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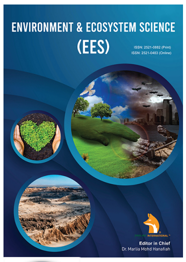

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RESEARCH ARTICLE

GIS-BASED LAND SUITABILITY ANALYSIS FOR EX-SITU PRODUCTION OF THREATENED *Citropsis articulata* IN UGANDA

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ABSTRACT

Citropsis articulata (Spreng.) is a potent medicinal plant that is increasingly threatened by unsustainable harvesting and habitat destruction due to deforestation. This calls for enhancement of ex-situ conservation of *C. articulata* through offsite production. However, the success of offsite production of this species heavily rests on precisely assessing the suitability of the land for its production. In this study, an integrated GIS based multi-criteria evaluation approach was used to depict suitable areas for production of *C. articulata* based on key factors of; climate, soil and topography. Results revealed that only 13.04% (31495.77 km^2) of Uganda's land is very suitable to support natural production of *C. articulata* and is mainly situated in the western and central regions. Findings further revealed that 76.4% (24062.77 km^2) of very suitable land area is situated outside protected areas, thus implying availability of potential sites for ex-situ and commercial production of *C. articulata* in the country. Findings also indicated that *C. articulata* has potential of thriving in well drained, moderately acidic soils and pleasantly warm regions endowed with moderately high precipitation and humidity. Since current stocks of *C. articulata* are mainly restricted to protected areas, cultivating this species will provide alternative sources of the plant harvest. This will help to relieve current pressures on the wild populations of *C. articulata*, thus providing a safety backup to the current in-situ conservation efforts.

KEYWORDS

Land suitability; Multi-Criteria Evaluation; Citropsis articulata; GIS; Ex-situ production.

1. INTRODUCTION

Medicinal plant-based products continue to play an indispensable role in primary healthcare in many parts of the world (Kelly, 2009). Currently the herbal medicine sector is reported to support the health care of over 5 billion people around the globe with the highest proportion from developing countries (WHO, 2002). The increased demand for herbal medicine-based products coupled with other factors such as climate change, unsustainable methods of harvesting, environmental degradation, agricultural expansion, grazing pressure and urbanization have wielded imminent pressure and threat on wild medicinal plant species (Brummitt et al., 2015; Hawkins, 2007; Volis, 2016). Unfortunately, this trend has endangered a lot of medicinal plants with some reported to be on the verge of extinction from the wild. For instance, *Citropsis articulata* (Spreng.) Swingle and Kellerm., family (Rutaceae) is listed among the vulnerable species on the International Union for Conservation of Nature (IUCN) red list for Uganda (MTWA, 2018). Furthermore, *C. articulata* has been reported to be declining at a frightening rate in Uganda (Okeowo, 2007). This plant is well known for its aphrodisiac properties and recent studies have proven its antiplasmodial potential too (Lacroix et al., 2011; Vudriko et al., 2014). Unfortunately, the plant part most harvested is the root. This coupled with deforestation have greatly endangered the survival and occurrence of this plant, besides it is presently restricted to protected areas of Uganda. Therefore, there is need to develop and enhance offsite (ex-situ) conservation of *C. articulata*. This will provide a safety backup for *in-situ* conservation techniques and rekindle humanity's hope for more potent therapeutic agents and molecules that medicinal plants have to offer (Maxted and Kell, 2009).

Ex-situ conservation of medicinal plants can be realized through a number of approaches such as DNA storage, seed storage, pollen storage, in vitro conservation; botanical gardens and cultivation (ex-situ production) on large scale (FAO, 2010; Sharma and Thokchom, 2014). However, despite the increase in cultivation practice of medicinal plants, there are a number of impeding factors that have deterred production of some medicinal plant species. These factors include for example, possession of certain biological

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features and or ecological requirements (Jusaitis, 1995). Thus, the success of any *ex situ* production of a plant entails using multifaceted approaches in understanding physiological needs and drivers of the targeted species (Jaramillo and Baena, 2002). Therefore, before introducing a plant species in a new area, land suitability assessment is a prerequisite to achieving an optimum utilization of the available land resources for a sustainable agricultural production (Barbaro et al., 2011; FAO, 1976).

