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Land suitability analysis for sorghum crop production in northern semi-arid Ethiopia: Application of GIS-based fuzzy AHP approach

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Abstract: The mismatch between the actual requirements and what is actually implemented in a given land could be avoided through land suitability evaluation through its contribution in identifying the inherent land potentials and constraints. This study aims to assess suitability for sorghum (Sorghum bicolor L. Moench) crop by integrating geographic information system (GIS), fuzzy set models and analytical hierarchy process (AHP) methods. Soil, climate and topographic characteristics were considered in the study. As evidenced from the model output, 29,534 ha (30.54%), 34,984.74 ha (36.17%), 17,455 ha (18.05%), 14,744.61 ha (15.24%) of the area is moderately suitable, marginally suitable, currently not suitable and permanently not suitable for sorghum crop production respectively. Slope gradient, altitude, temperature, length of growing period, available water capacity, mean weight diameter, total nitrogen, available phosphorus and soil organic carbon contents were found the main limiting factors constraining cultivation of that crop in the area. Organic and inorganic fertilizer application, tillage and soil and water management activities are needed to boost the productivity of the area.

Subjects: Crop science; Soil science; Climatology; Geomorphology; Landscape

Keywords: suitability class; sorghum; geographic information system; multi-criteria decision-making; analytical hierarchy process

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PUBLIC INTEREST STATEMENT

Ethiopia has large potential of arable land supporting the growth of diverse crops. Unwise use of natural resources and lack of appropriate soil management practices commonly observed in smallholder farmers of the country are, however, resulting in below global average yield of crops. Land suitability evaluation is crucial to identify land potentials and constraints and accordingly recognize portions of land (un)suitable for crop production. This helps to develop appropriate land management. Land suitability evaluation for sorghum crop production was conducted. Topographic, climatic and edaphic factors (though with varying degrees) severely limited the cultivation potential of the area for sorghum crop. This indicates the area is in need of soil fertility, tillage and soil and water management practices in order to boost its sorghum crop yield.
1. Introduction

The unbalanced increase in population growth and food production (FAO, 2009; Grafton, Daugbjerg, & Qureshi, 2015; McKenzie & Williams, 2015; Scherer, Verburg, & Schulp, 2018) supported by greater reliance of rural livelihoods on agriculture-led income sources (Davis, Giuseppe, & Zezza, 2017) is leading to a decline in health and productivity of global land resources (Cowie et al., 2018). Land and soil degradation emanated from such factors is the main concern of the world (Keessstra et al., 2016; Popp, Lakner, Harangi-Rakos, & Fari, 2014) today as it might lead to serious threats in sustainability of agricultural systems. Limited natural resources, degradation, water scarcity and climatic variability are critically constraining agricultural development of arid to dry sub-humid areas (Elalem, Comber, & Fisher, 2011; Robinson, Erickson, Chesterman, & Worden, 2015). Even though not evenly distributed, Ethiopia has large potential of arable land (Chamberlin, Jayne, & Headey, 2014; Kebede, 2002; You et al., 2011) supporting the suggestion noting the presence of vast acreages of suitable but unused land in the world (IIASA/FAO, 2012) in general and Africa (Deininger & Byerlee, 2011) in particular for crop production. Agriculture in Ethiopia, however, is mostly rain-fed subjected to high inter-annual and seasonal rainfall variability (Mekuriaw, 2017; Seleshi & Camberlin, 2006) and land degradation (Abegaz, Winowiecki, Vågen, Langan, & Smith, 2016; Gebreselassie, Kirui, & Mirzabaev, 2016; Nyessen, Frankle, Zebele, Deckers, & Poesen, 2015; Pender, Place, & Ehui, 2006). Unwise use of natural resources (Negusse, Yazew, & Tadesse, 2013) and lack of appropriate soil management practices are commonly observed (Worqlul et al., 2017; Yebo, 2015) in smallholder farmers.

Moreover, timely and reliable land resources information with respect to their nature, extent and spatial distribution are missing in the country even though they are very fundamental for optimal utilization of available natural resources on a sustained basis (Karlen & Rice, 2015; Sahu, Reddy, Kumar, & Nagaraju, 2015; Tóth, Jones, & Montanarella, 2013). Observation of high cereal yield gaps in the country (Van Ittersum et al., 2016) might be related with those factors. Its increase in agricultural production, due those reasons, could never been able to keep pace with raising demands of its drastic population growth in the past decades (Beyene, 2008). More than 65% of the land in Tigray region of northern Ethiopia is under cultivation (Beyene, Gibbon, & Haile, 2006). It has rugged topography and variable and erratic but intense rainfall (Vanmaercke et al., 2010; Hadgu Tesfaye, & Mamo, 2015; Meaza et al., 2017; Tesfaye, Birhane, Leijnse, & van der Zee, 2017). Its soils are not well studied in terms of their fertility and productivity classes. Similarly, the study area which is located in Enderta dry midlands of southern Tigray is characterized by limited information on soil characteristics, their potentials and limitations; climate and topographic derivatives despite they are fundamental requirements of developing appropriate land-use planning. The degrees of suitability of the area for crop production purposes, accordingly, do not well studied. Goals of sustainable agriculture would, however, be achieved when lands were categorized and utilized based up on their different use (FAO, 1993).

