Catena 213 (2022) 106154

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Identification of suitable areas for fodder production in Ethiopia

Abeyou W. Worqlul [a,*], Yihun T. Dile [b], Melkamu Bezabih [c], Aberra Adie [c], R. Srinivasan [a,b], Nicole Lefore [d], Neville Clarke [d]

[a] Blackland Research Center, Texas AgriLife Research, Temple, TX, USA
[b] Spatial Sciences Laboratory, Texas A&M University, College Station, TX, USA
[c] International Livestock Research Institute, Addis Ababa, Ethiopia
[d] The Norman Borlaug Institute for International Agriculture, Texas A&M AgriLife Research, College Station, TX, USA

ARTICLE INFO

Keywords:
Land suitability
Fodder
Groundwater
Multi-criteria
Napier, alfalfa
Desho
Oats and vetch

ABSTRACT

Despite Ethiopia's significant livestock population, the largest in Africa, productivity is constrained by the seasonality of feed quality and quantity. Developing improved fodder production systems can contribute to poverty reduction goals and thereby enhance social-ecological resilience through building risk buffering assets. Therefore, this study focuses on evaluating the suitability of lands for selected fodder crops in Ethiopia applying GIS-based Multi-Criteria Evaluation (MCE) techniques and accessing the irrigation potential of the shallow groundwater. Groundwater data collected from the British Geological Survey (BGS) was used to assess the groundwater irrigation potential. The fodder crops selected were Napier (*Pennisetum purpureum*), alfalfa (*Medicago sativa*), oats (*Avena sativa*), vetch (*Vicia sativa*), and desho (*Pennisetum pedicellatum*). The key factors that significantly affect land suitability for fodder production evaluated include climate (rainfall and evapotranspiration), physical land features (land use, soil, and slope), and market access (livestock population and proximity to roads). The factors were weighted with a pairwise comparison matrix followed by reclassification and overlaying to identify suitable areas for irrigated fodder production. The results indicated that ~ 31% of the country (~350,500 km^2) is highly suitable for producing desho, followed by vetch (23%), Napier (20%), Alfalfa (13%), and Oats (12%). The basin level analysis indicated that the Abbay river basin has the largest suitable area for Napier and Oats production while the Genale-Dawa River basin has the largest suitable area for alfalfa, vetch, and desho production. The analysis also indicated that the suitable area has access to groundwater that could be accessed with simple water-lifting technologies (≤30 m from the surface). This study provides useful insights for decision-makers, practitioners, and the private sector to prioritize and scale fodder production in Ethiopia.

1. Introduction

Agricultural growth is central to improving both food security and economic development in Sub-Saharan Africa (Conceição et al. 2016). In Ethiopia, agriculture provided 35 percent of gross domestic product (GDP) in 2017/18 (WB 2019), while accounting for 74 percent of employment as of 2013 (Bundervoet et al. 2017). Livestock is an integral part of the agricultural system of Ethiopia, making a direct contribution to GDP of 17% (Shapiro et al. 2017), accounting for about 40% of the domestic agricultural product and employing the majority of the agricultural labor force (Asresie and Zemedu 2015). In addition, the livestock sector is a critical source of nutrition for households through multiple pathways throughout Ethiopia, including intake of nutrient-dense animal source foods and through income; increased intake of animal source foods for children has been recommended to reduce stunting and contribute to nutritional security (Haileselassie et al. 2020). The Federal Democratic Republic of Ethiopia (FDRE) policy for agricultural transformation aims to improve agriculture and livestock production systems to both reduce poverty and support sustainable development. Relevant policies include Growth and Transformation Plan (GTP), Agriculture Growth Program (AGP), Policy and Investment Framework (PIF), Food Security Program (FSP) (Berhane et al. 2013, Chanyalew et al. 2010, MoFED 2010). The second GTP emphasizes the livestock sector and outlines a master plan (LMP) that improves livestock productivity and thereby mobilizes the potential for economic growth (Shapiro et al. 2015).

Despite Ethiopia's considerable livestock population, the largest in Africa, productivity is constrained by feed quality and quantity,

* Corresponding author.
E-mail address: aworqlul@brc.tamus.edu (A.W. Worqlul).

https://doi.org/10.1016/j.catena.2022.106154
Received 12 October 2021; Received in revised form 8 February 2022; Accepted 19 February 2022
Available online 1 March 2022

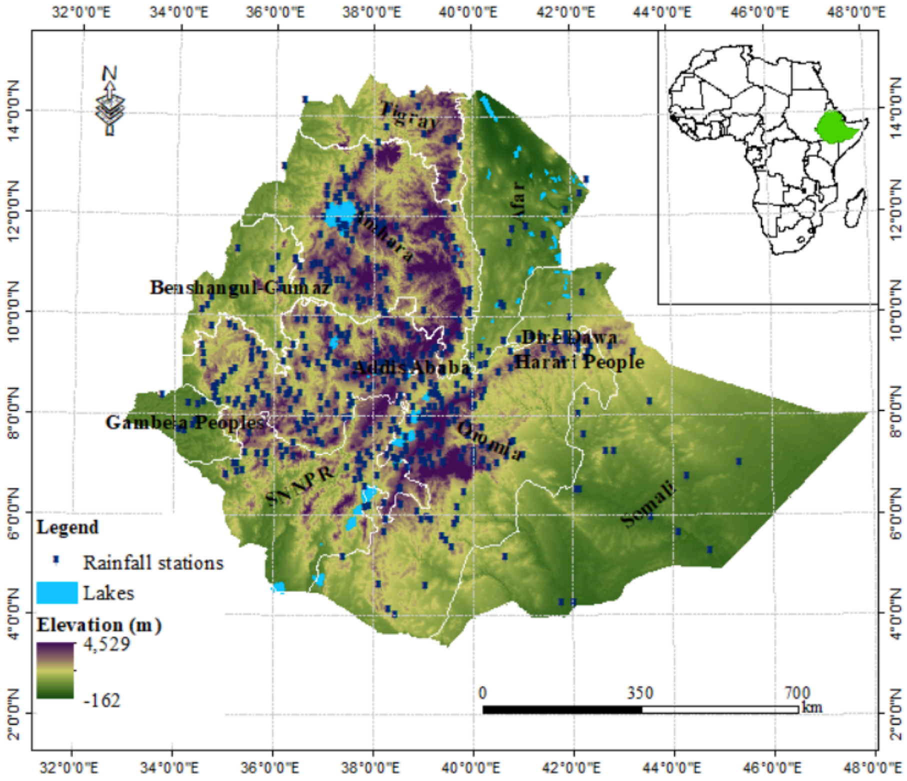

Fig. 1. Map of Ethiopia showing lakes, regions, and rainfall stations with a 30 m resolution digital elevation model as background. The insert at the right top corner shows the location of Ethiopia in an Africa map.

seasonality, market linkages, and poor veterinary services (Assefa and Nurfeta 2013, Belay 2002, Tahir et al. 2018, Tassew and Seifu 2009). Development of improved fodder production systems that address bottlenecks in feed quantity and quality can contribute to poverty reduction goals and thereby enhance social-ecological resilience through building risk buffering assets such as productive livestock (Ahmed et al. 2004, Benin et al. 2003). The identification of high potential fodder production sites across Ethiopia could enable the prioritization of investment areas and support for initiatives and policies. Therefore, this study aims to identify potential fodder production sites using a GIS-based Multi-Criteria Evaluation (MCE) technique including the potential to irrigate fodder using shallow groundwater. MCE provides tools to systematically rank factors to make a complex decision and provides a single indexed suitability map. It provides a mutual understanding of experts towards the studied variable, it goes also beyond considering a single factor such as biophysical but also socioeconomic and other factors.

Very little research has been done to evaluate the suitability of the land for fodder production to improve livestock productivity in Ethiopia. The previous studies were not crop-specific land suitability analyses. The study by (Kebede and Ademe 2016, Teka and Haftu 2012, Worqlul et al. 2017, Yohannes and Soromessa 2018) in Ethiopia focuses on a general suitability assessment of the land for irrigation without considering a specific crop. Alemayehu et al. (2020) evaluated the suitability of the land for a specific crop; alfalfa production for the current and future time horizons applying a GIS-based multi-criteria evaluation technique. MCE improves our ability of decisions making considering multiple factors. The MCE provides tools to systematically rank factors to make a complex decision and provides a single indexed suitability map. It provides a mutual understanding of experts towards the studied variable, it goes also beyond considering a single factor such as biophysical but also socioeconomic and other factors.

A GIS-based MCE technique examines multiple factors affecting the suitability of a particular interest subject and provides a single indexed outcome. For example, the MCE technique was successfully used to map potential irrigation sites in different parts of the world (Chandio et al. 2011, Karami 2006, Ren et al. 2019, Worqlul et al. 2015), the impact of climate change on land suitability for irrigation (Hood et al. 2006, Worqlul et al. 2019), erosion hot spot areas (Assefa et al. 2015, Baigorria and Romero 2007, Narra et al. 2019), groundwater potential recharge zones (Feizizadeh et al. 2014, Kaliraj et al. 2014, Nithya et al. 2019, Singh et al. 2018), and susceptibility to a landslide (Feizizadeh et al. 2014, Mondal and Maiti 2012) among others. This study uses biophysical and socio-economic factors to identify the suitability of specific fodder crops, particularly Napier *(Pennisetum purpureum)*, alfalfa *(Medicago sativa)*, oats *(Avena sativa),* vetch *(Vicia sativa),* and desho (*Pennisetum pedicellatum*).