Land suitability assessment is one of the approaches used in land evaluation. This involves enactment and interpretation of basic surveys of key parameters of climate, soils, vegetation and other aspects of land to measure the degree of appropriateness of land for a definite use (FAO, 1976; Halder, 2013). In this regard geospatial tools and analysis have unearthed many possibilities of research in agricultural production and management. Thus, land suitability assessment using a multi-criteria decision analysis (MCDA) approach integrated in Geographic Information Systems (GIS) has become a common practice in agricultural production (Yohannes and Soromessa, 2018). A number of investigations have been conducted world over to assess land suitability for agricultural production using GIS-approaches (Barbaro et al., 2011; Bydekerke et al., 1998; Ceballos-Silva and Lopez-Blanco, 2003; Kamau et al., 2015; Mendoza, 2000; Mustafa et al., 2011; Naughton et al., 2015; Perveen et al., 2007). Nonetheless most of these studies have largely focused on food crops but with limited adoption in ex-situ production of medicinal flora in Uganda. Consequently, the land suitability assessment for *C. articulata* production in Uganda has not been empirically explored. Therefore, the objectives of this study were to depict environmental requirements for production of *C. articulata* and develop a suitability map revealing potential areas for production of *C. articulata* in Uganda based on key climatic, soil and topographic parameters. The suitability map development involved the use of Analytical Hierarchy Process (AHP) in integrating multi-criteria evaluation (MCE) with GIS.

2. Methods

2.1 Study Area

Uganda is located in the eastern part of Africa. The country is situated at latitude 1º30'S and 4ºN and longitude 29º 45'E and 35ºE with area coverage of approximately 241474.23 km². The country is divided into four major regions (Central, Eastern, Western and Northern) as shown in Figure 1. Uganda has a warm tropical climate which is characterized by relatively high rainfall and temperature throughout the year. The rainfall is at an average of 1180 mm with a bimodal pattern in March-May and September-November (Mubiru et al., 2012; Nsubuga et al., 2013). The country's annual high temperatures range from 24ºC to 33ºC (Figure 3c). The warm tropical climate favors flourishing of both flora and fauna across the country. To safeguard its immense natural treasure gifted by nature and with high biodiversity, Uganda has established a number of semi-autonomous entities and authorities whose aim is to protect its biodiversity. These among others include; Uganda Wildlife Authority (UWA), National Forestry Authority (NFA) and National Environmental Management Authority. These bodies work in collaboration with global organizations such as Wildlife Conservation Society (WCS), World Wide Fund for nature (WWF), International Union for Conservation of Nature (IUCN) and United Nations Educational, Scientific and Cultural Organization (UNESCO). However, most of these organizations' mandate is restricted to protected areas (PA). Therefore, despite their efforts to protect biodiversity, there is continued depletion and degradation of most of the country's natural resources. This is threatening the existence of some floral species including *C. articulata.* Thus, the need to enhance their efforts through cultivation of *C. articulata* outside protected areas to conserve what exists in the protected wild.

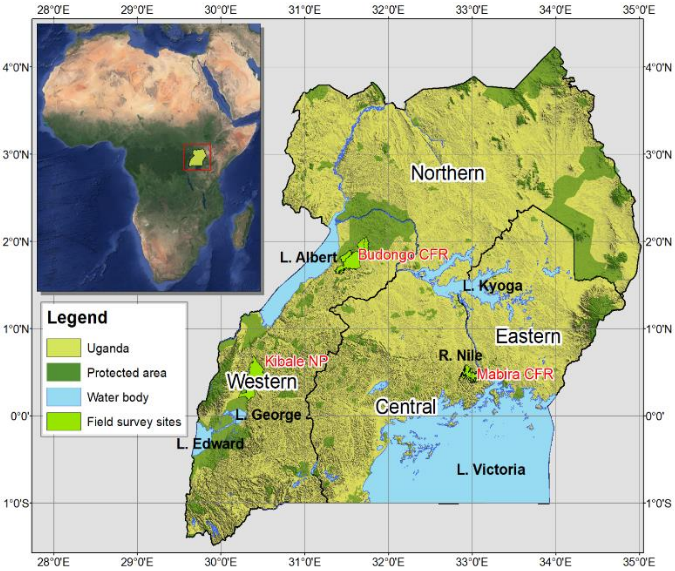

Figure 1: Map showing location of study area.

