	2
K						1	1.71	2.4	0.12	5
CaCO ₃							1	1.4	0.074	7
ECe								1	0.05	8

CR=0.002

Table 14 Criteria (reclassification) for land suitability of teff crop in Ambesh watershed

Land quality	Land characteristics	Unit of measurement	Suitability class			
			Highly Suitable (S ₁)	Moderately Suitable (S ₂)	Marginally Suitable (S ₃)	Not Suitable (N)
Climate	Temperature (t)	°C	16–20	13.74–16	20–25	25–30
	Rain fall (rf)	mm	400–908.1	908.1–1000	1000–1402	< 400; > 1402
Topography	Altitude (alt)	masl	1700–2200	2200–2400	2400–2800	< 1000, > 2800
	Slope (s)	degree	0–4.3	4.3–7.6	7.6–11.7	11.7–25.45
Physical soil properties	Soil texture(txr)	css	C, CL	Si, L	SiL, L, SL	S
	Soil structure(str)		VF, F	F	M	C
	Soil depth(dp)	cm	> 50	25–50	10–25	< 10
Chemical soil properties	Organic matter	%	3.3–5.2	2.7–3.3	1–2.7	< 1
	Ele. conductivity	µs/cm	14.7–25.1	25.1–34.6	34.6–48.1	48.1–71.3
	Soil pH:H ₂ O	H ₂ O	5.2–5.5	5–5.2	5.0–5.2	< 4.5; > 8
	CEC	meq/100 g	29.9–31.5	29.3–29.9	28.7–29.3	–
	Total N	%	–	–	0.17–0.28	0.085–0.017
	Phosphorous (P)	ppm	–	–	12.9 – 13.48	12.5–12.9
	Potassium (K)	ppm	–	–	0.57–0.58	0.5–0.57
	CaCO ₃	%	20.3–21.8	21.8–22.4	22.4–23.1	23.1–24.2

Source: Adapted from Dereje and Eshetu (2011); Gorfu and Ahmed (2012); Belay and Wondie (2022); Abew et al. (2020); Young and ISAACSON (1976); Landon (2014); FAO (1983); FAO (1984); FAO/UNDP (1989); Sys et al. (1991); Yizengaw and Verheye (1994); Assen and Le Roux (2005); Abate (2011)

Table 15 Chemical properties of a soil PWCM of wheat

Soils Chemical properties	OM	pH	CEC	TN	P	K	CaCO ₃	ECe	Weight	Rank
OM	1	1.5	1.6	1.6	1.6	2	3.67	4.4	0.221	1
pH		1	1.07	1.07	1.07	1.36	2.5	1.07	0.134	5
CEC			1	1	1	1.27	2.3	2.8	0.139	2
TN				1	1	1.27	2.33	2.3	0.135	4
P					1	1.27	2.3	2.8	0.139	2
K						1	2.33	2.2	0.113	6
CaCO ₃							1	1.2	0.058	8
ECe								1	0.061	7

CR=0.011

of the land was calculated in terms of percentage of LMUs for the all crops (Table 17). For instance, *VRe-LPq* (Fig. 11a) and *LPK.Pq-FLc* (Fig. 11d) land mapping units has a resemblance highly overall suitability class curve (good overall suitability record in S₁, S₂ and S₃ with lower values for N) for all crops as shown in overall suitability graph Fig. 11 below. This is mainly due to a relatively higher OM content, CEC and TN content in the LMUs. However, land mapping unit *VRe - NTu* (Fig. 11b) and *NTu-VRe* (Fig. 11c) has lower overall suitability values for S₁ suitability class (0.05% and 10.6%, respectively) and higher values in S₂, S₃ and N

suitability classes. These types of LMUs are characterized by steep slopes, shallow soil depth, land degradation such as soil erosion, lower soil OM content, very low P and N, low CEC value and soil acidity problems for agricultural crops.