Land suitability evaluation made by matching land characteristics with land utilization requirements (Mustafa et al., 2011) is needed to match land resources and land use in an effective and logical way (Abd-Elmabod et al., 2017; Bagherzadeh & Gholizadeh, 2016; Jiao, Zhang, & Xu, 2017; Li et al., 2017). It is fundamental to reduce unwise utilization of natural resources (AbdelRahman, Natarajan, & Hegde, 2016; Yu, Shi, Huai, & Li, 2013) by avoiding the mismatch between the actual requirement and what is actually implemented in the field (Hegde, Niranjan, Nataraman, & Naidu, 2012) and accordingly develop strategies for achieving optimum agricultural outputs (Pramonik, 2016; Zabihi et al., 2015) by identifying its inherent potentials and constraints (Bagherzadeh, Ghdiri, Darban, & Gholizadeh, 2016; Mousavi, Sarmadian, Alijani, & Taati, 2017). Apart from this, land evaluation is necessary for land-use planners in avoiding costly mistakes and improving efficiency of investments (Young, 2000) and sustainability of crop production over time (Qureshi, Singh, & Hasan, 2018).
Land suitability, however, needs information integration from different streams of science (Otgonbayar et al., 2017) and asks multiple criteria (Duc, 2006; Kidanu, Kindu, & Chernet, 2009; Prakash, 2003; Yalew, Van Griensven, Mul, & van der Zaag, 2016b). Geographical information systems (GIS) is a powerful tool in storing, retrieving, processing and analyzing multi-source spatial/temporal data needed for spatial planning and management (Kamkar, Dorri, & da Silva, 2014; Singh, Jha, & Chowdary, 2017). However, GIS does not take in to account criteria preferences as all criteria are not equally important (Gigović, Pamućar, Bajić, & Drobnjak, 2017; Kazemi, Sadeghi, & Akinci, 2016). It cannot overcome the issue of inconsistency when judging and assigning relative importance of criteria (Rad & Haghyghy, 2014) required for land suitability evaluation. In such conditions, advancements in geo-spatial domain generated multiple-criteria decision-making (MCDM) tools to expand the decision support capabilities of GIS (Malczewski & Rinner, 2015). Those techniques aid decision-makers in formally structuring multi-faceted decisions and evaluating the alternatives (Greene, Devillers, Luther, & Eddy, 2011; Zavadskas, Stević, Tanackov, & Prentkovskis, 2018) by ranking sets of alternatives for problem solving (Romano, Dal Sasso, Liuzzi, & Gentile, 2015).

Due to these reasons, planners are encouraged to use MCDM tools in combination with GIS (Mosadeghi, Warnken, Tomlinson, & Mirfendereski, 2015) for in integrating and handling multiple and heterogeneous factors (Harper, Anderson, James, & Bahaj, 2017; Houshyar, Smith, Mahmoodi-Eshkaftaki, & Azadi, 2017; Torrieri & Batô, 2017). Those techniques provide structured and spatially explicit evaluation frameworks (Seyedmohammadi, Sarmadian, Jafarzadeh, Ghorbani, & Shahbazi, 2018; Yalew et al., 2016b) and facilitate evidence-based judgments for sustainable land-use management practices (Musakwo, 2017; Singh & Swain, 2016). Moreover, those methods are proved to be flexible, effective and powerful approaches in the area of land suitability (Al-Mashreki, Akhir, Rahim, Lihan, & Haider, 2011a; Bagheri, Sulaiman, & Vaghefi, 2013; Xu & Zhang, 2013) as they present options for developing feasible land suitability maps (Van Chuong, 2008). Analytical hierarchy process (AHP) technique is one of the most commonly used MCDM techniques in GIS-based suitability procedures (Din & Yunusova, 2016) because of its appropriateness for making decisions on the basis of multiple factors ranked according experts’ preferences (Qureshi et al., 2018; Wijenayake, Amarasinghe, & De Silva, 2016).

Integrating AHP with fuzzy set theory provides more sophisticated results as fuzzy set theories use advanced algorithms to address uncertainties, incompleteness and vagueness (Elaalem, 2012; Pamućar, Gigović, Bajić, & Janošević, 2017; Zhang & Achari, 2010) and increase robustness associated with suitability criteria (Liu, Jiao, Liu, & He, 2013; Malmir, Zarkesh, Monavari, Jazi, & Sharifi, 2016; Pichaimani & Manjula, 2016). Several researchers all over the world (Table 2) used GIS techniques and multi-criteria analysis in land suitability evaluation of different purposes. The objective of this study was to identify suitable lands for sorghum crop production using GIS-based fuzzy AHP techniques for Enderta dry midlands of northern semiarid Ethiopia.

| Table 1. Data used for land suitability, their details and data sources |
|-----------------------------|---------------------------------|---------|
| Data type                   | Source                          | Year    |
| Soil morphological and environmental characteristics | Field work survey | 2016 |
| Soil physical and chemical properties | Laboratory analysis results (Tigray agricultural research institute; soil laboratory section) | 2016 |
| Landform information (slope and elevation) | Topographic maps (1:50,000 scale) (Ethiopian mapping authority) | 1997 |
| Aster DEM | | 2015 |
| Climate variables | National and regional meteorological services agency of Ethiopia | 2015 |
Table 2. Review of papers that used GIS-based MCDM for land suitability evaluation