2. Materials and methods

2.1. Description of the study area

This study was carried out in the FDRE located between 3°00′ to 15°00′ N and 32°00′ to 48°00′ E in the eastern part of Africa (Fig. 1). The country is the most populated landlocked country in the world with a total area of 1.1 million km^2. Its elevation ranges between −160 and 4530 m above mean sea level (m amsl); approximately 65% of the country is considered lowland with an elevation below 1500 m amsl. The lowland area is dominated by pastoral systems, where most of the livestock for export comes from (Hurrissa and Eshetu 2002). Rainfall in Ethiopia is highly variable (Seleshi and Camberlin, 2005), ranging between 100 and 2000 mm/year. Generally, there are three climate seasons in Ethiopia. These include *Kremt,* which is the main rainfall season spanning the period from June to August; *Belg*, which is the small rainfall season from September to November; and *Bega*, which is the dry season from December to May. Notably, Ethiopia has one of the largest livestock populations in Africa with significance for the national economy

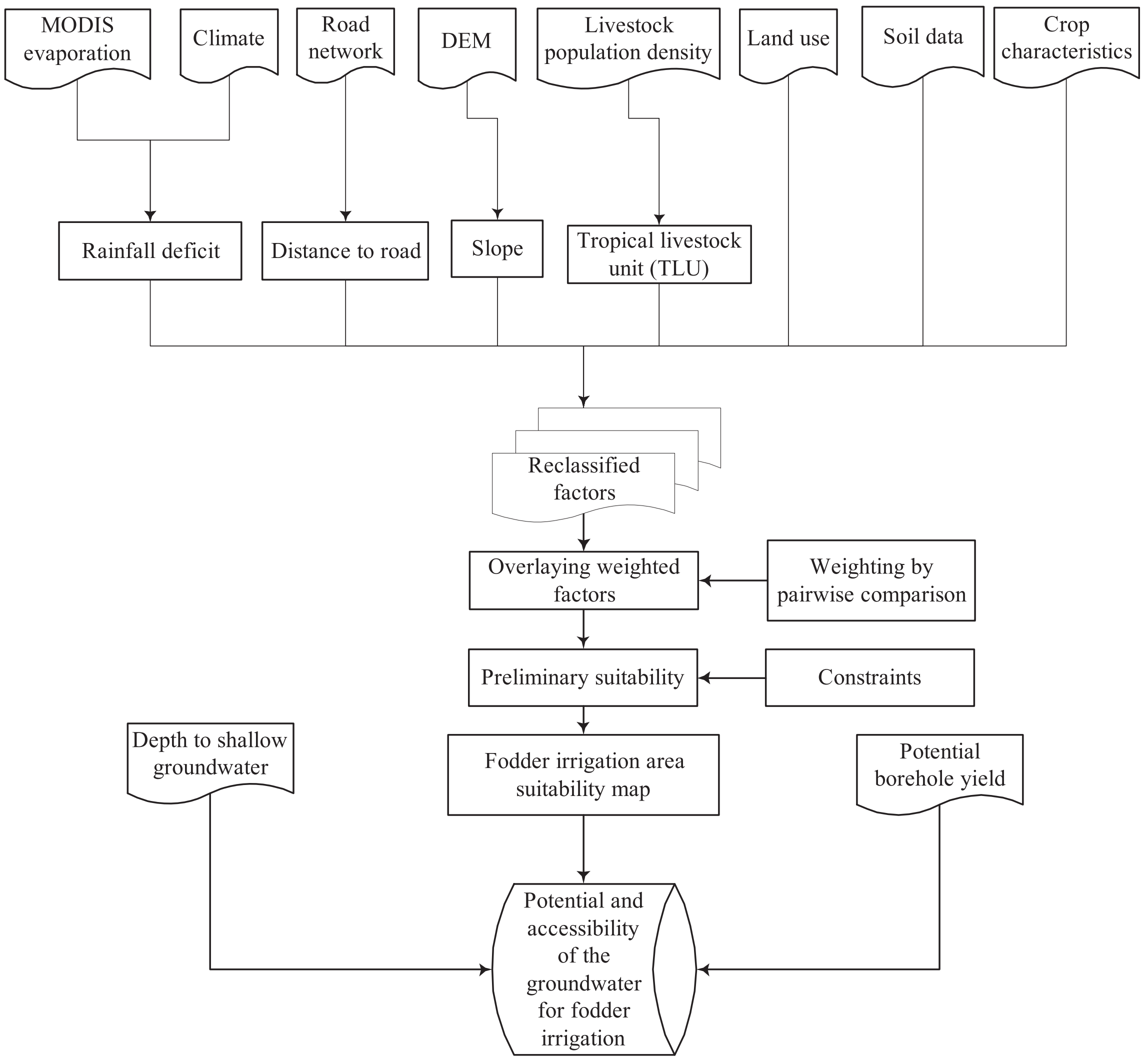

Fig. 2. Framework to identify potential suitable fodder production suitable area and groundwater irrigation potential.

and livelihoods (Shapiro et al. 2017).

2.2. Methodology

The potential suitable area for sustainable fodder production across the country was identified using a GIS-based MCE technique. In MCE, the major factors affecting the suitability of the land for fodder production were mapped, weighted, reclassified, and overlaid to develop a single-index fodder suitability map. The biophysical factors included climate (temperature, rainfall, and potential evaporation), soil (soil texture, pH, and soil depth), land use, and slope while the socio-economic factors were access to market and feed demand. The access to the market was represented with proximity to paved roads, and livestock feed demand was represented with livestock density applying the concept of Tropical Livestock Unit (TLU) (Hiernaux et al. 1997). The fodder suitability analysis incorporated specific crop characteristics data from the FAO-EcoCrop database (Ecocrop 2000) to determine the main niche for optimal fodder production sites. The fodder types were selected based on local stakeholder consultations organized by the International Livestock Research Institute (ILRI). The selected fodder crops for the suitability analysis include Napier *(Pennisetum purpureum)*, alfalfa *(Medicago sativa)*, oats *(Avena sativa)*, vetch *(Vicia sativa)*, and desho (*Pennisetum pedicellatum*). The FAO-EcoCrop database provides crop characteristics guidelines for land suitability, including the range of temperature, soil pH, and soil depth required for optimal and absolute growth. The weighting of factors was determined by applying a pairwise comparison matrix (Saaty 1977). The weights of the factors were distributed to the different classes by an equal interval ranging technique. The general methodological framework of fodder production suitability analysis, input data source, and their respective spatial resolution are presented in Fig. 2 and Table 1.

Groundwater data which includes depth to groundwater and potential borehole yield from the British Geological Survey (BGS) (MacDonald et al. 2012) was used to evaluate the irrigation potential of the shallow groundwater using simple water-lifting technologies such as pulley and bucket, rope, and washer pump, and solar pump. In a previous study, Worqlul et al. (2017) compared the BGS depth to groundwater and potential borehole yield with observed groundwater yield data in the central part of Ethiopia, in which the results indicated a reasonable agreement. Once the suitable land for fodder production were identified, the BGS's depth to groundwater and potential borehole yield data were used to assess if sufficient shallow groundwater is available to cultivate fodder using simple water lifting irrigation technologies.

2.2.1. Biophysical factors

The study identifies and maps the biophysical factors that affect the suitability of certain land to sustainably scale a fodder production system in Ethiopia. Listed below are the major biophysical factors affecting the suitability of certain land for fodder production:

Table 1
Input data source and spatial resolution used for the land suitability analysis.

Data	Source	Spatial resolution (m)
Land-use	Global Land Cover Datasets (GlobeLand30)	30
Soil	Africa Soil Information Service (AfSIS), 2015	250
Soil pH	Africa Soil Information Service (AfSIS), 2015	250
Soil depth	Africa Soil Information Service (AfSIS), 2015	250
Digital Elevation Model (DEM)	Enhanced Shuttle Land Elevation Data from the United States Geological Survey (USGS), 2000 released in 2015	30
Road network	Digital Chart of the World (DCW), 2006	–
MODIS potential evaporation (mm)	MOD16 Global Terrestrial Evapotranspiration Data Set (2000 to 2010)	1000
Rainfall (mm/year)	Ethiopian National Meteorological Agency (ENMA) from 2000 to 2010	–
Fodder crop characteristics	FAO-EcoCrop database	–
Livestock population density	Ethiopian Central Statistical Agency (ECSA)	–
Potential borehole yield (l/s)	British Geological Survey, 2012	5000
Groundwater depth (m)	British Geological Survey, 2012	5000

Climatic factors (rainfall and evaporation): Rainfall deficit was used to represent the relative suitability of the climate for fodder crop growth. It was estimated by computing monthly rainfall deficit (i.e., rainfall minus potential evapotranspiration) (Worqlul et al. 2015) throughout the fodder growing period. This analysis used daily rainfall data from 509 weather stations for the period 2000 to 2010 and eight-day MODIS potential evapotranspiration (Mu et al. 2011) data for the period 2000 to 2010. The gauged rainfall data were obtained from the Ethiopian National Meteorological Services Agency. The annual rainfall and potential evapotranspiration are presented in Fig. 3a and b, respectively. The potential evaporation represents the evaporation potential of the climate, which is the evaporation that would occur if a sufficient water resource is available.

The monthly average temperature data for the period 1970 to 2000 were collected from WorldClim version 2 (Fick and Hijmans 2017). The WorldClim data was produced using extensive global, regional, national, and satellite-derived data, and it is available at 1 km spatial resolution. The average annual temperature across Ethiopia is presented in Fig. 3c.

The slope of the landscape is one of the main factors that determine the suitability of land for irrigation affecting irrigation efficiency and the required initial investment to prepare the land for agricultural practices including irrigation. The percentage slope of the land was estimated using a 30 m resolution Digital Elevation Model (DEM) from the Shuttle Radar Topography Mission (SRTM) (Farr et al. 2007) (Fig. 3d). A slope map in percentage can have a value ranging from zero to near-infinite, a slope of zero represents a flat land, where infinite slope refers to a vertical cliff. The average slope of the country is ∼13.8%.

Land-use data informs the use of the land for the suitability analysis. The land use data were collected from the GlobeLand30 (GL), which is developed by the National Geomatics Center of China (NGCC). The Chinese government donated this data to the United Nations as its contribution to global sustainable development and climate change

