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A GIS based land suitability analysis for sustainable agricultural planning in Gelda catchment, Northwest Highlands of Ethiopia

Ebrahim Esa[1*] and Mohamed Assen[2]

[1]College of Social Sciences, Department of Geography and Environmental studies, University of Gondar, P.O. Box: 196, Ethiopia.
[2]Department of Geography and Environmental studies, Addis Ababa University, P.O. Box: 150116, Ethiopia.

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The present study was carried out to examine the suitability status of plots of land for selected land utilization types (*teff -Eragrostis tef*, maize - *Zea mays* and finger millet - *Eleusine coracana*). The land mapping units of the study area, prepared from land resource survey, were used for the purposes of land evaluation. The methodology used for land suitability evaluation was GIS-based multi-criteria evaluation following FAO (1976) guidelines involving matching diagnostic land qualities against crop requirements and assigning suitability rates for each land qualities. The weighted overlay analysis combining diagnostic soil, climate and topographic factors showed that the largest coverage (76.04, 69.52 and 67.79%) of the study area is classified as moderately suitable for *teff*, maize, and finger millet cultivation, respectively. The vector overlay analysis results revealed that about 20.25 and 63.92% of the catchment are moderately suitable and marginally suitable for cultivation of all selected land utilization types. This showed that competitions for the same parcel of land by different uses were possible. Thus, farmers could have freedom to choose a range alternative land utilization types with the same suitability level and allocate land utilization type that best meet his/her interest. Therefore, land suitability analysis for agricultural crops using multi-criteria evaluation in a GIS environment is a strong tool for measuring and valuating land in terms of the varying importance to decision makers for sustainable rainfed agriculture.

Key words: GIS, land utilization type, multi-criteria evaluation, weighted overlay analysis, vector overlay analysis, suitable land allocation, sustainable rainfed agriculture.

INTRODUCTION

Land is one of the most important natural resources, and maintaining its health is essential for meeting an ever increasing demand for food, fiber, fodder and fuel (Mohammad and Mohd, 2014). It is a significant resource mainly for countries where their economy is based on rural activities, such as agriculture (AGRA, 2013).

*Corresponding author. E-mail: ebroissa@yahoo.com, ebrahimesas036@gmail.com, Ebrahim.Esa@uog.edu.et.

Therefore, maintaining the productivity of land is a determinant factor to obtain sustainable services and goods from land. The demands for goods and services increase overtime in association with a rapid growth of human population, which can be obtained either by intensification or expansion of land use e.g. for crop, fuel and fodder production. Land use intensification requires high available technology, which for many developing Sub-Saharan countries is less attainable (UN Department of Economic and Social Affairs/UNDESA, 2012; Ruben and Piters, 2005). However, further expansions of cultivation land are very limited or will be at the expenses of other life support systems, such as forest resources. In most of the African countries, population pressure has resulted in an expansion of cultivated land into other land use/ cover (LULC) classes and a reduction in the average available farm per capita (Sherbinin et al., 2007). Moreover, other LULC categories e.g. urban land uses and settlement have expanded into best prime agricultural land and this further reduces available land for agricultural expansion (Solomon et al., 2014).

In the highlands of Ethiopia, an uncontrolled agricultural land expansion onto fragile and less productive land e.g. steeper slopes coupled with low agricultural land productivity and population pressure have led to land degradation (Dula, 2010). In addition, long history of settlement and traditional agriculture in the highlands of Ethiopia are also responsible for deteriorating land quality and quantity (Ebrahim, et al., 2014). Despite the limitations caused by unsustainable land uses, the highlands of Ethiopia are classified as high potential cereal (HPC) zone (FAO, 1986). Cereals, such as *teff* (*Eragrostis tef*), maize (*Zea mays* L.), finger millet (*Eleusine coracana*), barley (*Hordeum vulgare* L.), sorghum (*Hordeum vulgare*), oats (*Avena sativa)*, and wheat (*Triticum* spp.) make up 85% of the total production of field crops and account for over 90% of input household consumption in Ethiopia (CSA, 2000). The sustainable production of these crops and acquiring of other services from the Ethiopian highlands are achievable only through implementing appropriate land use plan (Benin et al., 2003).

Agricultural land use planning involves making knowledgeable decisions about land use and the environment (Mohammad and Mohd, 2014). Allocation of land for particular use requires evaluations of the land quality with respect to its potential and constraints. The evaluation based on potential and constraints of land is critical for sustainable land use planning (Sarkar et al., 2014). Many researchers have attempted to provide a framework for optimal agricultural land use because much agricultural land used currently, in different parts of the world, are below its optimal capability and some has led to processes of degradation (Ebrahim, 2014). In Ethiopia, agricultural land use is often conducted without a correct pre-assessment of its potential and leading challenges, which has caused widespread degradation and significant decline in soil productivity (Asmamaw et al., 2015).

The available land resources, which include soil, topographic, water and associated climatic features, can deeply influence the cropping pattern and crop productivity in specified areas because each crop requires definite soil, climatic and site conditions for its optimal growth (Mohammad and Mohd, 2014). Crop production capacity of farmlands is influenced by land quality variations influenced by the inherent physical and chemical characteristics of soils that may or may not be economically controlled (Pound and Ejigu, 2005). These required farmers, in modern agriculture, to have some level of understanding on the physical capability and nutrients status of the soils to make informed choices of specific uses of land (Dickson et al., 2002). This has given rise to the need for land evaluation studies prior to actual land uses to decide rational decisions (FAO, 1976). These studies provide information on the choice of crops to be grown on best suited soil units for maximizing the crop production percapita, labor and inputs (Mohammad and Mohd, 2014). Managing the physical requirements of crops allows farmers to improve nutrient status of soils before the imbalances become so severe that it becomes a clearly observable factor for plant growth (Nafiu et al., 2012). Therefore, the success and failure of cropping is largely determined by the availability of both water and plant nutrients, which is in turn controlled by the physicochemical properties and micro environment of the soils. Agricultural land use practices in study area was not largely based on the matching of crop climatic, topographic and soil requirements to land qualities for optimum production. However, the land use decisions by local farmers are usually driven largely by long-term traditional farming experience on farmers' preference to adopt a particular cropping pattern and other social factors. This has generally led to low productivity and degradation of the available land resources. Accordingly, a thorough analysis of land in terms of their potentials and constraints is needed to make rational decisions on mechanisms of enhancing the potential and curbing the challenges of small-scale rainfed agriculture.

Computer based decision support models have been developed towards land evaluation following the advancement of information and communication technology (Sarkar et al., 2014). The advent of GIS and remote sensing technologies opened the door to the wider application of quantitative and qualitative land evaluation methods (Ashraf, 2010). It has the ability to perform numerous tasks utilizing both spatial and attribute data, and helps in the manipulations of assessment factors into land suitability maps (Neupane et al., 2014). In the context of land suitability analysis, GIS support for spatial decisions making process, i.e., to determine what locations are most or least suitable for specific purpose and hence the spatial variations in suitability status of land for specific purpose can be adequately discerned.