| Author                                      | MCDM technique | Criteria used                                                                                           | Suitability Field       |
|---------------------------------------------|----------------|---------------------------------------------------------------------------------------------------------|-------------------------|
| Hossain and Das (2010)                      | AHP            | Water temperature, water pH, dissolved oxygen, Nitrate-N, Phosphate-P, total dissolved solids, texture, slope, pH, soil organic carbon, land use, distance to road, distance to electricity, distance to market, distance to fry source, labor availability | Aquaculture              |
| Feizizadeh and Blaschke (2012)              | AHP            | Elevation, slope, aspect, fertility, pH, temperature, precipitation, ground water storage                | Rainfed and irrigated agriculture |
| Mendas and Delali (2012)                    | ELECTRE Tri    | Easily utilizable water reserve, drainage, permeability, pH, EC, CaCO3, CEC, texture, soil depth, slope, labor availability, distance to road | Durum wheat             |
| Walke, Reddy, Maji, and Thayalan (2012)     | MOS            | Precipitation, temperature, LGP, RH, Slope, erosion, drainage, flooding, AWC, stoniness, texture, coarse fragments, soil depth, CaCO3, gypsum, CEC, PBS, SOC, EC, texture | Cotton                  |
| Akinci, Özalp, and Turgut (2013)            | AHP            | Soil group; LUCS, LUCSS, soil depth, slope, aspect, elevation, erosion, other soil properties            | General agriculture     |
| Ayehu and Besufekad (2015)                  | AHP            | Slope, soil depth, temperature, precipitation, pH, texture                                             | Rice                    |
| Mighty (2015)                               | AHP            | Precipitation, temperature, soil group, geology, distance to roads, Easily utilizable water reserve, elevation, slope | Coffee                  |
| Mishra, Deep, and Choudhary (2015)          | AHP            | Distance to roads, drainage, soil groups, slope, geology, LULC                                        | Organic farming         |
| Zhang, Su, Wu, and Liang (2015)             | Fuzzy AHP      | Precipitation, temperature, sunshine hours, soil soluble chlorine, pH, SOC, AN, AP, AK, calcium, magnesium, molybdenum, relief, elevation, slope, soil types | Tobacco                 |
| Zolekar and Bhagat (2015)                   | AHP            | Slope, soil depth, texture, SOC, WHC, pH, TN, AP, exchangeable potassium, erosion, LULC                | General agriculture     |
| Gigović, Pamučar, Lukić, and Marković (2016)| Fuzzy DEMATEL  | Elevation, slope, aspect, visibility, precipitation, temperature, geology, soil cover, vegetation type and density, LULC, reservation, stable water, distance from settlements, distance from road, distance from cultural sites and negative factors (constraints) | Ecotourism development |
| Pramanik (2016)                             | AHP            | Slope, elevation, LULC, soil moisture, drainage, texture, geology, aspect, distance from roads, distance from water sources | General agriculture     |
| Yalew et al. (2016a)                       | AHP            | Soil moisture, stoniness, soil group, water resources, elevation, slope, soil depth, distance from roads | General agriculture     |
| Yalew et al. (2016b)                       | AHP            | LULC, slope, stoniness, soil group, soil depth, soil moisture, elevation, distance from settlements, distance from roads, water resources | General agriculture     |
| Aburas, Abdullah, Ramli, and Asha‘ari (2017)| AHP            | Elevation, slope, texture, population density, LULC, distance from roads, distance to infrastructures    | Urban planning          |
| Diop, Ndiaye, Sambou, Dacosta, and Sambou (2017)| AHP        | Elevation, slope, ground water level, soil type, distance between dwelling areas and wetlands          | Flood vulnerability     |

(Continued)
| Author | MCDM technique | Criteria used | Suitability Field |
|--------|----------------|---------------|-------------------|
| Gigović, Parnučar, Božanić, and Ljubojević (2017) | DEMATEL, ANP and MABAC | Wind speed, LULC, distance from settlements, distance from constraints, distance from power lines and telecommunication, slope, distance from roads, aspect, population density | Wind farm |
| Maleki, Kazemi, Siahmarguee, and Kamkar (2017) | AHP | Temperature, precipitation, sunshine hours, frost hazard, RH, permeability, texture, pH, elevation, slope, aspect | Saffron |
| Otgonbayar et al. (2017) | AHP | Slope, elevation, soil humus, depth of soil humus, texture, pH, stoniness, SOC, above ground biomass, NDVI, LAI, GPP, Temperature, precipitation, river density, permafrost distribution, water index, distance from settlements, population density, availability of water resources | Cropland agriculture |
| Owusu et al. (2017) | AHP | LULC, slope, soil unit, flow accumulation, transmissivity, regolith, water availability, borehole, distance from roads, population density | Aquifer storage and recharge site locations |
| Bagdanavičiūtė et al. (2018) | AHP | EC, current velocity and stability, suspended materials, marine protected areas, distance from roads, ice cover, water resources | Zebra mussel farming |
| Buruso (2018) | AHP | LULC, slope, distance from settlements, availability of water resources, elevation | Hillside development |
| Dell'Ovo, Capolongo, and Oppio (2018) | MC-SDSS | Distance from settlements, building density, accessibility to public, private and parking areas, green area, distance to infrastructures, noise pollution, air pollution, unhealthy industries | Hospital installation |
| Kazemi and Akinci (2018) | AHP | LULC, SOC, pH, EC, texture, erosion, precipitation, temperature, sunshine hours, slope, elevation | Rainfed agriculture |
| Purnamasari, Ahamed, and Naguchi (2018) | ANP and AHP | LULC, slope, precipitation, temperature, water resources availability, elevation, soil group, NDVI | Cassava |
| Raza, Mahmood, Khan, and Liesenberg (2018) | AHP | Leaf emergency, tillering, panical primoda, flowering, milky dough, ripening, soil group, drainage, pH, EC | Rice |
| Ristić, Maksin, Nenković-Riznić, and Basarić (2018) | AHP and Delphi process | Protection level of natural heritage, restrictions in protection, bearing capacity, seismicity, Erosion, landslide, rockfall, exposure, slope, hypsometry, distance from power lines, snowfall, avalanche, ground water storage, flooding, LULC | Site selection for protected areas |
| Roy and Saha (2018) | AHP | Precipitation, temperature, slope, relief, water resources, geology, texture, depth, pH, TN, AP, exchangeable potassium, micro nutrients | Rice |
| Tomić, Mastelić Ivić, and Roić (2018) | AHP and PROMETHEE | Share of agricultural land, average size and shape of agricultural parcel, number of agricultural holdings and their fragmentation index, share of state owned agricultural land, regional development index | Land consolidation suitability |