2.2 Data and Methods

Factors adopted for the land suitability assessment for *C. articulata* production were identified through expert opinion from; foresters, agroforestry scientists, silviculturists, and botanists at National Forestry Authority (NFA) and Mbarara University of Science and Technology collected through a questionnaire. The criteria for selection of the experts was based on the following: 1) expertise on habitat requirements of *C. articulata*, 2) expertise in agroforestry, 3) experience in ex-situ production, 4) expertise in plant physiology and 5) experience in agronomy. The expert opinions were supplemented by appropriate and relevant literature reviews. A field-based survey on spatial variability of *C. articulata* was undertaken in three forest areas in Uganda where this species is known to occur. The generated spatial data that were used in depicting the critical requirements for areas suitable for growing *C. articulata* (Table 2). The factors identified for land suitability analysis were aligned to climate (relative humidity, rainfall and temperature), soil (texture, pH, drainage, Cation exchange capacity, total Nitrogen, Phosphorus, Potassium, Bulk density, organic carbon) and geomorphology (altitude and slope). The summary of data and methods implemented in this study are outlined in Table1 and Figure 2 respectively.

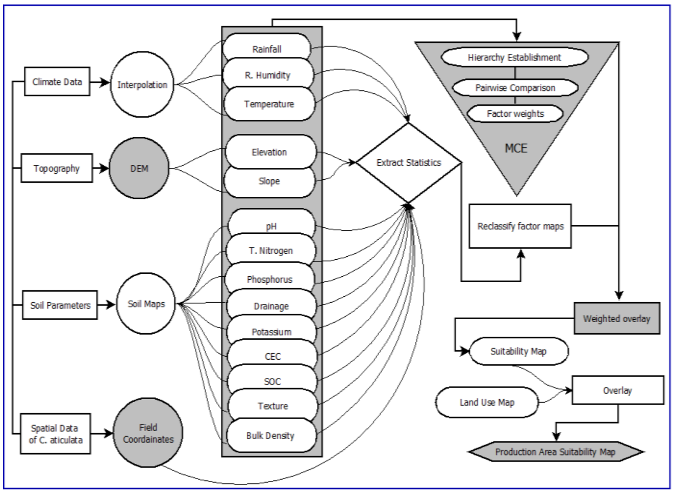

Figure 2: Summary of GIS based methods.

Table 1: List of datasets and sources used in the study.

Data	Description	Source
Rainfall	Derived from weather data of 181 spatial points averaged from a 36-year period.	NASA power project data
Humidity	Derived from weather data of 181 spatial points averaged from a 36-year period.	NASA power project data
Temperature	Derived from weather data of 181 spatial points averaged from a 36-year period.	NASA power project data
Drainage	Generated using the Africa Soil Profiles Database and classification based on FAO, 2006	International Soil Reference and Information Centre (ISRIC)
Texture	Derived from sand, silt and clay contents predicted using the Africa Soil Profiles Database (AfSP) and classification based on USDA system	International Soil Reference and Information Centre (ISRIC)
Bulk Density	Measured for soil fine earth and predicted using the Africa Soil Profiles Database (AfSP) at 250m spatial resolution	International Soil Reference and Information Centre (ISRIC)
pH	Generated using Africa soil profiles data at 250m spatial resolution	International Soil Reference and Information Centre (ISRIC)
Phosphorus	Spatially predicted for 0-30cm depth interval at 250m spatial resolution based	International Soil Reference and Information Centre (ISRIC)
Total Nitrogen	Spatially predicted for 0-30cm depth interval at 250m spatial resolution	International Soil Reference and Information Centre (ISRIC)
Potassium	Spatially predicted for 0-30cm depth interval at 250m spatial resolution	International Soil Reference and Information Centre (ISRIC)
Soil organic carbon	Measured for soil fine earth predicted using the Africa soil profiles data at 250m spatial resolution	International Soil Reference and Information Centre (ISRIC)
Cation Exchange Capacity	Generated from Africa Soil Profiles Database (AfSP) at 250m spatial resolution	International Soil Reference and Information Centre (ISRIC)
Elevation	STRM DEM encompassing Uganda at 30m spatial resolution	NASA Earth data
Slope	Generated from a 30m spatial resolution SRTM DEM	NASA Earth data
Spatial data on C. *articulata*	Ground points (n=305) at sites of occurrence of C. articulata	Field Survey
Land use/ land cover map	Land Use/Land cover Shapefile of Uganda	National Forestry Authority (NFA)
Questionnaire	Influential factors for suitability analysis and rating the importance of each criterion to another (based on Saaty, 1980)	Expert opinion