The agricultural practices, in the study area, are largely characterized by small-scale, fragmented, traditional tillage, low fertility level with little irrigation activities along the main Gelda River. Irrigation was limited largely by the rugged topographic and lithologic conditions of the main river channel, except along the lower courses of the catchment. Thus, rainfed agriculture is the main source of income and form of survival for more than 90% of the households. Cereals and pulses are the major crops grown in the catchment. Traditional farming practices are common where crops are usually cultivated and chemical fertilizers are applied irrespective of the existing constraints and potentials of land. Thus, land suitability evaluation is essential to guide farmers to invest on land use options that would bring the greatest social and economic benefit, and minimum environmental costs. This will help to improve crop production and allocate the land to the most suitable use. Therefore, this study applied multi-criteria evaluation (MCE) integrated with GIS to delineate the suitable areas for three major locally grown subsistence food crops (*teff* -*Eragrostis tef*), maize - *Zea mays* L., finger millet-*Eleusine coracana*). The study was limited to evaluations of the physical requirements of crops for selected physical land quality characteristics.

MATERIALS AND METHODS

Study area description

The Gelda catchment is located between $11^0$38'14" and $11^0$46'15"N latitude, and $37^0$25'54" and $37^0$41'29"E longitude. It has about 26,264 hectares, covering about 2.2% of the Lake Tana watershed. It is drained by a stream named as Gelda (from where the name of watershed is given) flowing into Lake Tana from west direction (Figure 1). The landform of the catchment reflects its geological history where uplifting force created an initial elevated landmass and the subsequent outpouring of basaltic lava provided a thick protective cap and added on to the elevation (Eleni et al., 2013). According to the report of Geological Survey of Ethiopia (GSE, 1996), the catchment generally comprises materials ranges from alkaline to transitional basalts that often form shield volcanoes, with minor trachyte and phenolite flows called *"Tarmaber Gussa Formation"* in southeast and eastern parts of the catchment formed during the Oligocene to Miocene epochs of the Tertiary period. The western and northwestern parts of the catchment consist of alluvial and lacustrine deposits of the Quaternary period. The altitude ranges from 1780 to 2481meters above sea level.

The slope gradient is dominated by gentle slope (0-7.6%) covering about 48.5% (12,682 ha) and moderately steep (7.7-16%) with 37.13% ha (9,714) of the catchment. The steep (16.2-30.2%) and very steep (>30.3%) slope gradients cover about 11.22% (2,936 ha) and 3% (787 ha) respectively, commonly found in the southeast and southern corners of the catchment. Gleysols (54.9%) and Nitisols (30.5%) form the major soil types of the Gelda catchment. Gleyosols are poorly drained with seasonal water accumulation (FAO, 1997; FAO, 2001). The other soils are commonly found on the sloping lands.

There are about four weather stations within and nearby the catchment, however only Bahirdar station has longterm records and full weather variables. Consequently, temprature and rainfall records of Bahirdar station were considered in determining climate of the study catchment. Climate is generally sub-tropical with average rainfall amount of 1453 mm with relatively high inter-annual variability and a maximum effective rainy season of 120 days or more (Figure 2). The rainfall records for the period between 1961 and 2014 records showed that the pattern is predominantly uni-modal with long rainy season category (June to October), which accounted for about 90% of the total rainfall in the catchment. It is the main season that enables rainfed cultivation of crops (Figure 2). The dry season occurs between November and May where some alternative small-scale irrigation along Gelda River is possible. However, the topographic nature of the river is a physiographic-related limiting factor affecting agricultural production during the dry season in the catchment. In addition, the highest mean monthly temperature (30^0C) is recorded during April while the minimum (8^0C) is during December with monthly range of 5^0C (figure 2).

The local agroecology, which combines growing periods with temperature and moisture regimes associated with distinct soil, climate and land uses, generally is in the moist *weynadega* (largest coverage) and moist *dega* category. It is largely characterized by average length of growing period ranging from 120-240 days (Hurni, 1998). It is agroclimatic as well as ecologically most suitable conditions for rainfed farming, such as *teff* (*Eragrotis teff*), *nuog* (*Guizotia abyssinica)*, and maize (*Zea mais*). According to Dera Woreda ARD office (2013), vegetation species largely dominated by *Juniperus procera* (*Habesha tid*) are commonly found around churches and grave yards including *Hagenia abyssinica* (*kosso*); *Albizia* (*sassa*), *Podocarpus falcatus* (*zigba*); *Cordia africana* (*wanza*); and *Ficus vasta* (*warka*). However, field observation in the study area indicated that non-indigenous tree species like cypress (*yeferenj tid*), *Acacia sieberiana* (*Yeferenj girar*) and *Eucalyptus spp*. (*Bahir zaf*) are expanding.

Field observation in the study catchment revealed that subsistence rainfed agriculture, and to a lesser extent supplementary irrigation, livestock husbandry and bee keeping are the main stay of households. According to Hurni (1998), the most dominant Ethiopian agricultural belt is called *Weyna dega* (altitude from 1,500 to 2300m a.s.l and mean annual rainfall of ≤ 900 mm), which covers about 30% of the country. It is agroclimatically highly suitable for rainfed cropping allowing at least one cropping season per year, particularly teff and maize. The altitudinal difference (1778 and 2480m a.s.l), and mean annual rainfall (1453 mm) of the study area largely signify moist *Weyna dega* condition. Highlands reclamation study (HRS) also indicated that areas where the study catchment located are classified as high potential cereal zone (FAO, 1986). According to Dera Wereda Office of Agriculture and Rural Development (2014/15) production year report, 65,308 ha of arable land were covered with wide range of cereal and horticultural crops (Table 1). *Teff* (*Eragrostis tef*), maize (*Zea mays*), finger millet (*Eleusine coracana*) and potato (*Solanum tuberosum*) account for 22.8, 19, 18.4 and 8.5% of arable land of the wereda respectively. These are the major staple sources of food to the local people of the study area.