**Table 2.** (Continued)

AHP = analytical hierarchy process; ELECTRE Tri = ELimitation Et Choix Traduisant la Réalité; DEMATEL = Decision-Making Trial and Evaluation Laboratory; ANP = Analytic Network Process; MABAC = Multi-Attributive Border Approximation area Comparison; LUCS = land-use capability class; LUCSS = land-use capability sub class; EC = electrical conductivity; CaCO3 = calcium carbonate; CEC = cation-exchange capacity; LGP = length of growing period; RH = relative humidity; PBS = percentage base saturation; SOC = soil organic carbon; LULC = land use/cover class; AN = available nitrogen; AP = available phosphorus; AK = available potassium; WHC = water holding capacity; TN = total nitrogen; NDVI = normalized difference vegetation index; LAI = leaf area index; GPP = gross primary productivity; PROMETHEE = Preference Ranking Organisation Method for Enrichment Evaluation.
2. Materials and methods

2.1. Study area
The study area encompasses the central plateau regions of northern Ethiopia which lies between latitudes of 12º 55' N to 13º 20' N and longitudes of 39º 20' E to 39º 55' E with elevation ranging from 2000 to 3500 m above sea level (Figure 1). The area consists of rolling and undulating plains, medium to high gradient slopes consisting valleys, hills and mountainous landforms. Its land use is mainly subsistence rain-fed agriculture and has a semi-arid climate with mean annual rainfall of 500–850 mm and daily mean temperature of 15–30°C. The lithology comprises mesozoic Antalo limestone, Amba Aradom sandstone, Tertiary basalt and dolerites (Arndt & Menzies, 2005; Nyssen et al., 2004).

2.2. Data collection
Land characteristics influencing rain-fed sorghum production (Table 4) were identified based on different literatures and available data. Accordingly, climate, soil and topographic factors mostly taken as critical determinant parameters of land suitability evaluation (Al-Mashreki et al., 2011b; Bhagat et al., 2009; Guan, Wu, & Carnes, 2016; Mesgaran, Madani, Hashemi, & Azadi, 2017) were used to determine the overall suitability of the area for that crop. Data needed for land suitability modeling were collected from different sources (Table 1). Physical and chemical soil data were collected from laboratory analysis results while environmental and site factors were gathered during field work. Soil characteristics were averaged according to the effective rooting depth (control section) of sorghum which was taken as 1m (FAO, 1992). Slope and elevation information was obtained from Topographic maps of 1:50,000 scale and ASTER DEM (Advanced Spaceborne Thermal Emission and Reflection Radiometer) downloaded from Unites States Geological Survey (USGS) databases using different GIS softwares. Climate variables were assembled from national and regional meteorological agencies and then were exported to ArcMap10 and their spatial variability over the area was expressed by using “kriging” interpolation method.

Sorghum is among the major cereal crops grown in Ethiopia accounted for staple food of local people (Kidanu et al., 2009; Motuma, Suryabhagavan, & Balakrishnan, 2016). It grows in diverse agro-ecologies but adapts well to warm climates worldwide (AbdelRahman et al., 2016). It requires 450–650 mm rain and fairly long and frost-free growing season for high rain-fed production.

| Intensity of importance | Definition | Explanation |
|-------------------------|------------|-------------|
| 1                       | Equal importance | Two activities contribute equally to the objective. |
| 3                       | Moderate importance of one over another | Experience and judgment slightly favor one activity over another. |
| 5                       | Essential or strong importance | Experience and judgment strongly favor one activity over another. |
| 7                       | Demonstrated importance | An activity is strongly favored and its dominance is demonstrated in practice. |
| 9                       | Extreme importance | The evidence favoring one activity over another is of the highest possible order of affirmation. |
| 2, 4, 6, 8              | Intermediate values between the two adjacent judgments | When compromise is needed |
| Reciprocal of above non zero numbers | If activity “m” has one of the above non zero numbers assigned to it when compared with activity “n”, then n has the reciprocal value when compared with m. |
It is intolerant to low temperature conditions and permits completion of its growing period within the rainy season (FAO, 1987c). It needs at least 0.50 m soil depth (Verdoodt & Van Ranst, 2003), higher CEC, nutrient and moisture contained clayey soils but asks high fertilizer application when grown in light-textured soils (Naidu, Ramamurthy, Challa, Hegde, & Krishnan, 2006) to allow optimal growth. It moderately tolerates drainage, salinity and sodicity and has moderate fertility requirement but asks high workability (FAO, 1987c).

2.3. Methods

The overall methodology followed in the study is illustrated in Figure 2. Criteria maps showing the spatial distribution of attributes were constructed based on different GIS functions. Criteria maps showing the spatial distribution of attributes were constructed based on different GIS functions. Fuzzy membership functions which gives more informative results by reducing vagueness and uncertainty (Elaalem, 2012) with membership grades ranging from 0 (non-membership) to 1 (complete membership) were used to standardize criteria maps. Higher pixel score indicates a higher suitability level for that pixel. Suitable ranges of the factors that determine the lowest and greatest suitability levels were determined based on different scientific resources (Table 4) in order to apply fuzzy membership functions. Standardized factor maps (Figures 3 and 4) were accordingly developed using sigmoidal fuzzy membership function (Table 4) using the decision support tool of IDRISI software.