2.2.1 Climatic Parameters

Inter-annual data on rainfall, relative humidity and temperature were obtained from National Aeronautics and Space Administration (NASA) at https://power.larc.nasa.gov. The data were collected for a region encompassing Uganda at a location of Longitude 1.75ºS-4.35ºN and Latitude 29.25-35.75ºE. This comprised of weather data from 181 spatial points averaged from a 36-year period (1981-2017). The csv file was imported in ArcGIS 10.5 and interpolated using Kriging spatial analyst tool to generate climatic factor maps of rainfall, humidity and temperature (Figure 3a-c). The climatic factor maps were georeferenced to the Universal Transverse Mercator (UTM) coordinate system specifically WGS 84 / UTM zone 36N. In addition, the maps were classified using natural breaks (Jenks optimization) method in ArcMap. The Jenks optimization method, is a data classification method premeditated to determine the best arrangement of values into different classes. This method seeks to minimize the variance within classes and maximize the variance between classes (Rahadianto et al., 2015).

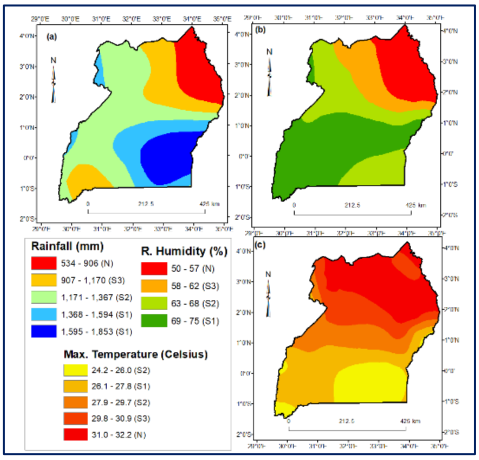

Figure 3: Climatic factor maps based on a 36-year period a) annual rainfall (mm), b) annual relative humidity c) annual maximum temperature.

2.2.2 Soil Parameters

Data on soil parameters were obtained from the International Soil Research Information Center (ISRIC) data hub at https://data.isric.org. The soil property maps for Africa here in are generated based on data from Africa Soil Profiles database (AfSP) and predicated using methods by Hengl et al (2017). For instance: Potassium (K) content in soil fine earth fraction in mg/kg was measured according to the soil analytical procedure of Mehlich 3 and spatially predicted for 0-30cm depth interval at 250 m spatial resolution. Total Nitrogen (N) content of the soil fine earth fraction in mg/kg was measured according to the soil analytical procedure of wet oxidation and spatially predicted for 0-30 cm depth interval at 250 m spatial resolution. Total Phosphorus (P) content of the soil fine earth fraction in mg/kg was spatially predicted for 0-30 cm depth interval at 250 m spatial resolution. Soil organic carbon content in fine earth at 15-30 cm depth was measured by dry combustion at 900^{0}C in g/kg and predicted using Africa soil profiles data at 250 m spatial resolution. Cation exchange capacity of soil fine earth was measured in 1 M NH4OAc buffered at pH 7 in cmolc/kg at 15-30 cm standard depth and predicted at 250m spatial resolution. Soil pH at 15-30 cm standard depth was predicted using Africa soil profiles data at 250 m spatial resolution. Bulk density of the soil fine earth measured by core method in kg/m^3 at 15-30 cm depth was predicted at 250 m spatial resolution. Soil textural classes were derived from sand, silt and clay contents at 15-30 cm depth and defined according to United States Department of Agriculture (USDA) system. Soil drainage was spatially predicted at 250 m resolution with classes defined by (FAO, 2006) guidelines for soil description. The Africa soil thematic maps of the above-mentioned parameters were imported in ArcGIS and the Uganda area extracted using the extract by mask spatial analyst tool. All soil maps at this point were georeferenced to WGS 84 / UTM zone 36N coordinate system. Furthermore, soil maps with nominal data (soil texture and drainage) were categorized according to unique values and labelled accordingly using the metadata description (Figure 4a and 4c). Soil factor maps with continuous data (bulk density, pH, Cation Exchange Capacity (CEC), soil organic matter, nitrogen, phosphorus and potassium) were classified using Jenks optimization method (Figure 4b and 5).