Methodology

Data sources and identification of land mapping units

Land mapping units (LMUs) are defined and mapped by natural

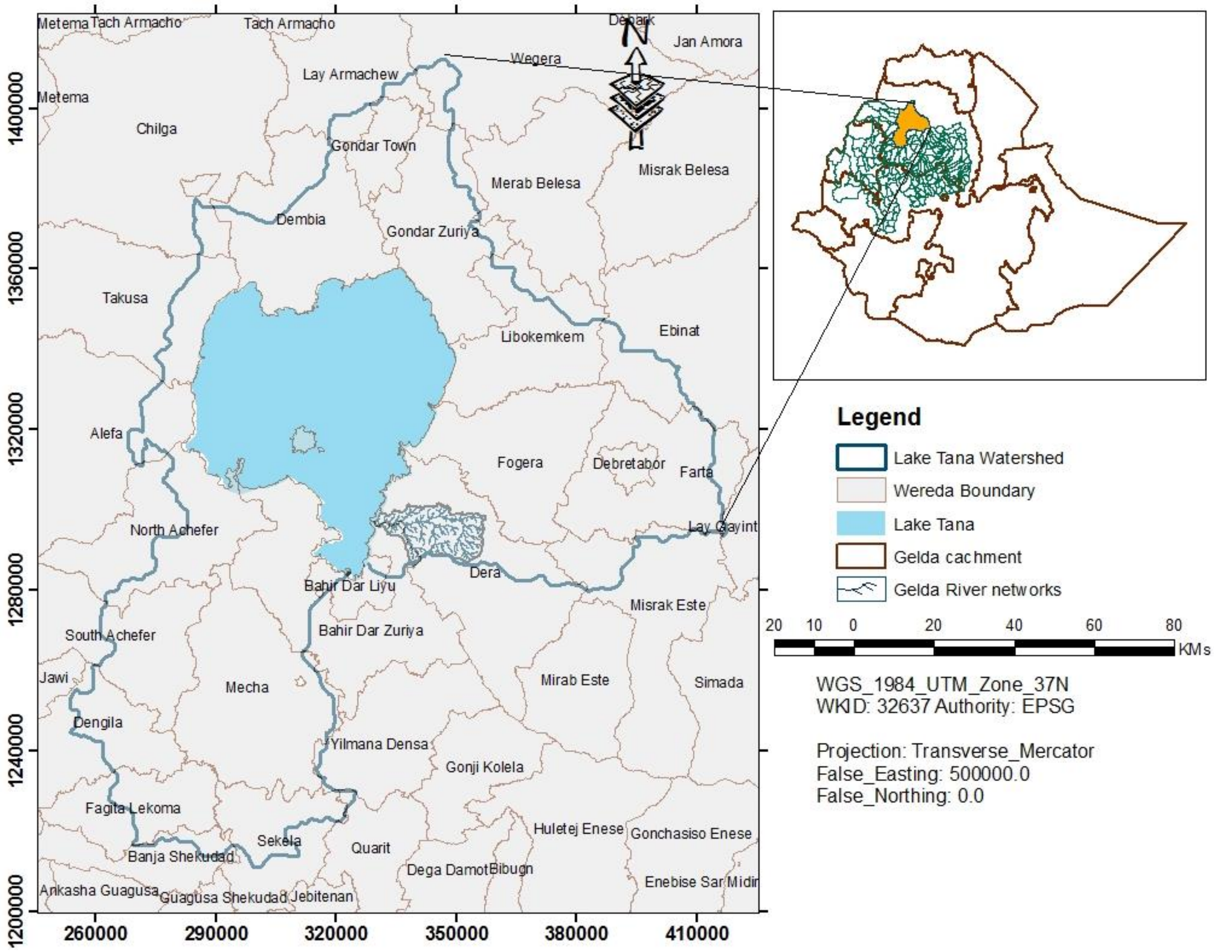

Figure 1. Location map of Gelda catchment, northwestern highlands of Ethiopia.

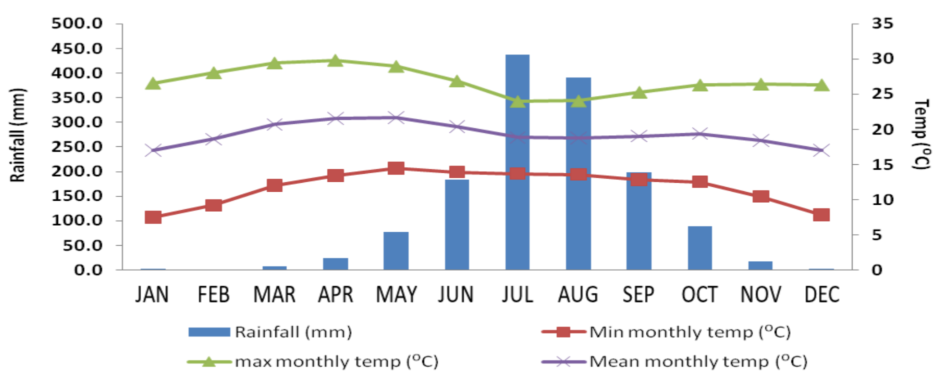

Figure 2. Mean monthly rainfall and mean monthly temperature rainfall records of Gelda catchment (1961–2014) based on the records of nearby Bahirdar station (NMA, 2014).

resource surveys, e.g. soil survey, LULC analysis and hydrology where the degree of homogeneity or of internal variation varies with the scale and intensity of the study (FAO, 1976). Soil survey is often the basis of dividing landscapes into basic spatial entities called mapping units. In this study, land resource survey was conducted between January and February 2014 to determine

Table 1. Major cultivated crops in Dera wereda, Northwestern Ethiopia.

Crop	Type of agriculture	Area (ha)	%
Teff (*Eragrostis tef*)	Rainfed	14,900	22.8
Maize (*Zea mays* L.)	Rainfed/supplementary irrigation	12,470	19.1
Finger millet (*Eleusine coracana*)	Rainfed	12,050	18.4
Potato (*Solanum tuberosum*)	Rainfed/supplementary irrigation	5583	8.5
Wheat (*Triticum aestivum*)	Rainfed	5460	8.4
Barley (*Hordeum vulgare*)	Rainfed	4400	6.7
Rice (*Oryza sativa)*	Rainfed	3648	5.6
Ethiopian Niger seed (*Guizotia abyssinica)*	Rainfed	2990	4.5
Linseed (*Linum usitattissimum*)	Rainfed	2200	3.4

Source. Dera wereda Agriculture and Rural Development Office Annual Report, 2013.

Table 2. LMUs identified in Gelda catchment, northwestern highlands of Ethiopia.

LMUs	Code	Area		Mean values for attributes associated to each LMU							
		Ha	%	Texture	Drainage	pH	EB	CEC	SOM	PAV	TN
Dystric gleysols	GlDy	13,986.5	53.3	CL	P	5.54	26.24	31.07	2.79	9.49	0.16
Dystric nitisols	NiDy	7962.2	30.3	C	VP	5.44	27.15	32.08	2.48	4.92	0.14
Eutric nitisos	NiEu	2776.4	10.6	SCL	P	5.52	33.33	38.04	3.55	1.04	0.21
Orthic luvisols	LuOr	1028.4	3.9	SL	SE	5.39	26.00	29.04	1.91	0.67	0.38
Eutric regosols	ReEu	510.5	1.9	CL	P	5.43	22.79	26.02	2.57	4.20	0.15

*Note: E= excessively drained; W= well drained; M= moderately drained; SE= somewhat excessively drained; P= poorly drained; VP= very poorly drained; C= Clay; CL= Clay loam; SCL= Silt-clay-loam; SiL= Silty-loam; L= Loam; SL= Sandy-loam.

LMUs. The spatial boundaries of land utilization types (LUTs) were determined from SRTM (30m×30m) image and Ethiopian soil database (1:1,000,000) using ArcGIS. During survey work, the diagnostic land quality characteristics were largely obtained from 21 surface sample points at a depth of 0-20 cm over the entire study catchment. As a result, a total of five LMUs were identified in Gelda catchment (Table 2 and Figure 3).These were the foundation for generating the thematic map layers in multi criteria decision-making (MCDM) process for selected LUTs.

Selection and description of land utilization types (LUTs)

The suitability of the LMUs was evaluated for the selected and locally grown major food crops of the study area, hereafter referred to as LUTs, and each LUT was described in order to determine its land use requirements (LURs). However, the LUTs in this research were prioritized and selected based on their spatial coverage in Dera wereda where the catchment is almost entirely found as well as field observation in the study area.