All criteria were ranked according to their significance following expert opinions and literatures. Accordingly, weights of criteria used for suitability evaluation were obtained using professional experiences of local experts in Hintalo Wajerat district supported by different scientific literatures through pair-wise comparisons following AHP (a widely accepted decision-making method (Eskandari, Homae, & Mahmoodi, 2012; Feizizadeh & Blaschke, 2013)) in IDRISI software. AHP constructs a pair-wise comparison matrix by assigning values in the range of 1–9 (Table 3) for each factor against every other (Saaty, 1980) which finally gives in eigenvector weights indicating...
Table 4. Ranges of factor suitability used for fuzzy membership function for rainfed sorghum

| Factor             | Shape of fuzzy membership function | Non-membership (unsuitable) | Membership grade (suitable range) | References                                                                 |
|--------------------|-----------------------------------|-----------------------------|-----------------------------------|---------------------------------------------------------------------------|
| Depth (cm)         | MI                                | <30                         | 30–100                            | Kaaya et al. (1994); Naidu et al. (2006)                                   |
| Structure (class)  | -                                 | -                           | Granular and crumb to sub-angular blocky | Crumb and granular structures are most suitable, (sub)-angular blocky and prismatic moderately suitable, single grain and massive marginally suitable (adapted from FAO (1987b) and Lal (1994)) |
| Consistency (class)| -                                 | -                           | Loose and (very) friable          | Loose and very friable are most suitable; friable moderately suitable; (extremely) hard marginally suitable (adapted from FAO (1987a,b), Lal (1994)) |
| Rock out crops (%) | MD                                | >40                         | 0–40                              | Nedeco (1997), IAO (2008)                                                 |
| Coarse fragments (%)| MD                               | >55                         | 0–55                              | Sys, Van Ranst, and Debaveye (1993)                                        |
| Drainage (class)   | MI                                | -                           | Well to moderately drained        | Well drained to moderately drained soils are highly suitable; imperfectly drained moderately suitable; very poor to extremely poor marginally suitable (Verdoodt and Van Ranst (2003); Naidu et al. (2006)) |
| Erosion (class)    | MD                                | -                           | Nil to moderate                   | Nil erosion level is highly suitable; slight is moderately suitable; moderate, severe and very severe marginally suitable (Elaalem, 2012) |
| Texture (class)    | SM                                | -                           | C, CL, SiCL, SC, L, SiL, SiC, SCI, SL, LS | C, CL, SiCL, and SC are highly suitable; L, SiL, SiC, SCI moderately suitable; Si and LS marginally suitable (Naidu et al. (2006); Ahmed and Jeb (2014); Van Orshoven, Terres, & Tóth, 2014) |
| Bulk density (g cm\(^{-3}\)) | MD                           | >1.6                        | 1.2–1.6                           | FAO (1987a,b), Lal (1994)                                                 |
| MWD (mm)           | MI                                | <0.5                        | 0.5–2.5                           | Lal (1994)                                                                |
| AWC (% vol/vol)    | MI                                | <7.5                        | 7.5–20                            | Naidu et al. (2006), Elaalem (2012)                                        |
| pH                 | SM                                | <5/>8.5                     | 5–8.5                             | Kaaya et al. (1994), Elaalem (2012)                                        |
| EC (dSm\(^{-1}\)) | MD                                | >10                         | 0–10                              | Naidu et al. (2006), Elaalem (2012), Ahmed and Jeb (2014)                 |
| CaCO\(_3\) (%)     | MD                                | >25                         | 0–25                              | Naidu et al. (2006)                                                       |
| CEC (cmol\((\text{Kg}^{-1})) | MI                        | <10                         | 10–30                             | Naidu et al. (2006)                                                       |
| PBS (%)            | MI                                | <35                         | 35–80                             | Kaaya et al. (1994), Naidu et al. (2006)                                   |
| Ex.bases (cmol\((\text{Kg}^{-1})) | MI                       | <2                          | 2–5                               | Sys et al. (1993)                                                         |
| ESP (%)            | MD                                | >15                         | 0–15                              | Naidu et al. (2006)                                                       |
| Ca\(^{2+}\) (cmol\((\text{Kg}^{-1})) | MI                      | <4                          | 4–10                              | FAO (1987a, b), Ahmed and Jeb (2014)                                      |
| Mg\(^{2+}\) (cmol\((\text{Kg}^{-1})) | MI                      | <0.3                        | 0.3–5                             | FAO (1987a, b)                                                            |
| K\(^{+}\) (cmol\((\text{Kg}^{-1})) | MI                      | <0.15                       | 0.15–0.4                          | FAO (1987a, b), Ahmed and Jeb (2014)                                      |

(Continued)
the relative importance of the various factors considered (Bagherzadeh & Gholizadeh, 2016; Li et al., 2017; Saatsaz, Monsef, Rahmani, & Ghods, 2018). Consistency ratio (CR) was used to evaluate the degree of consistency of comparison of the factors (Saaty, 1977). A CR value of less than 10% was considered acceptable (Brunelli, 2014; Liu, Peng, Zhang, & Pedrycz, 2017).