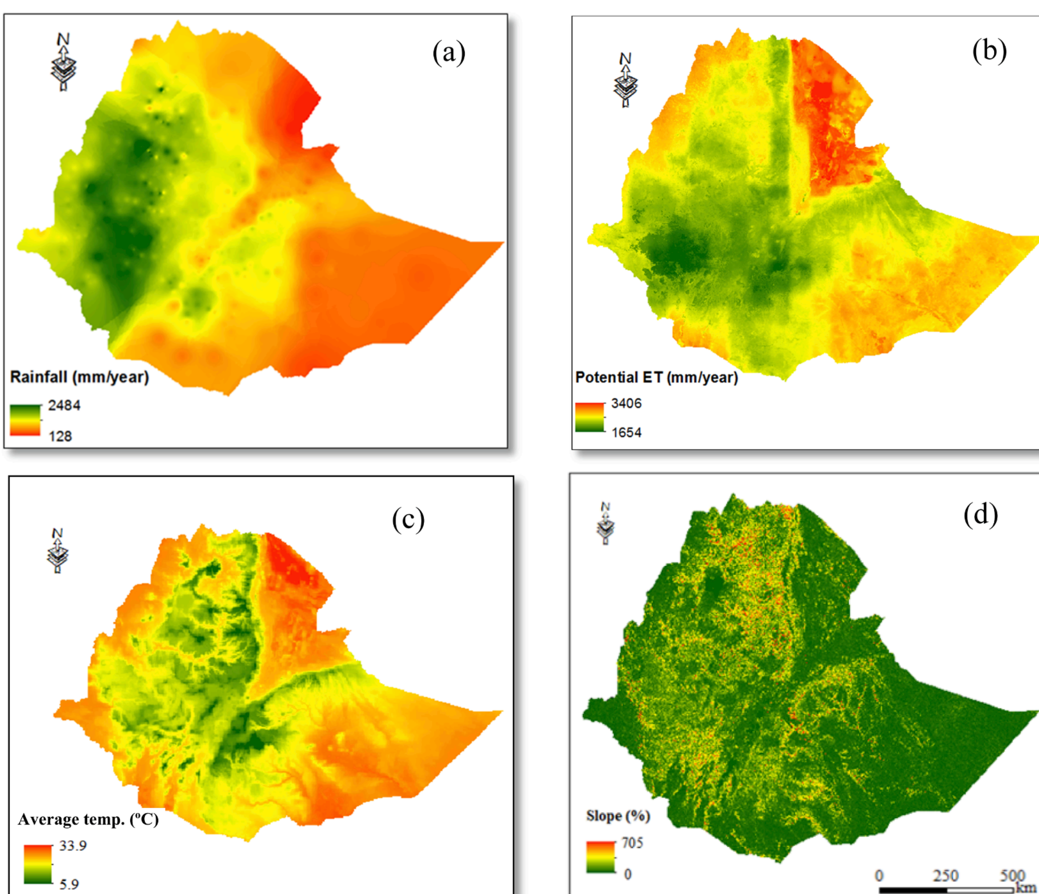

Fig. 3. Factors used to assess the land suitability for fodder production in Ethiopia. a) the average annual rainfall (mm) for the period 2000 to 2010, b) long-term annual average potential evapotranspiration (mm) (2000 to 2010), c) annual average temperature °C for the period 1970 – 2000, and d) slope in percent.

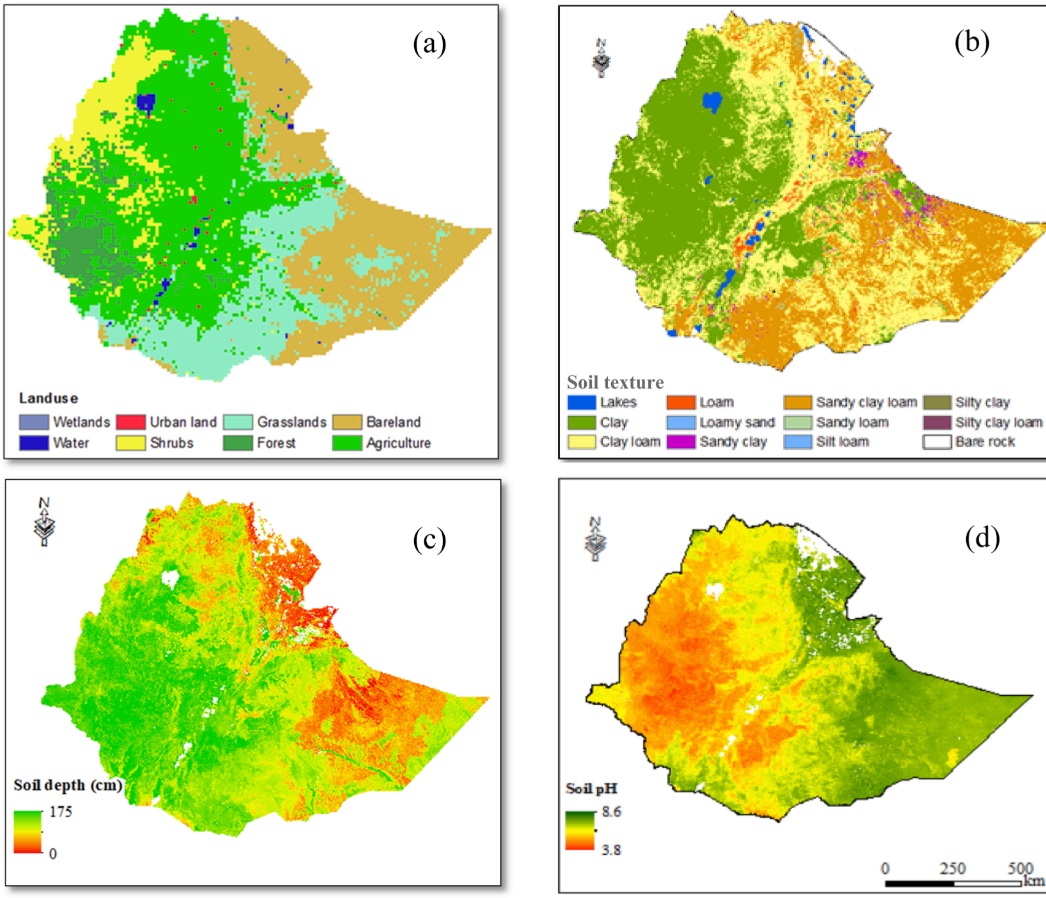

Fig. 4. Factors used to assess the land suitability for fodder production in Ethiopia. a) land use, b) soil texture, c) soil depth (cm), and d) soil pH.

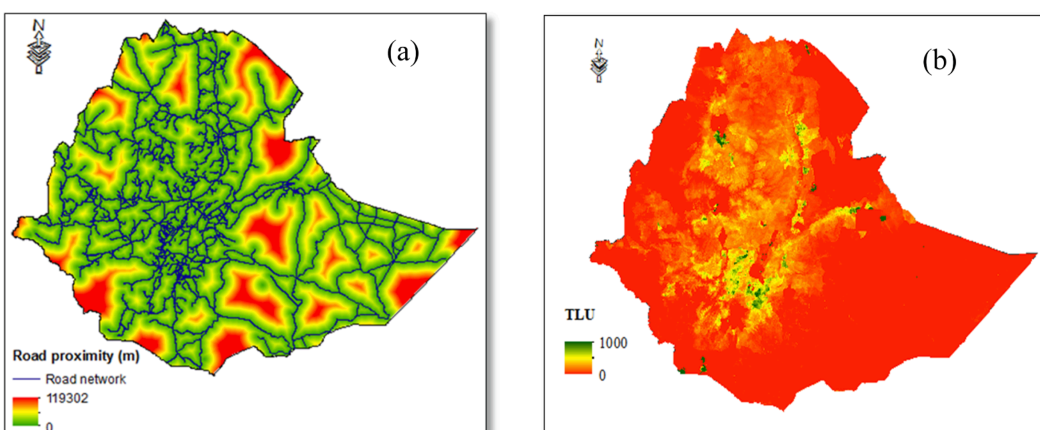

Fig. 5. Socio-economic factors used to assess the land suitability for fodder production in Ethiopia. a) distance to major paved roads (km), and b) Tropical Livestock Unit (TLU).

combating (Jun et al. 2014). The GL data was developed by integrating satellite images from Enhanced TM plus (ETM+), Landsat Thematic Mapper (TM), and Chinese Environmental and Disaster (HJ-1) (Brovelli et al. 2015). The data is available at 30 m spatial resolution for 2000 and 2010 scenes, and it has ten land-use groups. This study used the land use map of 2010 (Fig. 4a).

Soil data is vital to inform physicochemical soil's suitability for irrigation and agricultural practices in general. For example, soil depth is an important factor in providing water, nutrient, and mechanical support to plants. The soil pH, which measures soil's acidity and alkalinity, determines plant growth by affecting the soil properties and soil bacteria. The optimum soil pH range for most plants is between 5.5 and 7.0, while some crops grow under slightly acidic conditions. The study used soil data that include soil texture, pH, and depth which were collected from Africa Soil Information System (AfSIS) (Vågen et al. 2010). The AfSIS data is available at a spatial resolution of 250 m consisting of six layers (0–5 cm, 5–15 cm, 15–30 cm, 30–60 cm, 60–100 cm, and 100–200 cm) of soil data. The soil texture map was aggregated by weighted average using the first five layers (100 cm). The soil texture was classified using the USDA soil classification system resulting in eight

Table 2
Characteristics of studied fodder crops for fodder production suitability in Ethiopia (Ecocrop 2000, FAO 2011).

Fodder	Optimal temperature (°C)	Absolute temperature (°C)	Optimal soil PH	Optimal soil depth (cm)
Napier	25–40	15–25 & 40–45	5.0–6.5 (4.0/8.2)	> 150
Alfalfa	21–27	5–21 & 27–35	6.5–7.5 (6.0/8.6)	> 150
Vetch	16–21	8–16 & 21–35	6.0 – 7.0 (4.5/8.2)	>100
Oats	16–21	5–16 & 21–26	5.0–7.0 (4.5/8.6)	>50
Desho	20–25	15–20 & 25–35	5.5–7.0 (4.5/8.5)	50–150

soil classes across the country. A significant portion of the country is covered with sandy clay loam (49%) and clay loam (36%) (Fig. 4b). The soil data indicated an average soil depth of 116 cm (Fig. 4c). The central and south-western part of the country has a thicker soil layer compared to the north and eastern part of the country. The average soil pH in Ethiopia is 6.2, but the eastern part of the country has generally alkaline soil (Fig. 4d). The white area in Fig. 4d represents bare rock and therefore soil pH is not reported.

2.2.2. Socio-economic factors

The socio-economic factors identified and mapped to evaluate the potential suitable fodder production area across Ethiopia include access to a paved road and livestock population. These factors inform market access for the purchase of agricultural inputs and to sell agricultural produce.

The proximity of a certain land to a paved road was determined using the road network data, which was collected from the Digital Chart of the World for the year 2006. The distance of certain land from the paved road was calculated using Euclidean distance interpolation (Fig. 5a). The analysis indicated that the average distance of any area from a paved road in Ethiopia is ~19 km, while the farthest point is ~119 km away (Worqlul et al. 2017).

Livestock density data indicates the availability of demand for fodder production and thereby indicating whether a particular area is suitable for fodder production or not. Livestock population data for Ethiopia was obtained from the country's Central Statistical Agency (CSA). The data includes a zonal level population of cattle, sheep, goats, horses, donkeys, and camels for the year 2000–2007. The livestock density was used to determine feed demand applying the concept of the Tropical Livestock Unit (TLU), which aggregates the different livestock categories to a standard relative feed requirement. TLU conceptualization assumes a standard feed requirement for metabolizable energy requirements of one cattle with a bodyweight of 250 kg (Hiernaux et al. 1997, Jahnke et al. 1988). TLU conversion factors for the different livestock units are: cattle = 0.6, sheep (goats) = 0.1, pigs = 0.2, donkey (horse) = 0.8 and camel = 1.1 (Lambin et al. 2003). The livestock population data from CSA was converted to a common standard unit of TLU (Fig. 5b).