Teff (*Eragrostis teff*)

Teff is grown under diverse agro-climatic conditions in the altitude ranging from 1800 to 2100 meters above sea level (Fissehaye et al., 2009; Behailu, 2014). The report by National Academy of Sciences (NAS) in 1996 indicated that the average annual rainfall of *teff* growing areas is 1000 mm, but the range is from 300 – 2500 mm. Seyfu (1997) also reported that it grows at altitudes ranging from sea level to 2800 m above sea level. In fact, *teff* is able to withstand wet conditions, and even grows on partly waterlogged plots and acidic soils (pH < 5) perhaps better than any cereal crops other than rice (NAS, 1996). However, it cannot withstand largely waterlogged conditions unless it is sufficiently drained due to the shallow root system (Ebrahim et al., 2014). According to experiences gained so far from national yield trials, conducted at different locations across the country, *teff* performs excellently at an altitude of 1800 – 2100 m above sea level, annual rainfall of 750 – 850 mm, growing season rainfall of 450 – 550 mm and a temperature range of 10°C – 27°C (Seyfu, 1997). *Teff* has evolved on vertisols that frequently get waterlogged in the Ethiopian highlands with appropriate drainage (NAS, 1996). Although about a third of the land devoted to cereals in the country is under teff cultivation, production has been far below the potential, i.e., less than 0.50 t/ha due to poor soil fertility and soil moisture management (Fissehaye et al., 2009; Seyfu, 1997).

In most parts of Ethiopia, *teff* is grown during the main rainy season (*meher*); though there are places where it is grown during *belg* season (Seyfu, 1993). It usually needs high tillage frequency compared to other cereal grains in Ethiopia and moderate soil compaction by animal trampling (Behailu, 2014). In traditional farming, the *teff* seeds are broadcasted on a well ploughed land and lightly covered with soil for germination to occur in shorter period of time. However, despite the very small seed size of grains, row planting is an emerging practice as a means to boost

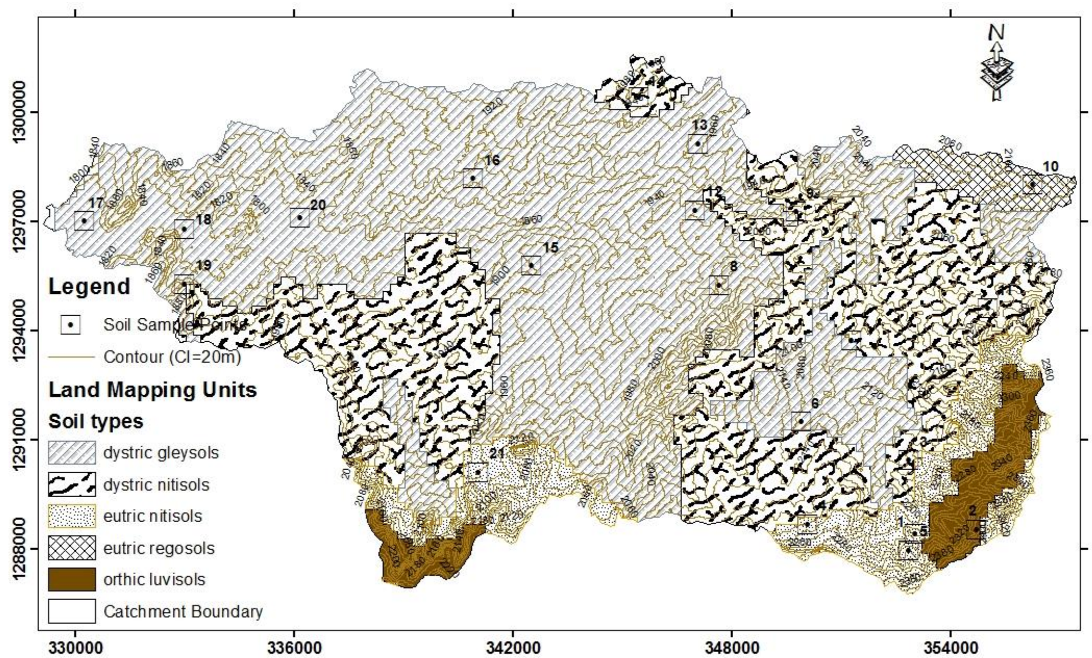

Figure 3. LMUs identified in Gelda catchment, northwestern highlands of Ethiopia.

production in rainfed agriculture. Research by Behailu (2014) in Minjar-shenkora wereda reported that row planting resulted in better *teff* yield than broadcasting. Repeated weeding is often required during the growing period (Assefa et al*.,* 2011). Harvesting is generally done in with ordinary sickles and straw is separated from the grain after it has been threshed into the ground with cattle. The straw is usually important for fodder during the dry season and construction material for houses made of mud. *Teff* is commonly used as a daily staple food *"injera"* (local sour pancake used as a staple food in Ethiopia) for more than 60% of the total population of the country (Behailu, 2014). It is also important in terms of the rate of consumption and amount of production (Berhe et al*.,* 2011). However, lack of high yielding cultivars, lodging, weed, water logging, moisture stress and low fertility conditions and poor harvest practices largely contributed to low productivity (Behailu, 2014).

Maize (*Zea mays* L.)

Maize shows tolerance to a wide range of environmental conditions and grows at optimal temperature between 18 – 32^0C, annual precipitation between 1000 – 1500 mm, and 500 – 1200 mm in the growing cycle (Sys et al*.*, 1993). During germination, the optimum temperature appears be around l8^{0}C; at temperatures below l3^{0}C germination is slow (Uriyo, 1982). However, its response to temperature varies with the growing stage of the crop. In humid-hot lowlands and tepid mid-altitude agroecologies of Ethiopia, maize has a long history of cultivation and served as a subsistence crop (Tesfa et al*.,* 2011). As a result, it is largely grown in *woyna dega* agroclimatoloy, which are highly suitable for rainfed farming in Ethiopia (Hurni, 1998). Well drained, well aerated, deep loam and silt loam soils with adequate organic matter are most suited for maize cropping (Sys et al*.*, 1993).

Maize requires tillage of farmlands 2 to 3 times before planting for suitable germination (EIAR, 2007). It is usually broadcasted in traditional farming; however row planting is also being practiced to improve production. Generally, maize is cultivated in subsistence and partially subsistence rainfed agriculture during the main rainy seasons in different parts of Ethiopia, but it can also be cultivated by irrigation during the dry seasons mainly for market (EIAR, 2007). Production of grain crops for private peasant holding report in 2014/15 production year in Ethiopia indicated that the percentage share of cereals was 80.3 and 87% of grain crop area and production, respectively (CSA, 2015). Harvesting is generally done in two stages such as the earheads are harvested with ordinary sickles and straw is cut to the ground; and earheads are heaped for 3-4 days to dry and then threshed with hand or cattle. Finally, the straw can be used for fodder and domestic source of energy.

Finger millet (*Eleusine coracana*)

It is locally called *dagussa* in Ethiopia, which can be grown throughout the year if temperature is more than 15 °C, i.e., a heat loving plant (Naidu et al*.*, 2006). The crop also tolerates cooler climate than other millets, but it grows best where the average maximum temperature exceeds 27°C and the average minimum does not fall below 18°C (NAS, 1996). The minimum mean annual rainfall requirement for successful cultivation is 460 mm, but the crop can be grown in higher rainfall area also (Naidu et al*.,* 2006). Finger millet is often cultivated in semi-arid and arid agro-ecology, where the area is frequently affected by drought (Masresha et al*.*, 2011). As a result, the crop possesses good drought tolerance but is highly sensitive to frost. However, it requires a moderate rainfall (500 – 1000 mm) that is well distributed during the growing season with an absence of prolonged droughts (NAS, 1996). It can also be grown on all types of soils ranging from poor to fertile soils, but performs well on well-drained loams or clay loam soils (Naidu et al*.*, 2006). The crop is frequently produced on reddish-brown lateritic soils with good drainage and has outstanding ability to utilize rock phosphate than other cereals do (NAS, 1996).