After weightings and rating of all criteria over the hierarchy obtained, standardized criteria maps were multiplied with these criteria weights (Ayoade, 2017; Romano et al., 2015) at each level of the hierarchy by pertaining weighted linear combination (the most common method in MCDA

*Table 4. (Continued)*

| Factor Shape of fuzzy membership function | Non-membership (unsuitable) | Membership grade (suitable range) | References |
|------------------------------------------|-----------------------------|-----------------------------------|------------|
| SOC (%) MI | <0.5 | 0.5–2 | Kaaya et al. (1994) |
| TN (cmolKg⁻¹) MI | <0.02 | 0.02–0.2 | Kaaya et al. (1994) |
| AP (ppm) MI | <3 | 3–40 | Kaaya et al. (1994) |
| ppt (mm) SM | <450>1400 | 450–1400 | Sys et al. (1993), Naidu et al. (2006) |
| T° (°C) SM | <15>32 | 15–32 | Sys et al. (1993), Elaalem (2012) |
| LGP (days) SM | <90>310 | 90–310 | FAO (1987c), Naidu et al. (2006) |
| Slope (%) MD | >16 | 0–16 | Naidu et al. (2006), Ahmed and Jeb (2014) |
| Altitude (m) SM | <500>2300 | 500–2300 | FAO (1988), Verdoodt and Van Ranst (2003) |

*Figure 2. Flow chart of the land suitability evaluation for sorghum crop.*
Figure 3. Standardized factor maps of criteria used for sorghum suitability.

Figure 4. Standardized factor maps of criteria used for sorghum suitability.
(Malczewski & Rinner, 2015)) in order to produce an overall sorghum crop suitability map following the equation below.

\[ SI = \sum Wi \times Xi, \text{ Where: } SI = \text{Suitability Index}, \ Wi = \text{weight of factor I}, \text{ and } Xi = \text{normalized criterion score}. \]

The map produced was reclassified as permanently not suitable (<0.2), currently not suitable (0.2–0.4), marginally suitable (0.4–0.6), moderately suitable (0.6–0.8) and highly suitable (>0.8) (FAO, 1976, 1983; Sys, Van Ranst, & Debaveye, 1991).

3. Results and discussion

According to the pair-wise comparison results (Table 5), climate, soil and topographic factors were assigned weight values of 0.4126, 0.3275 and 0.2599, respectively. From the climate sub-criteria, length of growing period (0.5396) followed by precipitation (0.2970) got high weight values. Contribution of slope was superior (0.6) over altitude (0.4) from the topographic sub-criteria in relation to sorghum crop production. Among the main soil factors, chemical (0.4434) followed by physical (0.3874) got higher values than site and morphological soil characteristics (which scored weight value of 0.1692). The matrix result indicated that depth (0.2613), erosion (0.2063) and coarse fragments (0.1687) from morphological; texture (0.2894) and bulk density (0.2894) from physical factors and soil organic carbon (0.1941), total nitrogen (0.1217) and available phosphorus (0.1204) from chemical factors were the most important factors for sorghum production. Drainage (0.0496) and consistency (0.0636) followed by soil structure (0.1119); mean weight diameter (0.1750); exchangeable sodium percentage (0.0180), electrical conductivity (0.0248) and calcium carbonate (0.0348) were considered least important from morphological, physical and chemical factors respectively for cultivation of that crop. For sorghum production, the matrix produced CR values ranging between 0.00 and 0.05 indicating that the results were within the 0.1 (the threshold value).

The result of land suitability classification for sorghum is presented in Figure 5 and Table 7. The area was moderately suitable (29,534.86 ha or 30.54% of it) scattered in the eastern and northwestern parts of the area, marginally suitable (34,984.74 ha/36.17%) concentrated in western, central and partly eastern locations of the area, currently not suitable (17,455.81 ha/18.05%) dominating the south and southwestern portions and permanently not suitable (14,744.61 ha/15.24%) to the south and southeast parts of the area (Table 7). Short length of growing period was more serious for that crop. Mean weight diameter, available water capacity, soil organic carbon, total nitrogen and available phosphorus (Figures 3 and 4) were below optimum posing very severe limitations. Taking in to account the weights of main and sub-factors. The weights of main and sub-factors (Table 5), overall weight of each factor (Table 6) was calculated by multiplying the weight of main factors and sub-factors.

Moreover, limitations of depth and coarse fragments (western parts of the area), bulk density (southern, eastern and northern parts), magnesium (central, western and north eastern locations) and precipitation (its southern parts) constrained the sorghum production capacity of the area (Figures 5 and 6). Altitude and temperature are above optimum level resulting in moderate to severe limitations. Influences of high pH and calcium carbonate were noticeable in the valley floors, plateau and sloping land situated in central and (north) eastern part of the study area. Similarly, Ahmed and Jeb (2014) reported that areas in Bunkure Kano state of Nigeria were moderately suitable to permanently unsuitable for growing sorghum since they exhibited limitations in soil organic carbon, soil depth and rockout crops.