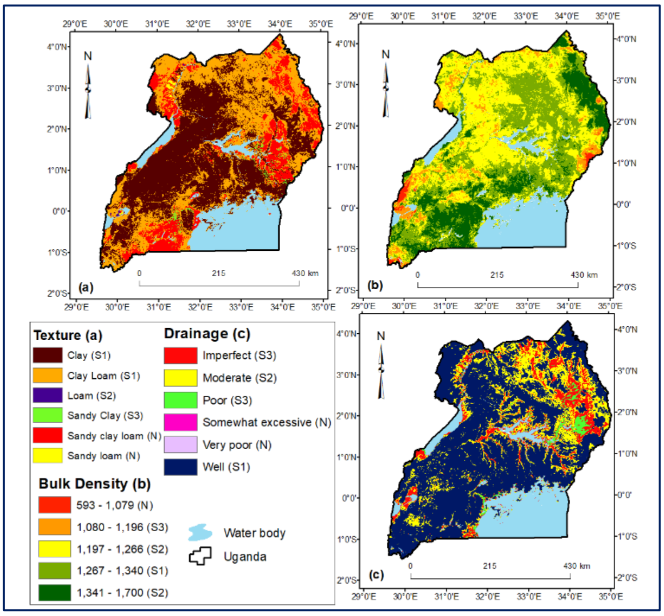

Figure 4: Soil physical factors a) soil texture, b) soil bulk density (kg/m^3), c) soil drainage.

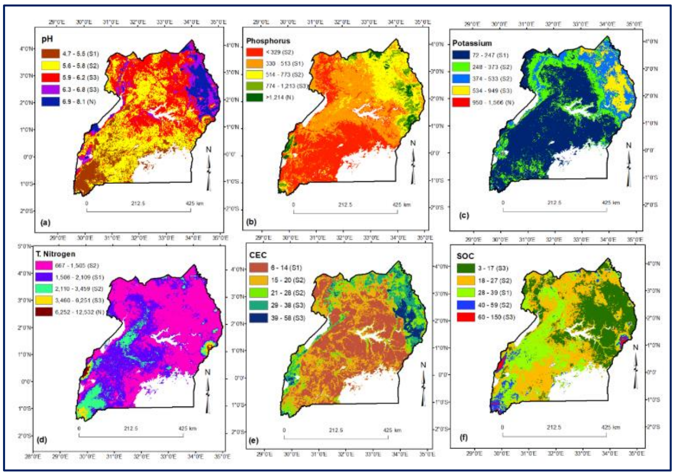

Figure 5: Soil chemical parameter maps a) soil pH, b) soil Phosphorus (mg/kg), c) soil potassium (mg/kg), d) total nitrogen (mg/kg), e) cation exchange capacity (cmolc/kg), f) soil organic carbon (g/kg).

2.2.3 Topographic Parameters

Land surface (Topography) can be represented using a Digital Elevation Model (DEM). A DEM is a geospatial data set that contains elevation values of a given area/region (Bolstad and Stowe, 1994; Hawker, 2018). DEMs are usually generated from remote sensing data or interpolation of point topographical data and contour lines extracted from topographic maps (Fisher et al., 2018; Hawker, 2018). In this study, thirty seven (37) tile SRTM (Shuttle Radar Topography Mission) DEMs encompassing Uganda at 30m spatial resolution were sourced from National Aeronautics and Space Administration (NASA) earth data at https://dwtkns.com/srtm30m/. The DEM tiles were combined to form one regional DEM in ArcGIS using the mosaic spatial analyst tool. Consequently, the Uganda area DEM was extracted from the regional DEM using the extract by mask spatial analyst tool. This constituted the elevation map of Uganda (Figure 6a). Another important topographic factor was slope. This is a measure of change in surface value over distance. Derivation of slope from a regularly gridded DEM is a common practice in terrain analysis (Tang and Pilesjö, 2011). The slope map was derived from the Uganda DEM map using the slope spatial analyst tool and expressed in degrees (Figure 6b). All topographic maps were georeferenced to WGS 84 / UTM zone 36N coordinate system and classified using Jenks optimization method.