In traditional farming of Ethiopia, the crop is generally planted in broadcasting after proper seedbed preparations. However, research by Tenywa et al. (1999) in Uganda confirmed row planting resulted in significantly better finger millet growth and yield than broadcasting. Harvesting is usually done in two stages such as the crop is cut with ordinary sickles and the grain is separated from the straw after threshing with cattle. After separation of grain from the straw, the straw is collected to be used for fodder and construction material for houses made of mud.

In Ethiopia, finger millet is the 6th important crop after *teff*, wheat, maize, sorghum and barley in terms of production and accounted about 5% of area devoted for cereal crops (Molla, 2012; EIAR, 2007). The crop is mainly grown in the northern, northwestern and western parts of the country, especially during the main rainy season (Asfaw et al*.,* 2011). It is grown by subsistence farmers and serves as a food security crop because of its high nutritional value and excellent storage qualities (Masresha et al*.,* 2011). This makes the farmer to store it for longer periods of time and sale whenever there is an attractive market price without significant damage by storage pests (EIAR, 2007; Tenywa et al., 1999). Finger millet is locally processed into various forms of food items such as *injera* and bread*.* However, it is mainly used for the preparation of traditional alcoholic beverages, locally called *Tella and Areki* in the country (Asfaw et al*.,* 2011).

Methods of land/crop suitability analysis

Land suitability assessment is inherently a multi-criteria approach where multiple factors are analyzed by GIS for spatial MCDM process. The criteria are measurable based on which decisions about land quality and its suitability for a specified use can be made (Sarkar et al., 2014). This is a standard and accepted by many researchers to evaluate the suitability of the land for intended land use (Dula, 2010; Lupia, 2012; Wubet et al*.,* 2013). Criteria identification can be done using the participatory approach by a group of experts from various disciplines, but it should adequately represent the decision making environment and must contribute towards the final goal (Lupia, 2011).

The methodology used for land suitability evaluation was the MCE based on FAO (1976) guidelines involving matching of diagnostic land quality against crop requirements and assigning suitability rates for each land quality factors. Each thematic layer in MCE represents a criterion for the land evaluation process (Lupia, 2012). Later on, the criteria were matched with the dominant crop requirements for selected crops (FAO, 1984; Sys et al., 1993; Teshome and Verhe, 1995; Mohammed, 2003; Naidu et al., 2006; Asmamaw et al., 2015). Once the criteria for suitability analysis have been arranged, combinations of the crop requirements and land quality values were made and factor rating for each LUT were decided. The values of the parameter or factor ratings calculated for each land quality parameters provide different suitability classes for each LUT. This can be determined by reclassification of spatial entities in terms of their representative attribute values of suitability for a given LUT (Burrough and McDonnell, 1998). Finally, the factor layers for each land quality parameters were standardized or rated before combination using "*reclass*" of ArcGIS. As a result, all the factors used for this study were reclassified into four land suitability class ratings, such as S1, S2, S3 and N1 (FAO, 1976, 1983, and 2007). These criteria maps are the input data to the GIS-based decision making procedure for the next higher level of suitability analysis.

The MCE process, in this study, involved information about the relative importance's of each criterion to decision makers in an overall suitability analysis. The derivation of weights is a central step in defining the decision maker's preferences as an indicative of its importance relative to other criteria under consideration (Lupia, 2012). As a result, the land suitability maps for the selected LUTs were produced using weighted overlay analysis (WOA) by "*Spatial Analyst Tool >>Overlay>>weighted overlay*" of ArcGIS; based on the relative significances of each factor layers on crop growth rate and yield. Finally, a suitable land allocation map was derived based on the results of land suitability map of each LUT using vector overlay analysis (VOA) by "*Analysis Tools>>Overlay>>Union*" of ArcGIS for sustainable rainfed crop production. Therefore, the methodological flow chart portrayed in Figure 4 indicated the overall procedures of land suitability evaluation in a step-wise process.

The AHP (Analytical Hierarchical Process) was developed by Saaty (1977) as a structured technique for organizing and analyzing complex decisions based on mathematics and psychology. It has been extensively studied and integrated with GIS software packages like ArcGIS "*AHPforArcGIS10.x*" weight derivation module. It is a means to calculate the needed weighting factors by help of a preference matrix where all identified relevant criteria are compared against each other with reproducible preference factors (Mohammed, 2014). The weights, in this study, were defined through the AHP module in ArcGIS 10.1 where the weights must add to 1.0 or 100%. All the criteria, which are considered relevant for a decision, were compared against each other in a pair-wise comparison matrix. It is a measure to express the relative preference among the factors using numerical values (Sarkar et al., 2014). The values expressed a judgment of the relative importance (or preference) of one factor against another ranging from 1 to 9 where a value of 1 expresses "*equal importance*" and a value of 9 is given for those factors having an "*extreme importance*" over another factor (Saaty and Vargas, 1991).

The weighting process in this study combined the experts' suggestion, literatures and researcher's estimation to produce the resultant suitability maps of the study area. After discussion and careful analysis of the set of evaluation criteria with experts and inspection of literature, all the pair-wise comparisons for the set of criteria were made for three LUTs. Thus, all possible combinations of two factors were compared and the AHP calculated a set of weights and a "*consistency ratio*" in a step-wise process. This ratio indicated any inconsistencies that may have been arisen during the pair-wise comparison process. Tables 3 and 4 revealed the weights of the soil and climate land quality factors for *teff*, maize and finger millet production in the AHP weight derivation. Table 5 also showed factor weights of diagnostic soil, climate and topographic land quality for sustainable rainfed *teff*, maize and finger millet production.

Determination of land use requirements (LURs)

The FAO (1976, 1983, and 2007) publications for land evaluation have given a framework of land suitability analysis for crops in terms of suitability classes from highly suitable (S1) to not suitable (N) based on the crop specific land use requirements. Land use requirements are conditions of land necessary or desirable for a successful and sustained practice of a defined land use type (FAO, 1983). These are usually expressed in terms of the need for favorable climatic, topographic, soil attributes and management requirements for optimum production of crops (Wubet et al., 2013). Evaluation of crop requirements is a useful tool in assessing crop adaptability and suitability in a given area (Dula, 2010). Require-ments are expressed by defining optimal, marginal and unsuitable conditions for each land attributes that influence directly