Low soil organic carbon, total nitrogen, available phosphorus and soil moisture of an agricultural farm in Tanzania (Kaaya, Msanya, & Mrema, 1994) limited its suitability for sorghum cultivation. Moreover, rainfall, temperature and calcium carbonate content expressed serious limitations in suitability of micro-water watershed for sorghum production (Mohan, 2008). Temperature of
Table 5. Pair-wise comparison matrix for evaluating relative importance of the factors used for suitability evaluation of sorghum crop

| Criteria and classes within each criteria | Pair-wise comparison matrix | Weight |
|-----------------------------------------|----------------------------|--------|
| Main criteria                            | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) | (13) |
| (1) Climate                              | 1   | 1   | 2   |     |     |     |     |     |     |     |     |     |     | 0.4126 |
| (2) Soil                                 | 1   | 1   | 1   |     |     |     |     |     |     |     |     |     |     | 0.3275 |
| (3) Topography                           | 1/2 | 1   | 1   |     |     |     |     |     |     |     |     |     |     | 0.2599 |
| Consistency ratio                        |     |     |     |     |     |     |     |     |     |     |     |     |     | 0.05   |
| Climate sub criteria                     |     |     |     |     |     |     |     |     |     |     |     |     |     |        |
| (1) Precipitation (ppt)                  | 1   | 2   | 1/2 |     |     |     |     |     |     |     |     |     |     | 0.2970 |
| (2) Temperature (°)                      | 1/2 | 1   | 13  |     |     |     |     |     |     |     |     |     |     | 0.1634 |
| (3) Length of growing period (LGP)       | 2   | 3   | 1   |     |     |     |     |     |     |     |     |     |     | 0.5396 |
| Consistency ratio                        |     |     |     |     |     |     |     |     |     |     |     |     |     | 0.01   |
| Topography sub-criteria                  |     |     |     |     |     |     |     |     |     |     |     |     |     |        |
| (1) Slope                                | 1   | 3/2 |     |     |     |     |     |     |     |     |     |     |     | 0.06   |
| (2) Altitude                             | 2/3 | 1   |     |     |     |     |     |     |     |     |     |     |     | 0.04   |
| Consistency ratio                        |     |     |     |     |     |     |     |     |     |     |     |     |     | 0.00   |
| Soil criteria: morphological, physical and chemical properties |     |     |     |     |     |     |     |     |     |     |     |     |     |        |
| (1) Morphological                        | 1   | 1/2 | 1/3 |     |     |     |     |     |     |     |     |     |     | 0.1692 |
| (2) Physical                             | 2   | 1   | 1   |     |     |     |     |     |     |     |     |     |     | 0.3874 |
| (3) Chemical                             | 3   | 1   | 1   |     |     |     |     |     |     |     |     |     |     | 0.4434 |
| Consistency ratio                        |     |     |     |     |     |     |     |     |     |     |     |     |     | 0.02   |
| Soil sub-criteria: morphological and site factors |     |     |     |     |     |     |     |     |     |     |     |     |     |        |
| (1) Depth                                | 1   | 3   | 4   | 2   | 2   | 1   | 4   |     |     |     |     |     |     | 0.2613 |
| (2) Structure                            | 1/3 | 1   | 2   | 1   | 1/2 | 1/2 | 3   |     |     |     |     |     |     | 0.1119 |
| (3) Consistency                          | 1/4 | 1/2 | 1   | 1/3 | 1/3 | 1/3 | 2   |     |     |     |     |     |     | 0.0636 |
| (Continued)                              |     |     |     |     |     |     |     |     |     |     |     |     |     |        |
Table 5. (Continued)

| Pair-wise comparison matrix | Weight |
|----------------------------|--------|
| **Criteria and classes within each criteria** |        |
| (4) Rockout crops | 1/2 1 3 1 1 1/2 3 | 0.1386 |
| (5) Coarse fragments | 1/2 2 3 1 1 1 2 | 0.1687 |
| (6) Erosion | 1 2 3 2 1 1 3 | 0.2063 |
| (7) Drainage | 1/4 1/3 1/2 1/3 1/3 1/3 1 | 0.0394 |
| **Consistency ratio** | 0.02 |
| **Soil sub-criteria: physical factors** |        |
| (1) Texture | 1 1 2 1 1 | 0.2894 |
| (2) Bulk density | 1 1 2 1 1 | 0.2894 |
| (3) Mean weight diameter | 1/2 1/2 1 1 1/2 | 0.1750 |
| (4) Available water capacity | 1 1 1 1 1 | 0.2463 |
| **Consistency ratio** | 0.02 |
| **Soil sub-criteria: chemical factors** |        |
| (1) pH | 1 4 2 1/3 1/2 1/2 1 3 3 2 4 1 5 | 0.0248 |
| (2) Electrical conductivity (EC) | 1/4 1 1/2 1/6 1/4 1/3 1/3 1/3 1/4 1/2 1/4 3 | 0.0348 |
| (3) Calcium carbonate (CaCO₃) | 1/2 2 1 1/5 1/3 1/3 1/2 1/2 1/2 1/3 1/3 1/4 4 | 0.0348 |
| (4) Soil organic carbon (SOC) | 3 6 5 1 2 2 3 4 4 3 4 2 8 | 0.1941 |
| (5) Total nitrogen (TN) | 2 4 3 1/2 1 1 2 3 3 2 3 1 6 | 0.1217 |
| (6) Available phosphorus (AP) | 2 4 3 1/2 1 1 2 3 3 2 3 1 5 | 0.1204 |
| (7) Cation exchange capacity (CEC) | 1 3 2 1/3 1/2 1/2 1 2 2 1 2 1 4 | 0.0754 |