As indicated in Table 17 below, overall suitability of the LMUs, land utilization types (malt barley, teff and wheat crops) and the percentage of its suitability classes calculated in percent. The overall suitability of land mapping units for the selected LUTs compared its area coverage per se. Thus, for each LMUs and LUTs (malt barley, teff and wheat crops) agricultural suitability land

Table 16 Criteria (reclassification) for land suitability of wheat crop in Ambesh watershed

Land Quality	Land characteristics	Unit of measurement	Suitability class			
			Highly Suitable (S ₁)	Moderately Suitable (S ₂)	Marginally Suitable (S ₃)	Not Suitable (N)
Climate	Temperature (t)	°C	15–20	13.74–15.20	22.5–25	< 13, > 28
	Rain fall (rf)	mm	908.1–1200	1200–1283	1283–1401	> 1401
Topography	Altitude (alt)	masl	2000–2600	2600–3000	3000–3300	< 1500; > 3300
	Slope (s)	degree	0–4.3	4.3–7.6	7.6–11.7	11.7–25.45
Physical soil properties	Soil texture (txr)	css	CL	C	SiL, L	S
	Soil structure (str)		VF, F	F	M	C
	Soil depth (dp)	cm	> 100	50–100	20–50	< 20
Chemical soil properties	Organic matter	%	4.1–5.1	3.3–4.1	2.7–3.3	1.5–2.7
	Ele. conductivity	µs/cm	14.7–35.1	35.1–71.3		
	Soil pH:H ₂ O	H ₂ O	5.5–5.8	5.1–5.5	5.0–5.1	4.6–5.0
	CEC	meq/100 g	29.9–31.42	29.3–29.9	28.76–29.3	–
	Total N	%	–	–	–	0.085–0.285
	Phosphorous (P)	ppm	–	13.1–13.5	12.8–13.1	12.5–12.8
	Potassium (K)	ppm			0.56–0.577	
	CaCO ₃	%	20.3–21.7	21.7–22.4	22.4–23.1	23.1–24.2

Source: Adapted from Young and ISAACSON (1976); Landon (2014); FAO (1983); FAO (1984); FAO/UNDP (1989); Sys et al. (1991); Yizengaw and Verheye (1994); Assen and Le Roux (2005); Abate (2011)

was computed in units of hectares and besides with its percent of coverage.

According to Table 18 below, the total area of land is about 1233.78 ha. Hence, malt barley, teff and wheat crops has a highly suitable (219.06, 217.6, and 168.9 hectares), moderately suitable (461.28, 483.23, and 679.47 ha), marginally suitable (490.75, 475.62, and 208.88 ha) and not suitable (62.69, 57.06, and 175.83 ha) of land, respectively. As indicated that based on its LUTs, 17.76% and 37.39% of Ambesh watershed are highly suitable and moderately suitable for malt barley crops production, respectively. Among the total area of land, 39.78% (490.75 ha) of land is marginally suitable for malt barley. Only 5.08% (62.69 ha) of the land is not suitable for malt barley crops production. This is mainly due to soil acidity, very low to low amount of macronutrients availability and its steep slope nature of the land. Moreover, malt barley needs more fertile soil and less tolerance to soil acidity than food barley (Kharub and Chander 2012; Terefe et al. 2018; Fekadu et al. 2022).

The result of this study showed that 13.7% (168.9 ha), 55.1% (679.47 ha), 16.94 (208.88 ha) and 14.26% (175.83 ha) of land has S₁, S₂, S₃ and N for wheat crop production in Ambesh watershed (Table 18). This is mainly due to soil acidity problem, slope steepness of the land, low soil P and OM content of the soil.

Accordingly, considering the LMUs, *LPk.Pq-FLc* is highly suitable followed by *VRe-LPq* LMU for wheat crop production (see Table 17 above). The least suitable LMU for wheat crop production is *VRe-NTu* in Ambesh watershed. *LPk.Pq-FLc* LMU has 108.15 ha (22.87%) of its land highly suitable for teff crops production in Ambesh watershed. About three fourth of the land is moderately and marginally suitable for malt barley crop production (Table 18). Due to relatively higher CEC, P and OM content than *VRe-NTu* LMU, all LMUs (*VRe-LPq*, *NTu-VRe* and *LPk.Pq-FLc*) except *VRe-NTu*, are highly suitable for teff crop production each having 83.74, 25.58 and 108.15 ha of land, respectively. The most limiting factor of *VRe-NTu* LMU is steep slope, low in P content, relatively lower in CEC, lower OM content and shallow soil depth (Fig. 12).