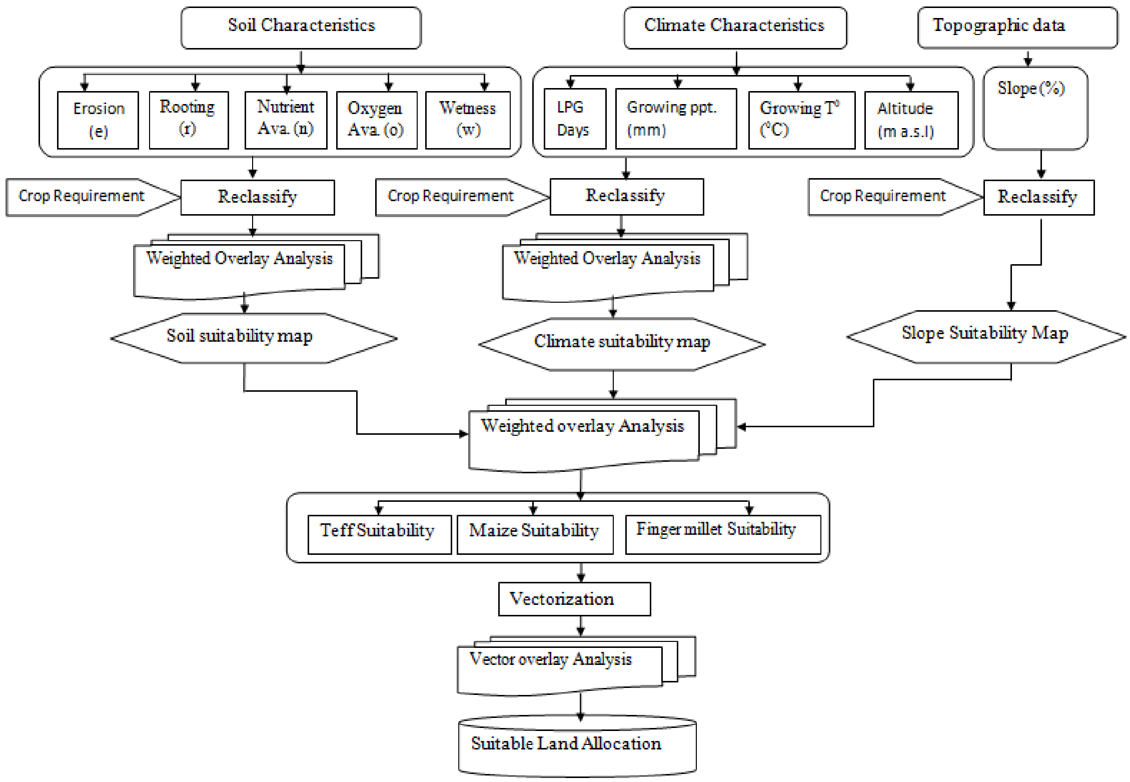

Figure 4. Methodological framework in MCDM process for land suitability evaluation.

Table 3. Criteria weights for LUTs regarding diagnostic soil factors calculated by AHP weight derivation module.

Soil quality factors for each LUTs	Weight (*Teff*)		Weight (Maize)		Weight (Finger millet)	
	%		%		%	
Texture (class)	0.086	8.6	0.088	8.9	0.077	7.7
Drainage (class)	0.073	7.3	0.055	5.5	0.055	5.5
Flood Risk (class)	0.057	5.7	0.055	5.5	0.055	5.5
Ph (H2O)	0.104	10.4	0.097	9.7	0.102	10.2
EB (cmol(+)/kg soil)	0.172	17.2	0.163	16.5	0.166	16.6
CEC (cmol(+)/kg soil)	0.218	21.8	0.189	18.9	0.209	20.9
SOM (%)	0.103	10.3	0.129	12.9	0.099	9.9
PAV (ppm)	0.129	12.9	0.129	12.9	0.124	12.4
TN (%)	0.057	5.7	0.095	9.4	0.113	11.3
Total	1.00	100	1.00	100	1.00	100
Consistency Ratio (CR)	-0.001*		0.109*		0.034*	

Note: * indicates that the CR <1.00 is considered to be consistent enough for all LUTs (table 3 – 5).

or indirectly plant growth, performance and biomass production (Sys et al., 1991). In the present study, soil, climate and landscape requirements of selected LUTs were considered as the major limiting factor or criteria for suitability analysis (Tables 6 – 8). Climate land quality factors considered in this study were moisture availability (precipitation of growing cycle and length of growing period) and temperature regime (mean temperature of the growing cycle and altitude). The topographic requirement was referred in form of slope steepness (%). The soil requirements referred are rooting conditions, oxygen availability, wetness and nutrient

Table 4. Criteria weights for LUTs regarding diagnostic climate factors calculated by AHP weight derivation module.

Land quality factors for each LUTs	Weight (Teff)		Weight (Maize)		Weight (finger millet)	
		%		%		%
Precipitation of growing cycle (mm)	0.31	31	0.267	26.7	0.213	21.3
Length of growing period (days)	0.562	56.2	0.564	56.4	0.408	40.8
Temperature of growing cycle (classes)	0.069	6.9	0.108	10.8	0.325	32.5
Altitude (m a.s.l)	0.058	5.8	0.062	6.2	0.054	5.4
Total	1	100	1	100	1	100
Consistency Ratio	0.03*		0.02*		0.25*	

Note: Spatial variations in diagnostic climate factors for all LUTs are mainly due to altitude over the entire study catchment.

Table 5. Criteria weights for LUTs regarding Land quality factors calculated by AHP weight derivation module.

Land quality factors for each LUTs	Weight (Teff)		Weight (maize)		Weight (finger millet)	
		%		%		%
Slope (percent rise)	0.209	20.9	0.204	20.4	0.265	18.5
Soil factors (classes)	0.461	46.1	0.465	46.5	0.624	52.4
Climate factors (classes)	0.329	32.9	0.331	33.1	0.293	29.3
Total	1.00	100	1.00	100	1.00	100
Consistency Ratio	0.03*		0.04*		0.3*	

Table 6. Land use requirements of *teff* (90-140 days) based on land characteristics data for small-scale rainfed agriculture (FAO, 1984; Lupia, 2012; Seyfu, 1997, Teshome and Verhe, 1995; Asmaamw et al*.,* 2015; Mohammed, 2003).

Land use requirements		Class, degree of limitation and rating scale			
Land quality	Diagnostic factors and unit	100-85%	85-60%	60-40%	<40%
		S1	S2	S3	N1
Moisture availability (m)	Precipitation of growing cycle (mm)	450-550	300-450 550-800	800-1200	<200, >1200
	Length of growing Period (days)	110-150	95-110	75-90; 150-180	<75 >180
Temperature regime (T)	Mean temperature of the growing cycle (^{0}C)	15-21	14-15, 21-22	11-14, 22-25	<11, >25
	Altitude (alt) in (m a.s.l)	1600-2200	1000-1600, 2200-2400	2400-2800	<1000,>2800
Erosion hazard (e)	Slope (%)	<13	13-25	25-50	>50
Rooting conditions (r)	Texture (class)	Si, SiC, C	SiCL	SiL, CL, L	S,SCL,SL
Oxygen availability(o)	Soil drainage (class)	M	P, W	VP	SE, E
Wetness (w)	Flood risk (F)	Fo	F1	F2	F3+
Nutrient Availability (n)	CEC(cmol(+)/kg soil)	>30	30-28	28-16	<16
	EB (cmol(+)/kg soil)	>27	27-15	15-10	<10
	pH ($H_2$01: 2.5)	5.5-7.5	5.2-5.5, 7.5-7.8	5.2-4.5, 7.8-8.5	<4.5, >8.5
	SOM (%)	>3.0	2.5-3.0	2.0-2.5	<2.0
	PAV (ppm)	>10	10-5	5-3	<3
	TN (%)	>0.20	0.20-0.15	0.15 -0.10	<0.10

Table 7. Land use requirements of Maize (120-150 days) based on land characteristics data for small-scale rainfed agriculture (FAO, 1984; Sys, et al., 1993; Mohammed, 2003).