2.2.3. Selected crops and their characteristics

The International Livestock Research Institute (ILRI) in Addis Ababa, Ethiopia, has identified potential fodder crops that could be scaled sustainably based on stakeholder consultation seminars. The selected fodder crops included perennials (Napier, alfalfa, and desho grass) and seasonal crops (vetch, and oats). The seasonal crops can be cultivated during the dry season under irrigation, and the perennial crops can be cultivated throughout the year with irrigation during the dry season. The basic characteristics of optimal and absolute growing conditions of the selected crops are presented in Table 2.

Napier grass is a tall perennial grass native to Tropical Africa and the sub-Saharan region (Clayton et al. 2014). It grows at an altitude ranging from sea level to 2000 m amsl (Ecocrop 2000). Napier grass contains higher nutrient content, including carbohydrates and protein, and it is

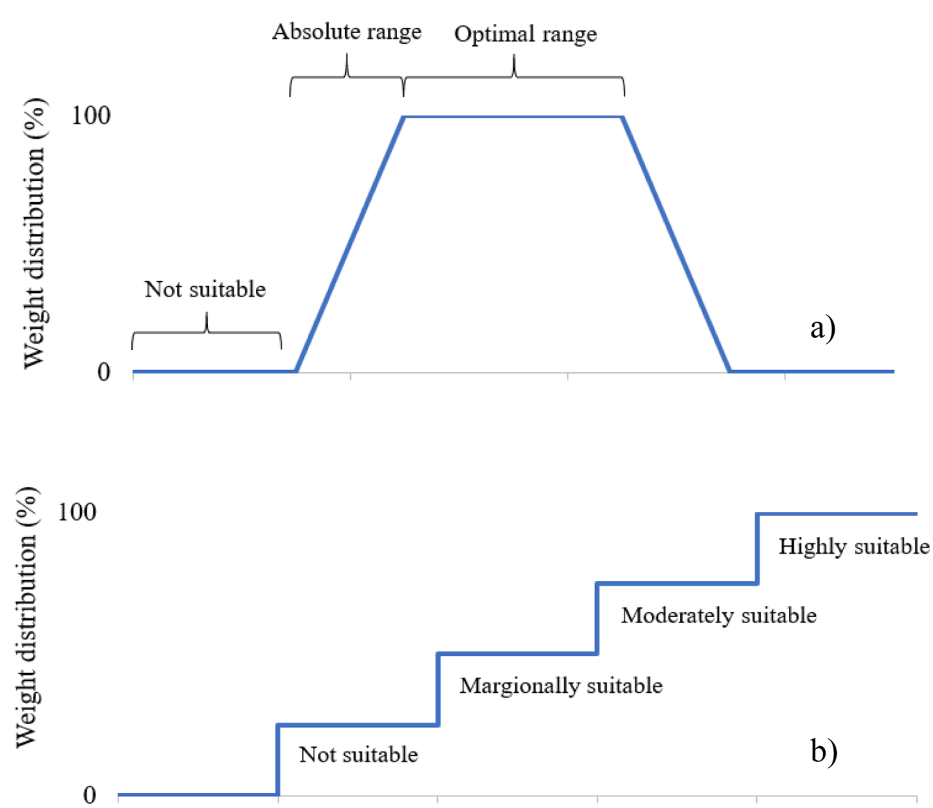

Fig. 6. Weight distribution of the crop related and other noncontinuous factors that affect the suitability of the land for fodder production. a) suitability classification for continuous variables. b) schematic skitch of suitability classification of categorical (noncontinuous) factors.

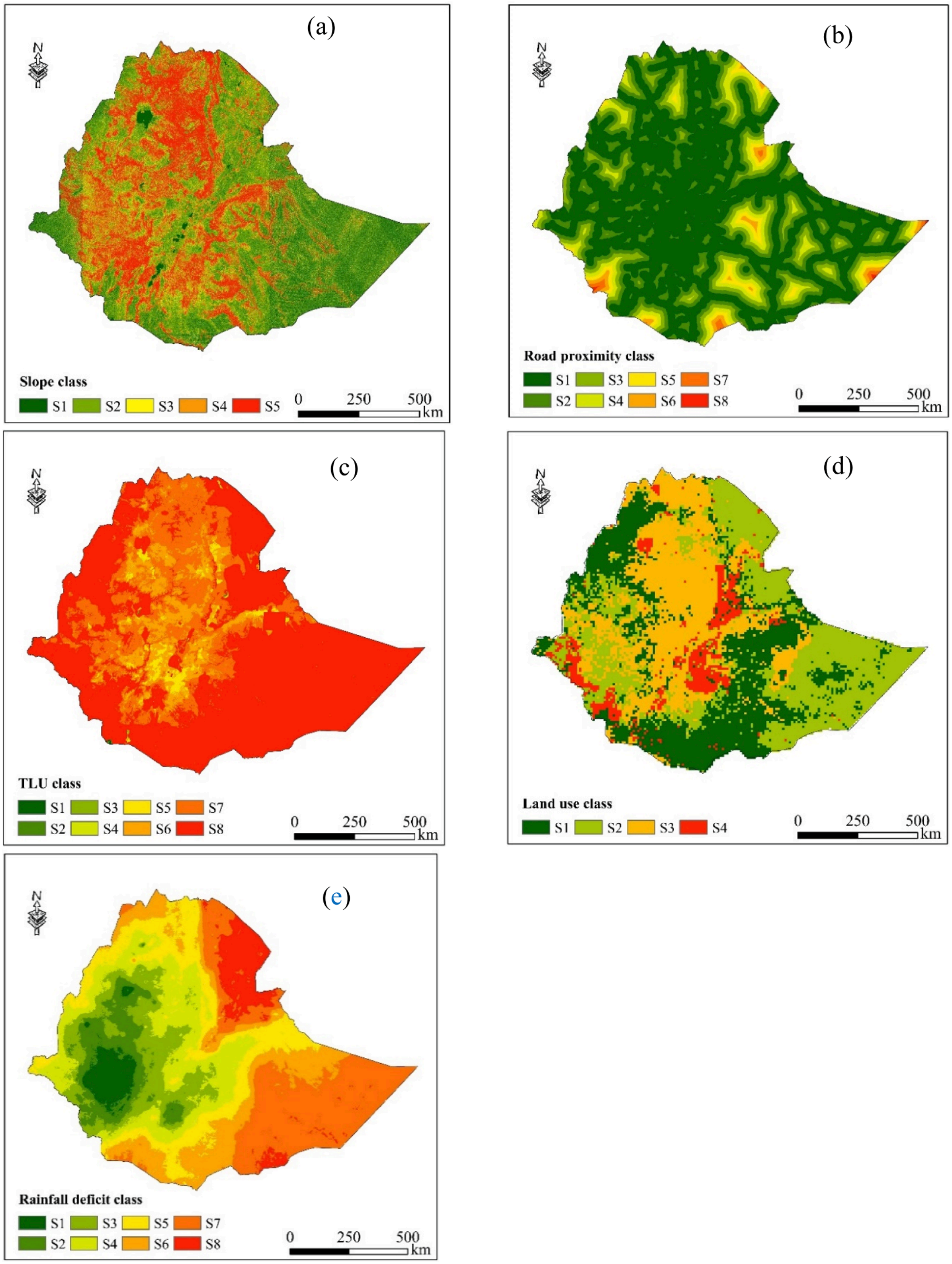

Fig. 7. Reclassified factor maps that affect the suitability of the land for fodder production: a) slope suitability class, b) distance to the road suitability class, c) TLU suitability class, d) land use suitability class and e) Rainfall deficit class. S1 classes represent highly suitable areas and as the number increases, the suitability level decreases.

an ideal feedstock for biogas production (Sawasdee and Pisutpaisal 2014). Napier grass grows best in high rainfall areas, but it is drought tolerant to grow in dry areas (Mwendia et al. 2017, Orodho 2006). Napier can grow in most soil types but thrives well in deep and well-drained soils. The optimal temperature for Napier grass ranges from 25 °C to 40 °C (Duke 1983, Ecocrop 2000). It does not grow at a temperature of less than 15 °C and is sensitive to frost (FAO 2011).

Oats is a cereal crop, the grain being very high in fiber and protein and low in starch (Stevens et al. 2004). It is cultivated for grain, forage, and fodder. The optimal temperature for oats production ranges from 16 to 21 °C (Ecocrop 2000). Commonly, forage oats are cultivated mixed with vetch to maintain soil fertility and increase productivity (Assefa and Ledin 2001, Lithourgidis et al. 2006). Oats grow well in loam or sandy soil and tolerate acidic and salty soil (Suttie and Reynolds 2004).

Vetch is an annual legume cover crop used for haymaking and green fodder. The optimal temperature for vetch production ranges from 16 °C to 21 °C (Ecocrop 2000). Vetch can grow in a wide range of soil types with a preference for deep and well-drained soils. Its root extends to 1–1.5 m deep. Vetch has the ability to fix soil nitrogen, and its residual biomass decomposes quickly (Sattell et al. 1999).

Table 3
The pairwise comparison matrix and weights of factors for Napier grass suitability analysis. The Pairwise comparison matrix and weights of factors for the other fodder crops are presented in Annex 1.