Conclusion

ALSA using remote sensing and GIS is an important application for decision making whether the land is proper for a given type of LUTs or not. An integrated application of MCDM using AHP could also provide many advantages to select the best criteria that contributes a maximum weight (most influential factor) for maximum productivity of crops. Priority Estimation Tool (PriEsT) also has a great advantage to do a PWCM of all the criteria considered in the ALSA. This study is

Table 17 Overall suitability of each LMU's with respect to suitability classes and selected crops

Land Mapping Units (LMUs)	Land utilization type (LUT)	Suitability classes (FAO 1976)						Total	
		S ₁ (ha)	Percent (%)	S ₂ (ha)	Percent (%)	S ₃ (ha)	Percent (%)		N (ha)
VRe-LPq (434.03 ha)	Malt barley	76.45	17.61	128.26	29.55	212.28	48.91	16.89	3.89
	Teff	83.74	19.29	158.96	36.62	175.98	40.55	15.12	3.48
	Wheat	60.34	13.90	223.77	51.56	83.57	19.25	66.35	15.29
	Overall suitability (%)		16.94		39.26		36.25		7.56
VRe-NTu (94.87 ha)	Malt barley	0.00	0.00	90.67	95.57	4.20	4.43	0.00	0.00
	Teff	0.13	0.14	17.54	18.49	77.14	81.31	0.00	0.00
	Wheat	0.00	0.00	35.04	36.93	39.75	41.90	19.87	20.94
	Overall suitability (%)		0.05		50.38		42.59		6.99
NTu-VRe (232.31 ha)	Malt barley	24.18	10.41	57.25	24.64	105.12	45.25	45.65	19.65
	Teff	25.58	11.01	76.88	33.09	87.85	37.82	41.94	18.05
	Wheat	24.10	10.37	105.36	45.35	20.02	8.62	82.83	35.65
	Overall suitability (%)		10.60		34.37		30.57		24.46
LPk.Pq-FLc (472.83 ha)	Malt barley	118.43	25.05	185.10	39.15	169.15	35.77	0.15	0.03
	Teff	108.15	22.87	229.85	48.61	134.65	28.48	0.00	0.00
	Wheat	84.46	17.86	315.30	66.68	65.54	13.86	6.78	1.43
	Overall suitability (%)		21.94		51.51		26.05		0.49

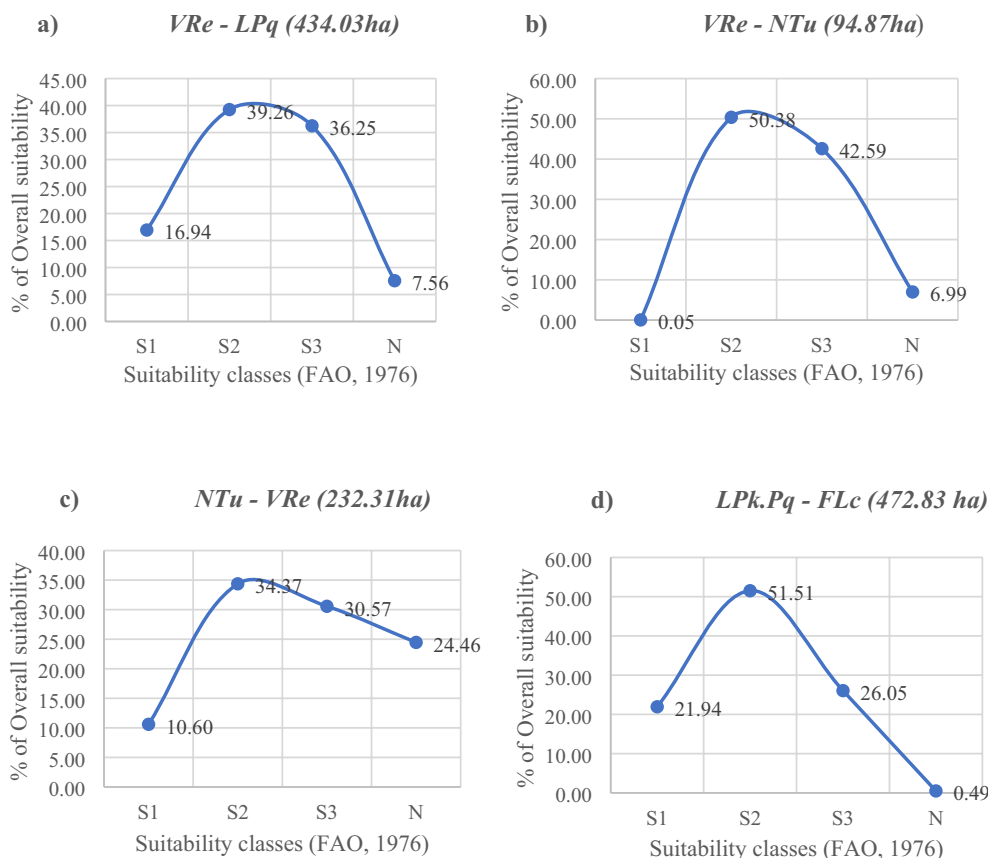


Fig. 11 Overall suitability versus suitability class of each LMUs **a** *VRe - LPq* **b** *VRe - NTu* **c** *NTu - VRe* and **d** *LPk.Pq - FLc*