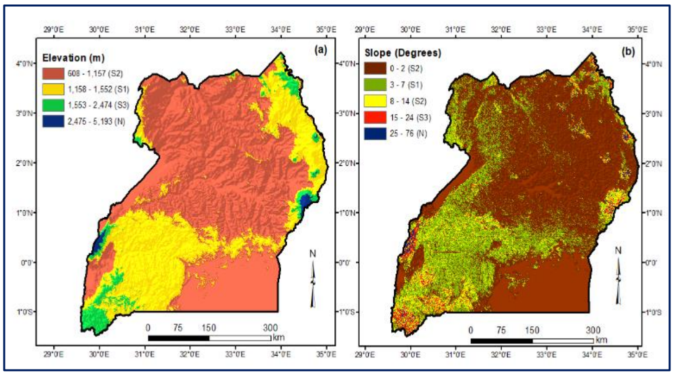

Figure 6: Topographic factors a) elevation (m), b) slope (degrees).

2.2.4 Land use land cover

The land use land cover (LULC) map is very important for consideration of landscape dynamic patterns in sustainable management and planning (AL-Taani et al., 2020; FAO, 1984; Mwanjalolo et al., 2018). In Uganda, the National Forestry Authority (NFA) through inventory is mandated to produce the only comprehensive National land use/cover mapping of the country. Therefore, the information pertaining the 2015 land use/cover was sourced from the National Forestry Authority in form of a shape file. The shape file was imported into ArcMap and converted into a 30m spatial resolution land use/cover raster using the polygon to raster conversion spatial analyst tool and the majority filter method used to enhance the land use/cover map visualization. Additionally, as indicated in Figure 7, the land use/cover classes were labelled accordingly in line with the National Biomass classification system (Mwanjalolo et al., 2018).

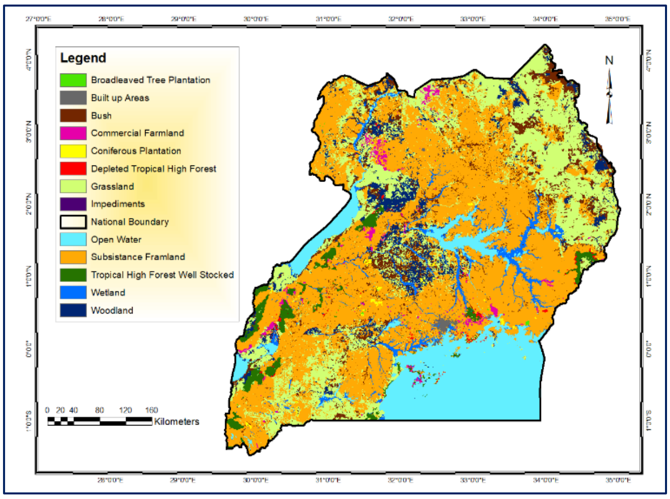

Figure 7: Uganda Land use/cover map for the year 2015.

2.2.5 Field Survey

A field survey was conducted to establish the spatial variability of *C. articulata* in three forest areas of Kibale forest national park whose management is under Uganda Wildlife Authority (UWA) and, Budongo and Mabira central forest reserves under NFA. The selection of the three forest areas was based on; reports of availability of *C. artculata*, variation in agroecological zones and management strategy. A total of 305 ground points at sites of occurrence of *C. articulata* from the three forest reserves; Kibale forest National Park (n=83), Budongo central forest Reserve (n=92) and Mabira central reserve (n=130) were collected and geo-referenced using a handheld GPS (Garmin GPSMAP® 64s). The spatial data obtained from this field activity were used in the assessment and identification of the environmental requirements (Table 2) of *C. articulata* by extracting multi-values to points from the factor maps (Figure 3-6) using spatial analyst tool.

Table 2: Summary statistics of the environmental requirements of *C. articulata*

Parameter	Factor	Statistic			
		Minimum	Maximum	Mean	Standard Deviation
Climate	Rainfall (mm)	1240.14	1741.98	1467.06	218.18
	Humidity (%)	64.65	73.03	69.71	3.16
	Max. Temperature (^{0}C)	26.23	29.73	27.68	1.31
Soil	PH	4.70	5.80	5.24	0.20
	Soil organic Carbon (g/kg)	23.00	40.00	31.88	3.61
	Phosphorous (mg/kg)	189.00	513.00	333.81	83.63
	T. Nitrogen (mg/kg)	1435.00	2577.00	2064.23	215.62
	Potassium (mg/kg)	115.00	217.00	153.04	16.16
	Cation Exchange Capacity (cmolc/kg)	6.00	22.00	10.04	2.57
	Bulk Density (kg/m^3)	1100.00	1400.00	1302.52	50.53
Topography	Elevation (m)	1040.00	1579.00	1209.31	124.06
	Slope (degrees)	0.33	11.74	4.15	2.39

Note: Statistics extracted from factor maps using n=305 ground points from three geolocations (Mabira Central Forest Reserve, Budongo forest reserve, Kibale National Park) in Uganda.