Factors	Soil texture	Soil depth	Soil pH	Land use	TLU	Rainfall deficit	Temp.	Road proximity	Slope	Weight (%)
Soil texture	1	1/2	1/2	3	1/2	2	1/2	1/2	1/3	7.7
Soil depth	2	1	1	2	2	2	2	2	1/2	14.4
Soil pH	2	1	1	2	2	2	3	2	1/2	15.2
Land use	1/3	1/2	1/2	1	1/3	1/2	1/2	1/3	1/3	4.7
TLU	2	1/2	1/2	3	1	1	1	1	1	10.7
Rainfall deficit	1/2	1/2	1/2	2	1	1	1/2	1/2	1/2	7.0
Temperature	2	1/2	1/3	2	1	2	1	1/2	1/3	8.7
Road Proximity	2	1/2	1/2	3	1	2	2	1	1/3	10.8
Slope	3	2	2	3	1	2	3	3	1	20.8

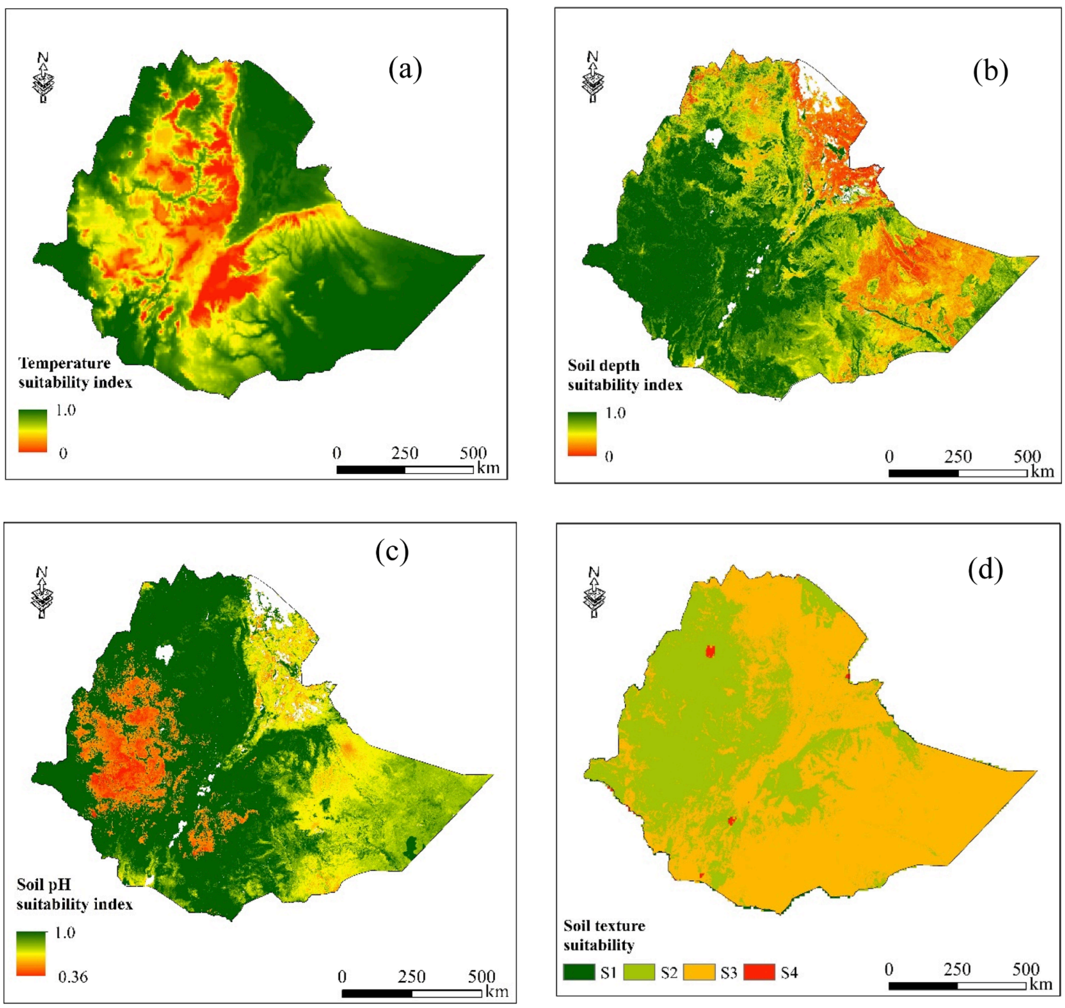

Fig. 8. Reclassified crop-specific factors index maps that affect the suitability of the land for Napier production: a) Temperature, b) Soil depth, c) Soil pH, and d) Soil texture.

Alfalfa is a perennial legume plant which is used for grazing, hay, and silage, as well as a cover crop. Due to its high nutritional value (Kung Jr et al. 2003) and high yield, alfalfa is one of the most valuable forage crops in Ethiopia. It can grow in a variety of soil types but grows well on deep, well-drained sandy to fertile loamy soils with 6.5 to 7.5 soil PH. Generally, alfalfa grows in higher altitudes of up to 4000 m amsl. It tolerates drought but it cannot stand prolonged flooding and heat stress (Armah-Agyeman et al. 2002). Its root can reach up to 400 cm deep into the soil.

Finally, desho is an indigenous perennial grass that has an extensive root system that anchors well with the soil. Desho grass can grow anywhere from 1700 to 2800 m amsl. It provides better forage grass yield when well fertilized (Schmelzer 1997). It grows on a wide range of soil types including in well-drained degraded sandy soils. It has drought tolerance, but it is susceptible to waterlogging.

2.2.4. Weighting of factors

The weights of the factors for each fodder crop were determined using a pairwise comparison matrix technique (Saaty 1977), in which factors are compared to each other to prepare the importance matrix. The highest value in the matrix corresponds to the absolute importance of one factor over the other and the lowest value represents absolute triviality inserted at the transpose position of the comparison matrix (Saaty and Vargas 1991, Worqlul et al. 2015, Worqlul et al. 2017). The

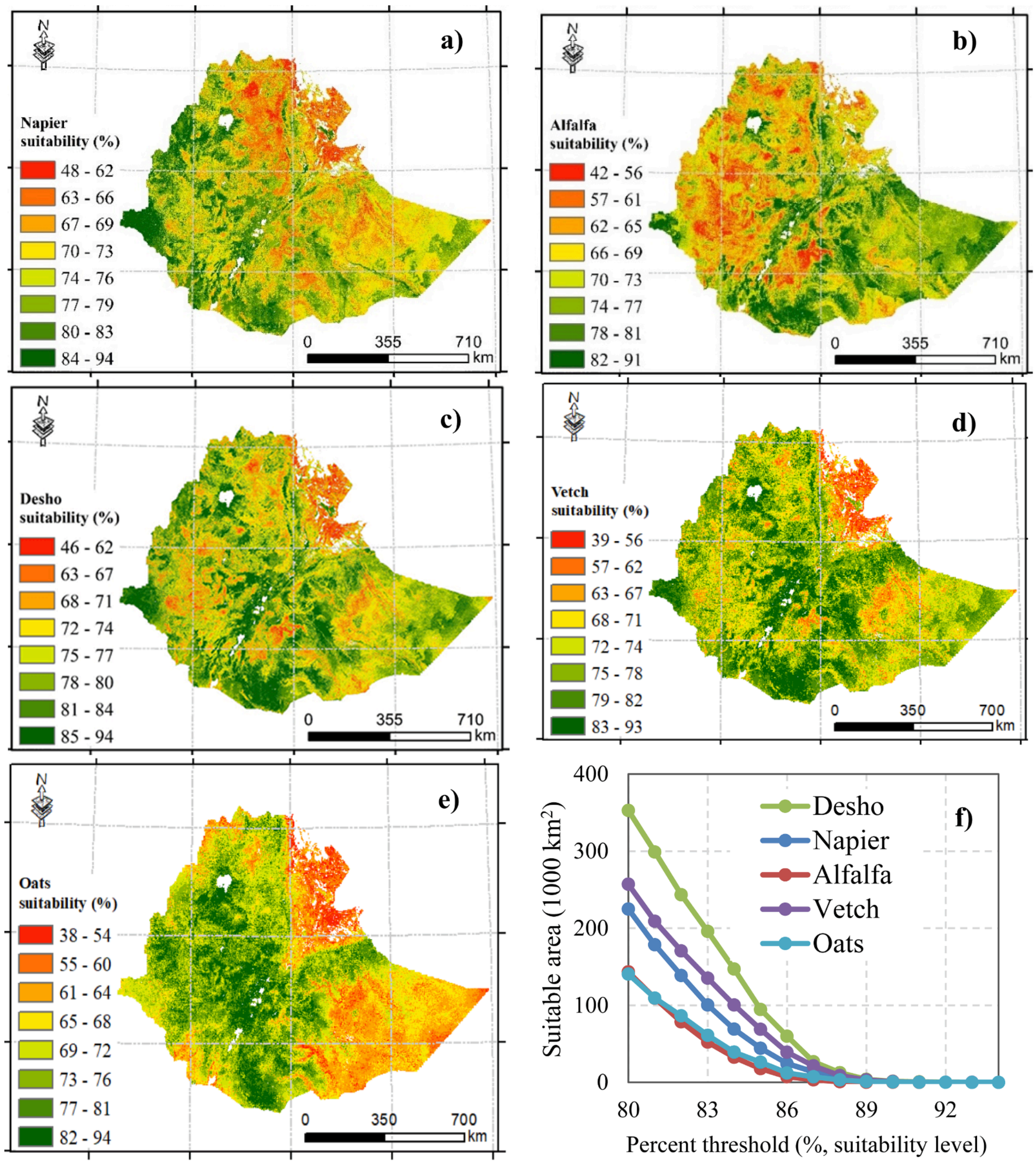

Fig. 9. A preliminary suitable land for fodder production. a) Napier, b) Alfalfa, c) Desho, d) Vetch, e) Oats and f) Fodder production suitable area (in 1000 km^2) at different suitability levels. For example, 226,000 km^2 of land is suitable for Napier production at a level of 80%. The highest shows the most suitable area for fodder production, while the lost value indicates the least suitable land for the respective fodder.

Table 4
Potential suitable fodder production area across the major river basins of Ethiopia.

		Potential growing site (km^2)					
River basin	**Basin area (km^2)**	**Napier**	**Alfalfa**	**Vetch**	**Oats**	**Desho**	**Total**
Abbay	198,891	60,720	9,856	47,897	48,377	66,065	431,806
Awash	110,439	14,547	18,813	22,470	10,362	29,377	206,008
Aysha	4321	–	7	2	–	80	4,410
Baro-Akobo	76,203	35,542	6,662	18,958	7,572	31,199	176,136
Afar/Denakil	63,853	1,898	2,889	2,703	346	4,067	75,756
Genale-Dawa	172,133	40,067	43,551	66,648	25,851	77,400	425,650
Mereb	5965	226	215	1,105	509	1,275	9,295
Ogaden	80,009	3,665	14,172	5,636	597	21,887	125,966
Omo-Ghibe	78,189	25,938	6,050	18,168	15,744	24,687	168,776
Rift Valley	51,989	18,937	10,878	23,853	16,946	26,171	148,774
Tekeze	86,455	8,408	3,506	13,440	3,675	19,829	135,313
Wabi-Shebelle	202,219	14,333	26,298	35,517	10,454	49,870	338,691
Total	**1,130,666**	**224,281**	**142,897**	**256,397**	**140,433**	**351,907**	**–**
Percent suitable area (%)	**–**	**20**	**13**	**23**	**12**	**31**	

Table 5
Groundwater depth and potential borehole yield evaluated for the most suitable fodder production sites.