Land Use Requirements		Class, degree of limitation and rating scale			
		100-85%	85-60%	60-40%	<40%
Land Quality	Diagnostic factors and unit	S1	S2	S3	N1
Moisture Availability (m)	Precipitation of growing cycle (mm)	500-750	400-500 750-1200	300-400 1200-1600	<300 >1600
	Length of growing period (days)	140-220	120-140; 220-270	90-120; 270-300	<90; >300
Temperature regime (T)	Mean temperature of the growing cycle (^{0}C)	24-19.5 24-32	19.5-16 32-35	16-14 35-40	<14 >40
	Altitude (alt) in (m a.s.l)	1500-2200	1000-1500, 2200-2400	2400-3000	<1000, >3000
Erosion hazard (e)	Slope (%)	0-8	8-16	16-30	>30
Rooting conditions (r)	Texture (class)	SiC,SiCL, Si, SiL, CL, SC,CL,L,C	SL,LS	S, SCL	S
Oxygen availability(o)	Soil drainage (class)	W	M, P	VP	E, SE
Wetness (w)	Flood risk (F)	Fo	-	F1	F2+
Nutrient Availability (n)	CEC(cmol(+)/kg soil)	>31	31-27	27-16	<16
	EB (cmol(+)/kg soil)	>25	25-15	15-5	<5
	pH ($H_2$01: 2.5)	7.0-6.0	6.0-5.5 7.0-7.8	5.5-5.2 8.2-8.5	<5.2 >8.5
	SOM (%)	>3	3.0-2.5	2.5-1.0	<1.0
	PAV (ppm)	>10	10-5	5-3	<3
	TN (%)	>0.20	0.20-0.15	0.15-0.10	<0.10

Table 8. Land use requirements of finger millet (120-150 days) based on land characteristics data for small-scale rainfed agriculture (FAO, 1984; Sys et al., 1993; Naidu et al., 2006).

Land use requirements		Class, degree of limitation and rating scale			
		100-85%	85-60%	60-40%	<40%
Land quality	Diagnostic factors and units	S1	S2	S3	N1
Moisture availability (m)	Precipitation of growing cycle (mm)	>900	600– 900	450– 600	<450
	Length of growing period (days)	>150	90 – 150	75– 90	<60
Temperature regime (T)	Mean temperature of the growing cycle (^{0}C)	28-34	25 – 27, 35 – 38	39 – 40, 19 – 24	>40, <19
	Altitude (alt) in (m a.s.l)	1500 – 2200	1200 –1500 2200 –2400	1000– 1200	<1000, >2400
Erosion hazard (e)	Slope (%)	<3	3-5	5-10	>10
Rooting conditions (r)	Texture (class)	L,SiL,SLSiC ,L,SCL	SiC, C, SC, CL	LS, S, C>60%	-
Oxygen availability(o)	Soil drainage (class)	W, M	P, SE	VP, E	-
Wetness (w)	Flood risk (F)	Fo	F1	F2	F3+
Nutrient Availability (n)	CEC(cmol(+)/kg soil)	>30	30 – 20	20 – 10	<10
	EB (cmol(+)/kg soil)	>25	25 – 15	15 – 3	<3
	pH ($H_2$01: 2.5)	5.5- 7.5	4.5 - 5.5; 7.6 - 8.5	4.0 - 4.4 ; 8.6 - 9.5	<4.4 <9.5
	SOM (%)	>2.8	2.8 - 2.0	2.0 - 0.8	<0.8
	PAV (ppm)	>14	14-5	5-2	<2
	TN (%)	>0.27	0.27-0.22	0.22-0.15	<0.15

Note: *PAV (ppm) and TN (%) are estimated from nutrient removals in kg/ha values (Tiwari, 2001).

Table 9. Area coverage of land suitability classes for selected LUTs in Gelda catchment, northwest highlands of Ethiopia.

Suitability classes	Teff		Maize		Finger millet	
	hectares	%	hectares	%	hectares	%
S2	19970.23	76.04	18258.47	69.52	17804.19	67.79
S3	6293.77	23.96	8005.53	30.48	8458.16	32.21
Total	26264	100	26264	100	26262.35	100

availability. Therefore, land quality factors such as soil, climate and topographic were considered as LUR in determining suitability status of the selected LUTs; such as *teff* (*Eragrostis tef*), maize (*Zea mays* L.) and finger millet (*Eleusine coracana*).

RESULTS AND DISCUSSION

Land suitability analysis results for selected LUTs

Table 9 and Figure 5 showed the results of WOA using MCE for diagnostic soil quality factors (rooting condition, oxygen availability, wetness, and nutrient availability); topographic factors (slope gradients) and climatic factors (moisture availability and temperature regime) for all selected LUTs. The analysis demonstrated that about 76.04, 69.52 and 67.79% of the study area are classified as moderately suitable (S2) for cultivation of *teff*, maize, and finger millet crops respectively. In addition, about 23.96, 30.48 and 32.21% of the study area were found to be marginally suitable (S3) for cultivation of *teff*, maize, and finger millet crops, respectively. However, none of the area in the study catchment was classified as highly suitable (S1) and unsuitable (N) classes. These indicated that the study area encountered limitations ranges from land having limitations which in aggregate are moderately severe to land having limitations which in aggregate are severe for the selected LUTs at sustained manner. The limitations were largely attributed to lower organic matter content; poor drainage condition in low-lying areas which are dominated by dystric gleysols; erosion in areas of south, southeast and eastern parts of the catchment dominated by steep slopes; and relatively acidic conditions of soils.

Suitable land allocation map analysis results for all LUTs

Figure 6 and Table 10 showed the suitable land allocation map, in the study catchment, along with their best suitability classes when multiple choices and competition were made for all selected LUTs on a particular parcel of land. The VOA results revealed that about 20.25 (5274.22 ha) and 63.92% (16644.38 ha) of the catchment are classified as moderately suitable (S2) and marginally suitable (S3) for cultivation of all selected LUTs, respectively. This showed that a particular plot of land was suitable for different LUTs at the same level of suitability classes. At this point, competitions for the same parcel of land by different LUTs were possible. Thus, farmers could have freedom to choose a range of land uses with the same suitability level and allocate one that best meet his/her interest. Conversely, about 4.38% (1140.87 ha) of land was moderately suitable (S2) for cultivation of both *teff* and maize, but marginally suitable (S3) for finger millet crops. Similarly, about 6.71% (1748.61ha) of land was marginally suitable (S3) for cultivation of maize and finger millet, but moderately suitable (S3) for *teff*. Thus, farmers could prefer cultivation of LUTs with higher level of suitability than others. These are indicatives of competition from among a range of LUTs at different suitability levels for the same parcel of land (Wubet et al*.,* 2013). The remaining suitable land allocation classes hold only small patches of lands over the entire study catchment. However, in the present study, none of the area fell into highly suitable class for all selected LUTs.