(Continued)
| Criteria and classes within each criteria | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) | (13) |
|-----------------------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|------|------|------|
| Exchangeable bases                      | 1/3 | 3   | 2   | 1/4 | 1/3 | 1/3 | 1/2 | 1   | 1/2  | 2    | 1/3  | 1    | 2    |
| Percentage base saturation (PBS)        | 1/3 | 3   | 2   | 1/4 | 1/3 | 1/3 | 1/2 | 1   | 1/2  | 2    | 1/3  | 1    | 2    |
| Exchangeable calcium (Ca)               | 1/2 | 4   | 3   | 1/4 | 1/3 | 1/3 | 1/2 | 1   | 2    | 1/2  | 3    | 1    | 2    |
| Exchangeable magnesium (Mg)             | 1/2 | 4   | 3   | 1/4 | 1/3 | 1/3 | 1/2 | 1   | 2    | 1/2  | 3    | 1    | 2    |
| Exchangeable potassium (K)              | 1/4 | 1   | 4   | 3   | 1/2 | 1   | 1   | 1   | 3    | 3    | 2    | 3    | 1    |
| Exchangeable sodium percentage          | 1/5 | 1/3 | 1/8 | 1/6 | 1/5 | 1/5 | 1/4 | 1/5 | 1/5  | 1/5  | 1/5  | 1/5  | 1/5  |
| Consistency ratio                       | 1   |     |     |     |     |     |     |     |     |     |     |     |     |

Consistency ratio = 0.03
| Main criteria | Level 1 | Level 2 | Partial weight | Overall Weight |
|---------------|---------|---------|----------------|----------------|
| **Climate**   | 0.4126  |         |                |                |
|               |         |         |                |                |
|               |         |         |                |                |
|               |         |         |                |                |
| **Soil**      | 0.3275  |         |                |                |
|               |         |         |                |                |
|               |         |         |                |                |
|               |         |         |                |                |
| **Morphological and site factors** |         |         |                |                |
|               |         |         |                |                |
|               |         |         |                |                |
|               |         |         |                |                |
| **Physical factors** |         |         |                |                |
|               |         |         |                |                |
|               |         |         |                |                |
|               |         |         |                |                |
| **Chemical factors** |         |         |                |                |
|               |         |         |                |                |
|               |         |         |                |                |
|               |         |         |                |                |

(Continued)
| Main criteria | Level1 | Level 2 | Partial weight | Overall Weight |
|---------------|--------|---------|----------------|----------------|
| Ex.bases      |        |         | 0.0466         | 0.0068         |
| PBS           |        |         | 0.0409         | 0.0059         |
| Ca²⁺          |        |         | 0.0722         | 0.0105         |
| Mg²⁺          |        |         | 0.0464         | 0.0067         |
| K⁺            |        |         | 0.1075         | 0.0156         |
| ESP           |        |         | 0.0180         | 0.0026         |
| Topography    | 0.2599 |         | 0.4434<sup>a</sup> |                |
|               |        |         | 0.1452<sup>b</sup> |                |
| Altitude      | 0.4    |         |                | 0.1040         |

<sup>a</sup> = weight value of soil criteria (morphological and site, physical and chemical factors); <sup>b</sup> = combined weight value of soil and its subdivisions (morphological and site, physical and chemical factors); ESP = exchangeable sodium percentage; Ex. bases = exchangeable bases
Wogdie district in south Wollo of Ethiopia, similarly, was found moderately and marginally suitable for cultivation of the crop (Motuma et al., 2016). Sorghum production in western Ethiopia was influenced by shallow depth, limited amounts of total nitrogen, organic carbon and available phosphorus (Yitbarek, Kibret, Gebrekidan, & Beyene, 2013). In a study by AbdelRahman et al. (2016), limitations posed by slope grouped the area under moderate suitability for that crop. In support of this result, slope steepness and low soil moisture content were found the major
problems influencing agricultural suitability of north western and central Ethiopian highlands (Yalew, Van Griensven, & van der Zaag, 2016a).

The study has shown that the area is potential for producing that crop. However, considerable attention should be given to crop selection that best fit the agro-ecology and proper management of the soils in order to get optimum yield.

4. Conclusion
Soil, climate and topographic characteristics were the main criteria used to generate land suitability evaluation for sorghum crop in Enderta dry midlands of northern semi arid highlands, Ethiopia. GIS-based fuzzy AHP model was employed in identifying potential sorghum areas. Soil, climate and topographic criteria were used in the study. According to the land suitability map produced, moderately suitable, marginally suitable, currently not suitable and permanently not suitable lands cover 29,534.86 ha (30.54%), 34,984.74 ha (36.17%), 17,455.81 ha (18.05%) and 14,744.61 ha (15.24%), respectively. Slope gradient, altitude, temperature, length of growing period, available water capacity, mean weight diameter, total nitrogen, available phosphorus and soil organic carbon contents and partly rockout crops, coarse fragments, depth, CaCO$_3$, bulk density and pH were severely limiting the cultivation potential of the area for sorghum crop. It should be noted that careful use of organic and inorganic (acidifying) fertilizers, tillage management, soil and water conservation measures should be taken into consideration in order to maintain soil health and accordingly improve the yield of the crop. Even though climate limitation is difficult to overcome, since the area best suits for very short maturing crop verities (60–90 days Yizengaw (1994)), growing crops which best fit LGP of the area should be taken into consideration. GIS integrated with MCDM analysis was found with great assistance in integrating soil, climate and topographic parameters for land suitability evaluation in the study. The criteria considered for land suitability evaluation were mainly biophysical and, hence, further studies can be made by incorporating socio-economic variables so as to improve the suitability results.

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Competing interests
The authors declare no competing interest.

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Table 7. Area and percentage distribution of suitability classes

| Level of suitability         | Area coverage | %  |
|------------------------------|---------------|----|
| Highly suitable (S1)         | 0             | 0  |
| Moderately suitable (S2)     | 29,534.86     | 30.54 |
| Marginally suitable (S3)     | 34,984.74     | 36.17 |
| Currently not suitable (N1)  | 17,455.81     | 18.05 |
| Permanently not suitable (N2)| 14,744.61     | 15.24 |

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