Fodder crop	Average depth to groundwater (m)	Potential borehole yield (l/s)
Napier	17.1	4.0
Alfalfa	22.3	5.8
Desho	27.4	4.3
Vetch	13.8	4.5
Oats	19.6	3.7

relative importance of the factors was then computed by normalizing the eigenvector of the factors by the cumulative sum. The consistency of the pairwise comparison was tested by applying a consistency ratio test (CR, Franek and Kresta 2014). The CR evaluates the likelihood of whether the weights are randomly assigned or not. For a consistent comparison matrix, Saaty (1980) suggested a CR value of less than 10%; if not, the comparison matrix should be revised (Kontos et al. 2005).

2.2.5. Classification of factors and preliminary suitability

The factors affecting the suitability of the land for fodder production

Table 1a
Pairwise comparison matrix and weights of factors for alfalfa.

Factors	Soil texture	Soil depth	Soil pH	Land use	TLU	Rainfall deficit	Temperature	Road proximity	Slope	Weight (%)
Soil texture	1	1/2	1/2	1	1/3	1/2	1/2	1/2	1/3	5.2
Soil depth	2	1	1	3	2	2	2	2	1/3	14.6
Soil pH	2	1	1	3	2	2	2	2	1/2	15.0
Land use	1	1/3	1/3	1	1/3	1/2	1/2	1/3	1/3	4.5
TLU	3	1/2	1/2	3	1	1	1	1	1	11.1
Rainfall deficit	2	1/2	1/2	2	1	1	1/2	1/2	1/2	7.8
Temperature	2	1/2	1/2	2	1	2	1	1/2	1/3	8.7
Road Proximity	2	1/2	1/2	3	1	2	2	1	1/3	10.7
Slope	3	3	2	3	1	2	3	3	1	22.3
									CR	3.8

Table 1b
Pairwise comparison matrix and weights of factors for Desho.

Factors	Soil texture	Soil depth	Soil pH	Land use	TLU	Rainfall deficit	Temperature	Road proximity	Slope	Weight (%)
Soil texture	1	1/3	1/2	1	1	1/2	1/2	1/2	1/3	5.8
Soil depth	3	1	2	2	2	2	2	2	1/2	16.7
Soil pH	2	1/2	1	2	2	1	1	1	1/2	10.8
Land use	1	1/2	1/2	1	1/3	1/2	1/2	1/3	1/3	5.1
TLU	1	1/2	1/2	3	1	1	1	1	1	10.2
Rainfall deficit	2	1/2	1	2	1	1	1/2	1/2	1/2	8.6
Temperature	2	1/2	1	2	1	2	1	1/2	1/3	9.7
Road Proximity	2	1/2	1	3	1	2	2	1	1/3	11.8
Slope	3	2	2	3	1	2	3	3	1	21.3
									CR	3.8

Table 1c
Pairwise comparison matrix and weights of factors for vetch.

Factors	Soil texture	Soil depth	Soil pH	Land use	TLU	Rainfall deficit	Temperature	Road proximity	Slope	Weight (%)
Soil texture	1	1/3	1/2	1	1	1/2	1/2	1/2	1/3	5.8
Soil depth	3	1	2	2	2	2	2	2	1/2	16.7
Soil pH	2	1/2	1	2	2	1	1	1	1/2	10.8
Land use	1	1/2	1/2	1	1/3	1/2	1/2	1/3	1/3	5.1
TLU	1	1/2	1/2	3	1	1	1	1	1	10.2
Rainfall deficit	2	1/2	1	2	1	1	1/2	1/2	1/2	8.6
Temperature	2	1/2	1	2	1	2	1	1/2	1/3	9.7
Road Proximity	2	1/2	1	3	1	2	2	1	1/3	11.8
Slope	3	2	2	3	1	2	3	3	1	21.3
									CR	3.7

Table 1d
Pairwise comparison matrix and weights of factors for Oats.

Factors	Soil texture	Soil depth	Soil pH	Land use	TLU	Rainfall deficit	Temperature	Road proximity	Slope	Weight (%)
Soil texture	1	1	1/2	1	1/3	1/2	1/2	1/2	1/3	5.6
Soil depth	1	1	1	1	1/2	1	1/2	2	1/3	8.4
Soil pH	2	1	1	1	1/2	1/2	1/2	2	1/2	9.0
Land use	1	1	1	1	1/3	1/2	1/2	1/3	1/3	5.9
TLU	3	2	2	3	1	1	1	1	1	14.9
Rainfall deficit	2	1	2	2	1	1	1/2	1/2	1/2	10.4
Temperature	2	2	2	2	1	2	1	1/2	1/3	12.5
Road Proximity	2	1/2	1/2	3	1	2	2	1	1/3	12.1
Slope	3	3	2	3	1	2	3	3	1	21.2
									CR	5.73

were classified into two groups: the first group contains factors which are directly related to specific crop characteristics (such as temperature, soil pH, and soil depth); the second group includes generic factors that are related to market and suitability of the land for fodder production (e.g., slope, land use, and market access). The crop-specific factors were reclassified using Table 2 and Fig. 6a for each fodder crop. The classification was defined by the absolute range (minimum and maximum at which the crop can grow) and the optimum range. At the optimal condition, the plant growth is not limited by the respective factor; however, at the absolute range, the plant growth will be limited by the respective factor. When the conditions are beyond absolute thresholds, the suitability index of zero was assigned (referring not suitable); when they are in between absolute and optimum thresholds, suitability scores ranging from 1 to 99% was distributed linearly, and when they are within the optimum conditions, a suitability score of 100% (highly suitable) was assigned (Fig. 6a).

The categorical (i.e., not continuous) factors were classified into multiple levels of suitability following the Food and Agriculture Organization's recommendation (FAO 1976, 1985, 1989, Walker 1989). These factors were classified as highly suitable (S1); moderately suitable (S2); marginally suitable (S3); and not suitable (S4) (Fig. 6b). For example, the grassland land-use was reclassified as S1; shrubland, which requires a higher initial investment for land preparation was reclassified as S2; agricultural land was reclassified as S3; while forest, water, urban, and wetland were reclassified as S4 since they provide other ecosystem services.

The percent slope map was reclassified into five levels of suitability classes (Fig. 7a). The levels of suitability were 0 to 2%, 2 to 8%, 8 to 12%, 12 to 20%, and above 30% which represented highly, moderately, marginally, low, and not suitable for fodder production, respectively. The major paved road network interpolated with Euclidean distance and TLU were reclassified into eight classes of suitability classes since both factors showed a higher variability. The classification was done applying an equal interval ranging technique (Fig. 6b). The rainfall deficit was aggregated for the growing period of seasonal and perennial fodder crops. Then the rainfall deficit was reclassified into eight levels of suitability applying an equal interval ranging technique. The soil texture was classified into four major groups based on water holding capacity, i.e., very high (silt, silt loam, and silty clay loam), high (silty clay, and clay), low (loamy sand and sandy loam, clay loam, sandy clay loam, and sandy clay), and very low (sands, and loamy sands) suitability.

Finally, after assigning the weight of the factors estimated with a pairwise comparison matrix a Weighted Overlay Analysis Tool under the Spatial Analyst toolbox in ArcGIS was used to assess the preliminary suitability of land for fodder production. The preliminary suitable map was then constrained by land-use types that limit the suitability of the land for fodder production such as water bodies, wetlands, urban, forest, and protected areas to create the final fodder suitability map.

3. Results and discussion

3.1. Weighting of factors for fodder suitability analysis

The pairwise comparison matrix and the overall weights of the studied factors affecting the suitability of the land for Napier production are presented in Table 3. The pairwise comparison matrix for the other fodder crops is presented in Annex 1. Evaluation of the consistency ratio for the Napier pairwise comparison provided a value of 5.1%, which showed a reliable assessment (Ceballos-Silva and López-Blanco, 2003; Saaty 1980). The pairwise comparison analysis indicated slope and soil properties (i.e. depth, and pH) were the most important factors for land suitability for Napier production. Proximity to the road and tropical livestock unit (TLU) showed a modest influence on the land suitability for Napier production while land use, rainfall deficit, soil texture, and temperature were the least important factors. Like the Napier suitability analysis, evaluation using consistency ratio for the other studied crops (Annex-1) provided values less than 10% indicating credible pairwise comparison matrix analysis. The pairwise comparison of other crops (Annex-1) indicated a similar pattern to Napier production for the weights of the studied factors, except for soil depth and soil pH, which were not the most important factors for oats. Oats can grow in shallow and degraded soil types and a wide range of soil pH.

3.2. Weight of factors and reclassification

3.2.1. Reclassification of factors common for the different fodder crops

The reclassification of common suitability factors affecting the suitability of the land for fodder production such as slope, TLU, proximity to the road, and land use were classified based on Fig. 6a. The percent slope map (Fig. 3d) was reclassified into five levels of suitability classes (Fig. 6a). Based on slope classification, 16% of the country was highly suitable land (i.e., slope < 2%) for fodder production. The major paved road network interpolated with Euclidean distance and TLU were reclassified into eight levels of suitability since both factors showed a higher variability (Fig. 7b and c). The rainfall deficit was aggregated for the growing period of fodder crops and then reclassified into eight levels of suitability applying an equal interval ranging technique. For example, the weight for land use, which was 4.7% for Napier grass (Table 3) was distributed to the four suitability classes; land-use groups classified as highly suitable (grassland and bareland) received a value of 4/4*(4.7%), the second most suitable land-use group (shrubland) received 3/4*(4.7%), the third suitable land-use group (agricultural land) received a weight of 2/4*(4.7%), and the least suitable group received 1/4*(4.7%) weights (Fig. 7d). The soil texture was reclassified into four major groups based on soil water holding capacity. The soil texture indicated that 37% of the soil is comprised of clay and silty clay soil which have a high water holding capacity.

3.2.2. Crop specific suitability factors

The weights of crop-related factors were distributed across the absolute and optimal range as illustrated in Fig. 6a. For example, the monthly temperature of Napier grass was weighted as 1 for minimum and maximum optimal temperature range, which is between 25 and 40 °C. For the temperature values in between the optimal and absolute range (i.e., between 15 and 25 & 40 – 45, Table 2), the weight was scaled linearly between one and zero. For temperature values outside the absolute range, a value of zero was assigned. A similar weighting distribution was applied for other crop-related factors (i.e., temperature, soil depth, and soil pH). The weighted crop-related factors for Napier are shown in Fig. 8a, b, c, and d. The suitability index indicated that 24%, 30%, and 43% of the growing season temperature, soil depth, and soil pH, respectively were not limiting factors for Napier production.