Table 18 Land suitability result for malt barley, teff and wheat crop (hectares and coverage in %)

Suitability classes	Malt barley		Teff		Wheat	
	Area coverage (ha)	Coverage (%)	Area coverage (ha)	Coverage (%)	Area coverage (ha)	Coverage (%)
S ₁	219.06	17.76	217.6	17.64	168.9	13.70
S ₂	461.28	37.39	483.23	39.18	679.47	55.10
S ₃	490.75	39.78	475.62	38.56	208.88	16.94
N	62.69	5.08	57.06	4.63	175.83	14.26
Total	1233.78	100	1233.51	100	1233.08	100

also important for land use planners to provide decision making for the selection of land utilization types and farmers to produce suitable crops based on physical land suitability assessment. Furthermore, classification of the land with land mapping units (an area having homogenous land quality) has also tremendous benefit to

take soil sampling easily and minimize the cost of labor and soil laboratory test by compositing many soil auger soil samples into a single CSS. In conclusion, LMUs, *VRe-LPq* and *LPK.Pq-FLc* LMUs has higher overall suitability for all the selected rain fed crops. However, LMUs (*VRe-NTu* and *NTu-VRe*) has lower overall suitability

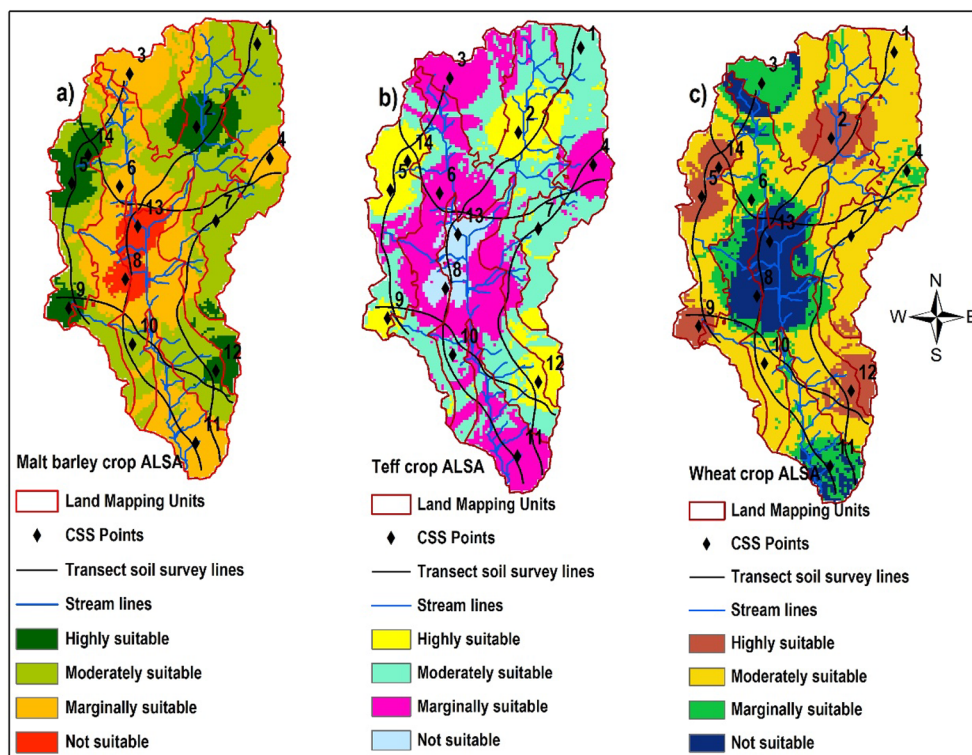


Fig. 12 Final ALSA maps (a) malt barley (b) Teff (c) Wheat crops

values particularly for S_1 suitability class (0.05% and 10.6%, respectively). However, the least suitable LMU is $VRe-NTu$ with 0.05% S_1 suitability class and above 99% of the land laid under the suitability classes of moderately suitable, marginally suitable and not suitable for the selected LUTs. To end with, majority (above two third's) of the watershed is under moderate and marginally suitable land, needs intensive land management activities to increase the land qualities and obtain high yields.

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