Conclusion

The results of land suitability and the suitable land allocation map analysis for *Teff* (*Eragrostis tef*), maize (*Zea mays*) and finger millet (*Eleusine coracana*) identified shortcomings for subsistence rainfed agriculture in the study area. These analyses provide mechanisms to overcome the identified limitations and optimize land use through the application of sustainable land management practices in the study catchment. Management practices involving measures that increase SOM levels and enhance soil fertility will have a significant effect on crop productivity. As a result, increased soil organic matter levels by organic fertilization could contribute improvement in soil structural stability, nutrient storing and exchanging capacity, water infiltration rates and reduced risk of soil erosion. Soil conservation measures could also be implemented in areas where soil erosion is by-far exceeding soil formation rates. This will considerably contribute runoff reduction by reducing

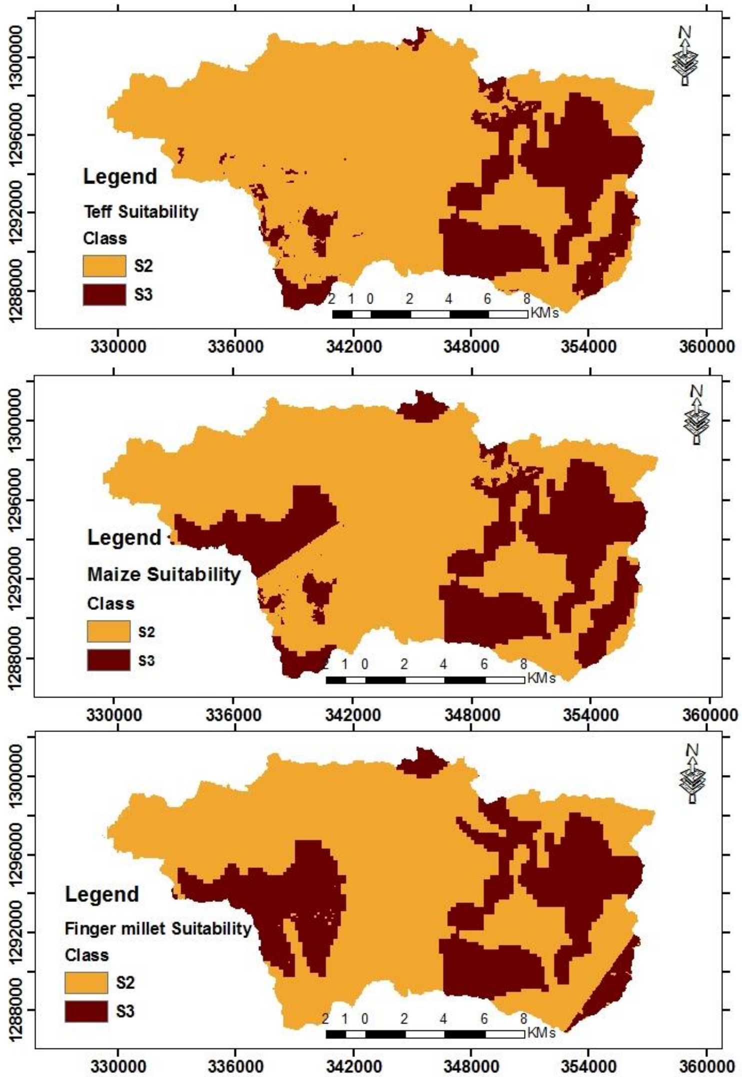

Figure 5. Land suitability maps for selected LUTs in Gelda catchment, northwest highlands of Ethiopia.

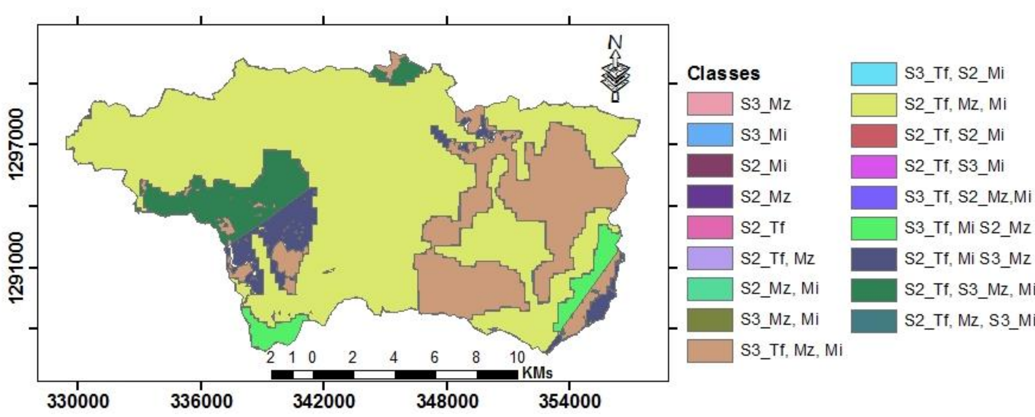

Figure 6. Suitable land allocation map with their respective degree of suitability in Gelda catchment, northwest highlands of Ethiopia. Note**:** Tf = *teff*, Mz = maize and Mi = finger millet.

Table 10. Suitable land allocation for the selected LUTs along with their area coverage.

Suitability land allocation code	Area coverage	
	Ha	%
S2_Tf	14.24	0.05
S2_Mz	20.65	0.08
S3_Mz	13.32	0.05
S2_Mi	21.6	0.08
S3_Mi	5.94	0.02
S3_Mz, Mi	8.82	0.03
S2_Tf, Mz	8.74	0.03
S2_Mz, Mi	21.82	0.08
S2_Tf, Mz	21.21	0.08
S3_Mz, Mi	7.11	0.03
S2_Tf,S3_Mi	10.34	0.04
S3_Tf, Mz, Mi	5274.22	20.25
S2_Tf_Mz, S3_Mi	1140.87	4.38
S3_Tf, Mi, S2_Mz	160.28	0.62
S2_Tf, S3_Mz, Mi	1748.61	6.71
S3_Tf, Mz, S2_Mi	737.67	2.83
S2_Tf, Mi, S3_Mz	134.13	0.52
S2_Tf, Mz, Mi	16644.38	63.92
S3_Tf, S3_Mz, Mi	40.95	0.16

slope length and steepness of farm plots. Proper soil and water conservation techniques (structural and non structural measures) are quite important to protect the top soil from being eroded in the highlands and retain water in soil for longer period of time, i.e., residence time increased in the catchment. These consecutively increase soil loss and runoff in the high slope areas; water retention and flooding in the lower slope areas; and sustain base flow of the main stream in the catchment, i.e., Gelda River. In areas where drainage problem and water logging is inherent, soil drainage practices such as construction of frequent diversion channels, waterways, etc can result in cost–effective mechanism of ensuring optimum production.

The results also showed that some plots of land were suitable for all LUTs at the same level of suitability classes where competitions for the same parcel of land are possible. Farmers could also prefer LUTs with higher level of suitability than others for plots of land that showed different suitability level for different LUTs. However, the parameters used for land suitability analysis in this study were entirely physical (soil, climate and topography) and much improvement can be made if an in-depth analysis on some socio-economic variables are considered. Therefore, land suitability analysis for agricultural crops using MCE in a GIS environment is a strong tool towards measuring and valuation of land in terms of the varying importance to decision makers for sustainable rainfed agriculture.

Conflict of Interests

The authors have not declared any conflicts of interest.

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