3.3. Preliminary land suitability analysis for fodder production

The reclassified and weighted factors provided the preliminary fodder suitable areas, which was further enhanced by excluding the constraints that limit the use of the land for fodder production to identify the actual potential suitable land (Fig. 9). The suitability values for Napier, alfalfa, desho, vetch, and oats production ranges between 48% and 94%, 42–91%, 46–94%, 39–93%, and 38–94%, respectively. The lowest value range represents the least suitable land area for the respective fodder crop while the highest value represents the most suitable land for the respective fodder crop (Fig. 9a to e). Fig. 9f presented the extracted most suitable land that has a suitability threshold value of more than 80% at a 1% increment. For example, at a threshold of 85%, about 2% of the landmass was suitable for Napier production using surface irrigation, while at the 80% threshold, about 9% (22,600 km^2) of the land was suitable for surface irrigation. The suitability analysis indicated that the country has the largest suitable area for Desho production (31%), followed by Vetch (23%), Napier (20%), Alfalfa (13%), and oats (12%) (Fig. 9f and Table 4). The analysis also indicated that 3% (31,800 km^2)

of the country is suitable for five of the studied crops and 12% of the country is suitable for four different fodder crops and at least 38% of the country is at least suitable for one fodder crop.

The potential fodder production sites of the respective crops were compared with the agricultural land. The analysis indicated that 40% of Napier production potential area is located on the grassland while 44%, 42%, 41%, and 31% of the suitable land for alfalfa, desho, vetch, and oats production, respectively are located on the grassland. The analysis also indicated that 29%, 25%, 29%, 36%, and 48% of the suitable production area of Napier, alfalfa, desho, vetch, and oats, respectively are located on the agricultural land. The potential fodder production areas that have a suitability threshold value of >80% were extracted for the major river basins in Ethiopia (Table 4). The results from this analysis can contribute to the development of a livestock master plan at the basin level. The Abbay basin (Upper Blue Nile basin), which is the largest basin in Ethiopia, has the largest suitable area for overall fodder production (431,806 km^2), followed by Genale-Dawa (425,650 km^2) and Wabi-Shebelle basins (338,691 km^2), respectively (Table 4). When it comes to specific crops, the Abbay basin has the highest suitable area for Napier and oats fodder crops, while Genale-Dawa has the largest suitable area for desho, alfalfa, and vetch (Table 4).

3.4. Groundwater availability and fodder potential area

The average groundwater potential yield in the highly suitable land (i.e., suitability value > 85%) is ~ 4 l/s; 5.8 l/s; ~4.3 l/s, ~4.5 l/s and ~ 3.7 l/s for Napier, alfalfa, desho, vetch, and oats, respectively (Table 5). The depth to groundwater on the most suitable lands for Napier, alfalfa, Desho, vetch, and oats were on average at depths of 17 m, 22 m, 27 m, 14 m, and 20 m, respectively. This suggested that there is substantial shallow groundwater that is accessible using simple water-lifting technologies for fodder production. Since there is a higher rainfall variability in Ethiopia, shallow groundwater can serve as a source of irrigation to buffer droughts and dry spells.

3.5. Uncertainty of the suitability assessment

MCE provides tools to systematically rank factors to make a complex decision. However, MCE involves a range of uncertainties and it is one of the concerns of the decision-making process (Benke et al. 2009). The source of uncertainty in MCE originates from the selection of factors (parameters) and their respective resolution, temporal scale of climate data, and weighting of factors (Benke et al. 2009, Zimmermann 2000). The major uncertainty in MCE is assigning weight to the factors, which is mainly determined based on expert opinion. Such weight assignment may introduce expert bias. To reduce the uncertainty associated with inconsistent weighting, a consistency ratio was used to evaluate experts judgment in their decision-making. As such the consistency ratio provides information on the reliability of the weighting of the factors. For example, the consistency ratio of less than 0.1 is considered satisfactory to yield robust suitability estimation (Franek and Kresta 2014). However, if the consistency ratio is greater than 0.1, the weight assignment is considered less reliable and the process of assigning weights should be repeated. The selection of the factors and their spatial resolution is another source of uncertainty, the selected factor should adequately represent the objective of the suitability assessment. In this study, the major factors affecting the suitability of the land for fodder production were considered however, their spatial resolution of the factors was different varying between 30 and 1000 m, the overlaying analysis was done by resampling all of the data to 30 m resolution. The resampling process will affect how well the reality in the ground is reflected. The other source of uncertainty is associated with the range of climate data used for the analysis. In this analysis due to lack of sufficient data ten years of climate data (2000 to 2010) were used to estimate the rainfall deficit. Despite the limitations of the suitability analysis, this study executed every effort (e.g., looking for the best available data in terms of spatial and temporal resolution, engaging with experts in the area, etc) to reduce the uncertainty of fodder suitability analysis.

4. Conclusions

This study provided spatially explicit land suitability maps for fodder production in Ethiopia. Although Ethiopia possesses a significant livestock population, productivity has been limited by inadequate quantity and quality of feed supply throughout the year. If the livestock production system is supported with sufficient quality and quantity of feed, then it can begin to reach the potential contribution to socio-economic development. This study showed that at least 38% of the country is suitable for at least one fodder crop studied, this indicates that there is a significant land area suitable for increased fodder production in Ethiopia that can produce a sufficient quantity of livestock feed. The identified suitable land is also situated in areas where there is substantial shallow groundwater accessible using simple water-lifting technologies for small-scale fodder production. With the recent expansion of road networks since the available 2006 data, the study may underestimate the potential suitable land areas. In terms of river basins, the Abbay basin (Upper Blue Nile) has the largest area suitable for fodder production followed by Genale-Dawa and Wabi-Shebelle basins, respectively. This study provides valuable insights for decision-makers, the private sector, and practitioners to prioritize and scale fodder production in Ethiopia.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This research is made possible by the support of the American People provided to The Feed the Future Innovation Lab for Small-Scale Irrigation (ILSSI) and The Feed the Future Innovation Lab for Livestock Systems (LSIL) through the United States Agency for International Development (USAID). The contents are the sole responsibility of the authors and do not necessarily reflect the views of USAID or the United States Government. Program activities are funded by the United States Agency for International Development (USAID) under Cooperative Agreement No. AID-OAA-L-14-00006 and contract No. AID-OAA-L-15-00003. We would like also to acknowledge the National Meteorological Agency Services of Ethiopia, British Geological Survey, United States Geological Survey, and African Soil Information Service for providing us with quality data.

Appendix A

See Tables 1a–1d.

References

Ahmed, M.A., Ehui, S. and Assefa, Y. (2004) Dairy development in Ethiopia, Intl Food Policy Res Inst.

Alemayehu, S., Ayana, E.K., Dile, Y.T., Demissie, T., Yimam, Y., Girvetz, E., Aynekulu, E., Solomon, D., Worqlul, A.W., 2020. Evaluating Land Suitability and Potential Climate Change Impacts on Alfalfa (Medicago sativa) Production in Ethiopia. Atmosphere 11 (10), 1124.

Armah-Agyeman, G., Loiland, J., Karow, R. and Bohle, M.G., 2002. Dryland alfalfa.

Asresie, A., Zemedu, L., 2015. Contribution of livestock sector in ethiopian economy: a review. Adv. Life Sci. Technol. 29, 79–90.

Assefa, D., Nurfeta, A., 2013. Assessment of feed resource availability and livestock production constraints in selected Kebeles of Adami Tullu Jiddo Kombolcha District, Ethiopia. African J. Agric. Res. 8 (29), 4067–4073.

Assefa, G., Ledin, I., 2001. Effect of variety, soil type and fertiliser on the establishment, growth, forage yield, quality and voluntary intake by cattle of oats and vetches cultivated in pure stands and mixtures. Anim. Feed Sci. Technol. 92 (1-2), 95–111.

Assefa, T.T., Jha, M.K., Tilahun, S.A., Yetbarek, E., Adem, A.A., Wale, A., 2015. Identification of erosion hotspot area using GIS and MCE technique for Koga