2.2.6 Multi-criteria evaluation process

A number of multi-criteria decisions making (MCDM) methods have been used for land suitability analysis including the Analytic Hierarchy Process (AHP). The AHP is a classical land suitability analysis procedure, which gives a systematic approach in making proper decisions for suitability analysis (Chandio et al., 2013; Zabihi et al., 2015). The AHP is used to determine the scale ratio by carrying out pair wise comparisons between factors. Pair wise comparisons can be attained through relative measurement based on a scale that reflects the relative strengths and preferences (Rahadianto et al., 2015; Saaty, 2008). In this study the AHP was implemented with integration of GIS spatial analysis for the land suitability analysis.

The data sets (factor maps) were each categorized into four suitability classes ranging from very suitable to not suitable as indicated in Table 3. The categorization was based on Food and Agriculture Organization guidelines of land suitability analysis backed by expert opinion, literature review and field observations (FAO, 1984). Given the fact that the fourteen factors (Figure 3-6) adopted in the suitability analysis are measured in different units, it is therefore imperative to standardize the parameters to the same scale of measurement (Malczewski, 2004). In this regard, each factor map was reclassified through linear scale transformation into 4-point scale (Table 3) using the reclassify spatial analyst tool. This ensures linear combination of factor maps during the multi-criterion evaluation (MCE). Furthermore, the outputs of the reclassified factor maps were resampled to a uniform spatial resolution of 30 m using the nearest neighbor resampling method in geo-processing environment. The fact that nearest neighbor resampling method does not alter any of the values of the output cells from the input raster dataset, renders the method suitable for nominal, ordinal or discrete data (Baboo and Devi, 2010).

Table 3: Land suitability classes and scores used in the study (Modified from (FAO, 1984))

Suitability level	Description	Scale
Very Suitable (S1)	Land has no significant limitations to sustain application of the given land utilization.	4
Moderately Suitable (S2)	Land has limitations which collectively are moderately severe for sustained application of the given land utilization.	3
Marginally Suitable (S3)	Land has limitations which collectively are severe for sustained application of the given land utilization and will reduce productivity.	2
Not suitable (N)	Land has so severe limitations which may impede successful sustained application of the given land utilization.	1

Factors were assigned weights through AHP specifically pairwise comparison (Saaty, 1980). This technique provides a more scientific avenue of assigning weights to the factors in suitability analysis. Use of multiple pairwise comparisons from several experts improves the accuracy of the weights assigned to a factor (criteria) rather than arbitrary weight assignment by guessing (Saaty, 2008). This study adopted Saaty's model of relative importance of paired factors in pairwise comparison. A questionnaire comprising of 91 pairwise comparisons generated for the data sets (factors) considered in this study was given to 10 experts to provide expert information on *C. articulata* production. The experts were selected basing on their knowledge and experience in forestry, agroforestry, botany and plant physiology.

The experts rated the importance of factors in each pair on a 9-point scale with increasing magnitude of importance. For instance, value 1 denotes that the two factors are equally important whereas 9 indicates that one factor is extremely important than the other. A reciprocal scale (1/1 to 1/9) was adopted for a decreasing magnitude of importance. For instance, a rating of 1/9 means a factor is extremely less important than the other. The expert data was pooled in Microsoft Excel (Microsoft®) and average scores of each paired element computed (Goepel, 2013). These scores were then used to generate a pairwise comparison matrix of factors (Table 4). Consequently, the individual factor weights were computed from the matrix. Here, normalization of the comparison matrix is created by dividing each value in the matrix by the sum of its column. The mean of each row of the normalized matrix constitutes the weight of the individual factor, given that these weights are already normalized their sum is 1 (Table 4).

In order to verify the consistency of comparisons, a consistency ratio (CR) was computed using the formulae below:

$$CI = \frac{\lambda max - n}{n-1} \quad \text{......} \quad 1$$

$$CR = \frac{CI}{RI} \quad \text{......} \quad 2$$

Where: CI- Consistency Index, λ_{max} – Maximum Eugene value in a matrix, n- number of factors in the Pairwise comparison, RI- Random Index extracted from (Saaty, 1980), CR- Consistency Ratio.