watershed in the Upper Blue Nile Basin, Ethiopia. Am. J. Environ. Sci. 11 (4), 245–255.
Baigorria, G.A., Romero, C.C., 2007. Assessment of erosion hotspots in a watershed: integrating the WEPP model and GIS in a case study in the Peruvian Andes. Environ. Model. Software 22 (8), 1175–1183.
Belay, K., 2002. Constraints to agricultural extension work in Ethiopia: the insiders' view. South African J. Agric. Extension 31, 63–79.
Benin, S., Ehui, S., Pender, J., 2003. Policies for livestock development in the Ethiopian highlands. Environ. Dev. Sustain. 5 (3–4), 491–510.
Benke, K., Pelizaro, C., Lowell, K., 2009. Crop modeling and decision Support. Springer, pp. 291–298.
Berhane, G., Dereje, M., Hoddinott, J., Koru, B., Nisrane, F., Tadesse, F., Taffesse, A.S., Worku, I., Yohannes, Y., 2013. Agricultural Growth Program (AGP) of Ethiopia–Baseline Report 2011. ESSP/EDRI Report. International Food Policy Research Institute, Addis Ababa.
Brovelli, M.A., Molinari, M.E., Hussein, E., Chen, J., Li, R., 2015. The first comprehensive accuracy assessment of GlobeLand30 at a national level: Methodology and results. Remote Sensing 7 (4), 4191–4212.
Bundervoet, T., Fuje, H.N., Ranzani, M., Lange, S., Iimi, A., Tsehaye, E., 2017. Ethiopia-Employment and Jobs Study. The World Bank.
Ceballos-Silva, A., López-Blanco, J., 2003. Delineation of suitable areas for crops using a Multi-Criteria Evaluation approach and land use/cover mapping: a case study in Central Mexico. Agric. Syst. 77 (2), 117–136.
Chandio, I.A., Matori, A.-N., Lawal, D.U., Sabri, S., 2011. GIS-based land suitability analysis using AHP for public parks planning in Larkana City. Modern Appl. Sci. 5 (4), 177.
Chanyalew, D., Adenew, B. and Mellor, J., 2010. Ethiopia's agricultural sector policy and investment framework (PIF)(2010–2020), Draft final report. Federal Democratic Republic of Ethiopia, Ministry of Agriculture and Rural Development. Addis Ababa.
Clayton, W., Govaerts, R., Harman, K., Williamson, H. and Vorontsova, M., 2014. World checklist of Poaceae. Richmond, UK, Royal Botanic Gardens, Kew.
Conceição, P., Levine, S., Lipton, M., Warren-Rodríguez, A., 2016. Toward a food secure future: Ensuring food security for sustainable human development in Sub-Saharan Africa. Food Pol. 60, 1–9.
Duke, J.A., 1983. Handbook of energy crops. Handbook of Energy Crops.
Ecocrop, 2000. Ecocrop Database, FAO. Nations, F.a.A.O.o.t.U. (ed), Rome.
FAO, 1976. A framework for land evaluation, Rome.
FAO, 1985. Guidelines: land evaluation for irrigated agriculture. Soils Bulletin 55, Via delle Terme di Caracalla, 00100 Rome, Italy.
FAO, 1989. Guidelines for Designing and Evaluating Surface Irrigation Systems (FAO Irrigation and Drainage Paper), Via delle Terme di Caracalla, 00100 Rome, Italy.
FAO, 2011. Grassland Index. A searchable catalogue of grass and forage legumes.
Farr, T.G., Rosen, P.A., Caro, E., Crippen, R., Duren, R., Hensley, S., Kobrick, M., Paller, M., Rodriguez, E. and Roth, L., 2007. The shuttle radar topography mission. Reviews of Geophysics 45(2).
Feizizadeh, B., Shadman Roodposhti, M., Jankowski, P., Blaschke, T., 2014. A GIS-based extended fuzzy multi-criteria evaluation for landslide susceptibility mapping. Comput. Geosci. 73, 208–221.
Fick, S.E., Hijmans, R.J., 2017. WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. Int. J. f Climatol. 37 (12), 4302–4315.
Franek, J., Kresta, A., 2014. Judgment scales and consistency measure in AHP. Procedia Econ. Financ. 12, 164–173.
Haileselassie, M., Redae, G., Berhe, G., Henry, C.J., Nickerson, M.T., Tyler, B., Mulugeta, A., de Souza, R.J., 2020. Why are animal source foods rarely consumed by 6–23 months old children in rural communities of Northern Ethiopia? A qualitative study. PLoS ONE 15 (1), e0225707.
Hiernaux, P., Fernández-Rivera, S., Schlecht, E., Turner, M. and Williams, T.O. (1997) Livestock-mediated nutrient transfers in Sahelian agro-ecosystems.
Hood, A., Cechet, B., Hossain, H., Sheffield, K., 2006. Options for Victorian agriculture in a "new" climate: Pilot study linking climate change and land suitability modelling. Environ. Modell. Software 21 (9), 1280–1289.
Hurrissa, B., Eshetu, J., 2002. Challenges and opportunities of livestock marketing in Ethiopia, pp. 1-13.
Jahnke, H., Tacher, G., Keil, P., Rojat, D., 1988. Livestock production in tropical Africa, with special reference to the tsetse-affected zone. Livestock Production in Tsetse-Affected Areas of Africa 3–21.
Jun, C., Ban, Y., Li, S., 2014. China: Open access to Earth land-cover map. Nature 514 (7523), 434.
Kaliraj, S., Chandrasekar, N., Magesh, N.S., 2014. Identification of potential groundwater recharge zones in Vaigai upper basin, Tamil Nadu, using GIS-based analytical hierarchical process (AHP) technique. Arab. J. Geosci. 7 (4), 1385–1401.
Karami, E., 2006. Appropriateness of farmers' adoption of irrigation methods: the application of the AHP model. Agric. Syst. 87 (1), 101–119.
Kebede, T., Ademe, Y., 2016. Evaluating land suitability for irrigation purpose in Abaya district, Borena zone, Ethiopia. African J. Agric. Res. 11 (46), 4754–4761.
Kontos, T.D., Komilis, D.P., Halvadakis, C.P., 2005. Siting MSW landfills with a spatial multiple criteria analysis methodology. Waste Manage. 25 (8), 818–832.
Kung Jr, L., Taylor, C., Lynch, M., Neylon, J., 2003. The effect of treating alfalfa with Lactobacillus buchneri 40788 on silage fermentation, aerobic stability, and nutritive value for lactating dairy cows. J. Dairy Sci. 86 (1), 336–343.
Lambin, E.F., Geist, H.J., Lepers, E., 2003. Dynamics of land-use and land-cover change in tropical regions. Ann. Rev. Environ. Resour. 28 (1), 205–241.
Lithourgidis, A.S., Vasilakoglou, I.B., Dhima, K.V., Dordas, C.A., Yiakoulaki, M.D., 2006. Forage yield and quality of common vetch mixtures with oat and triticale in two seeding ratios. Field Crops Res. 99 (2-3), 106–113.
MacDonald, A.M., Bonsor, H.C., Dochartaigh, B.É.Ó., Taylor, R.G., 2012. Quantitative maps of groundwater resources in Africa. Environ. Res. Lett. 7 (2), 024009. https://doi.org/10.1088/1748-9326/7/2/024009.
MoFED, E., 2010. Growth and transformation plan (GTP) 2010, 11-2014/15 Draft.
Mondal, S., Maiti, R., 2012. Landslide susceptibility analysis of Shiv-Khola watershed, Darjiling: a remote sensing & GIS based Analytical Hierarchy Process (AHP). J. Indian Soc. Remote Sens. 40 (3), 483–496.
Mu, Q., Zhao, M., Running, S.W., 2011. Improvements to a MODIS global terrestrial evapotranspiration algorithm. Remote Sens. Environ. 115 (8), 1781–1800.
Mwendia, S.W., Yunusa, I.AM., Sindel, B.M., Whalley, R.DB., Kariuki, I.W., 2017. Assessment of Napier grass accessions in lowland and highland tropical environments of East Africa: water stress indices, water use and water use efficiency. J. Sci. Food Agric. 97 (6), 1953–1961.
Narra, P., Coelho, C., Sancho, F., 2019. Multicriteria GIS-based estimation of coastal erosion risk: Implementation to Aveiro sandy coast, Portugal. Ocean Coast. Manage. 178, 104845. https://doi.org/10.1016/j.ocecoaman.2019.104845.
Nithya, C.N., Srinivas, Y., Magesh, N.S., Kaliraj, S., 2019. Assessment of groundwater potential zones in Chittar basin, Southern India using GIS based AHP technique. Remote Sens. Appl.: Soc. Environ. 15, 100248. https://doi.org/10.1016/j.rsase.2019.100248.
Orodho, A., 2006. The role and importance of Napier grass in the smallholder dairy industry in Kenya. Food and Agriculture Organization, Rome) Retrieved August 24, 2011.
Ren, C., Li, Z., Zhang, H., 2019. Integrated multi-objective stochastic fuzzy programming and AHP method for agricultural water and land optimization allocation under multiple uncertainties. J. Cleaner Prod. 210, 12–24.
Saaty, T.L., 1977. A scaling method for priorities in hierarchical structures. J. Math. Psychol. 15 (3), 234–281.
Saaty, T.L., 1980. The Analytic Hierarchy Process: Planning, Priority Setting, Resources Allocation. McGraw 281, New York.
Saaty, T.L., Vargas, L.G., 1991. Prediction, projection, and forecasting: applications of the analytic hierarchy process in economics, finance, politics, games, and sports, Kluwer Academic Pub.
Sattell, R., Dick, R., Hemphill, D.D., Selker, J.S., Brandi-Dohrn, F.M., Minchew, H., Hess, M., Sandeno, J. and Kaufman, S.M., 1999. Nitrogen scavenging: using cover crops to reduce nitrate leaching in western Oregon.
Sawasdee, V., Pisutpaisal, N., 2014. Feasibility of Biogas Production from Napier Grass. Energy Procedia 61, 1229–1233.
Schmelzer, G., 1997. Review of Pennisetum section Brevivalvula (Poaceae). Euphytica 97 (1), 1–20.
Shapiro, B., Gebru, G., Desta, S., Negassa, A., Nigussie, K., Aboset, G., Mechale, H., 2017. Ethiopia livestock sector analysis. ILRI Project Report. Nairobi, Kenya: International Livestock Research Institute (ILRI).
Shapiro, B.I., Gebru, G., Desta, S., Negassa, A., Negussie, K., Aboset, G. and Mechal, H., 2015. Ethiopia livestock master plan: Roadmaps for growth and transformation.
Singh, L.K., Jha, M.K., Chowdary, V.M., 2018. Assessing the accuracy of GIS-based Multi-Criteria Decision Analysis approaches for mapping groundwater potential. Ecol. Ind. 91, 24–37.
Stevens, E., Armstrong, K., Bezar, H., Griffin, W., Hampton, J., 2004. Fodder oats an overview. Fodder oats: a world overview. In: Food and Agriculture Organization of the United Nations, pp. 1–9.
Suttie, J.M., Reynolds, S.G., 2004. Fodder oats: a world overview. Food Agricult. Org.
Tahir, M.B., Wossen, A.M., Mersso, B.T., 2018. Evaluation of livestock feed balance under mixed crop–livestock production system in the central highlands of Ethiopia. Agricult. Food Secur. 7 (1), 19.
Tassew, A., Seifu, E., 2009. Smallholder dairy production system and emergence of dairy cooperatives in Bahir Dar Zuria and Mecha Woredas, Northwestern Ethiopia. World J. Dairy Food Sci. 4 (2), 185–192.
Teka, K., Haftu, M., 2012. Land suitability characterization for crop and fruit production in Midlands of Tigray, Ethiopia. Momona Ethiopian J. Sci. 4 (1), 64–76.
Vågen, T., Shepherd, K., Walsh, M., Winowiecki, L., Desta, L.T., Tondoh, J., 2010. AfSIS technical specifications: soil health surveillance. World Agroforestry Centre, Nairobi, Kenya.
Walker, W.R. (1989) Guidelines for designing and evaluating surface irrigation systems.
Wb,, 2019. Ethiopia Economic Update 7: Special Topic-Poverty and Household Welfare in. World Bank Group.
Worqlul, A.W., Collick, A.S., Rossiter, D.G., Langan, S., Steenhuis, T.S., 2015. Assessment of surface water irrigation potential in the Ethiopian highlands: The Lake Tana Basin. Catena 129, 76–85.
Worqlul, A.W., Dile, Y.T., Jeong, J., Adimassu, Z., Lefore, N., Gerik, T., Srinivasan, R., Clarke, N., 2019. Effect of climate change on land suitability for surface irrigation and irrigation potential of the shallow groundwater in Ghana. Comput. Electron. Agric. 157, 110–125.
Worqlul, A.W., Jeong, J., Dile, Y.T., Osorio, J., Schmitter, P., Gerik, T., Srinivasan, R., Clark, N., 2017. Assessing potential land suitable for surface irrigation using groundwater in Ethiopia. Appl. Geogr. 85, 1–13.
Yohannes, H., Soromessa, T., 2018. Land suitability assessment for major crops by using GIS-based multi-criteria approach in Andit Tid watershed, Ethiopia. Cogent Food Agricult. 4 (1), 1470481. https://doi.org/10.1080/23311932.2018.1470481.
Zimmermann, H.-J., 2000. An application-oriented view of modeling uncertainty. Eur. J. Oper. Res. 122 (2), 190–198.