Values of consistency ratio (CR) are on a scale 0 to 1. A Consistency ratio value close to 1 indicates the probability that the matrix's rating was randomly generated in other words the scores were arbitrarily assigned. On the other hand, a CR of 0.1 or less is acceptable level of consistency (Malczewski, 1999; Saaty, 2008). The CR value for the paired comparisons matrix of factors adopted for land suitability analysis was 0.098 indicating a high degree consistency thus the weights assigned are acceptable.

Table 4: Pairwise comparison matrix of criteria

	RF	R.H	Temp.	PH	Drainage	Texture	K	P	T. N	CEC	SOC	BD	Altitude	Slope	Weight	Rank
RF	1.00														0.094	4
R.H	0.33	1.00													0.037	12
Temp.	1.00	3.00	1.00												0.104	2
PH	1.00	6.00	3.00	1.00											0.111	1
Drainage	0.33	2.00	0.33	1.00	1.00										0.090	5
Texture	1.00	3.00	1.00	0.50	0.50	1.00									0.072	9
K	2.00	2.00	0.50	1.00	1.00	0.50	1.00								0.076	7
P	0.50	2.00	0.50	1.00	0.33	2.00	1.00	1.00							0.072	8
T. N	0.50	3.00	1.00	1.00	0.25	3.00	1.00	2.00	1.00						0.084	6
CEC	1.00	1.00	0.33	1.00	0.50	0.50	1.00	1.00	1.00	1.00					0.061	10
SOC	0.50	1.00	0.50	1.00	1.00	0.50	0.25	0.33	1.00	0.33	1.00				0.045	11
BD	0.50	0.50	0.33	0.50	0.33	0.33	0.50	0.50	0.25	0.25	0.33	1.00			0.026	14
Altitude	0.33	0.33	0.20	0.25	0.50	0.25	0.33	0.50	0.25	0.50	0.50	3.00	1.00		0.028	13
Slope	1.00	2.00	1.00	0.33	3.00	2.00	2.00	0.50	1.00	4.00	4.00	2.00	2.00	1.00	0.102	3
C.R = 0.098															∑=1	

Note: RF-Rainfall (mm), RH-Relative Humidity (%), Temp-Temperature (^{0}C), K- Potassium (mg/kg), P-Phosphorous (mg/kg), T.N-Total Nitrogen (mg/kg), CEC -Cation Exchange Capacity (cmolc/kg), SOC-Soil Organic Carbon (g/kg), BD-Bulk Density (kg/m^3)

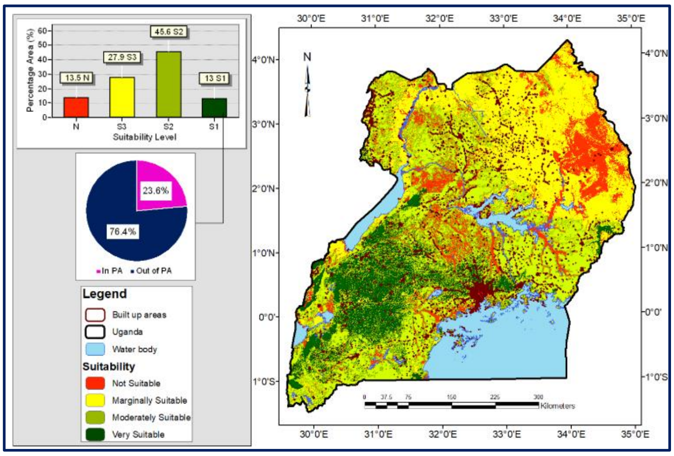

Figure 8: Suitability map for production of *Citropsis articulata* in Uganda.

With weights assigned to each factor, the standardized datasets (factor maps) were aggregated in ArcGIS using the weighted overlay method. Thus, the final output is a suitability map that characterizes areas from very suitable to not suitable for *C. articulata* production. The suitability map was classified in accordance with Food and Agriculture Organization parametric model of land index to generate the suitability map for *C. articulata*. Finally, in a bid to detect differences as well as similarities between the present land use and the potential land use, the present land use/land cover map of Uganda and the suitability map for *C. articulata* were overlaid. This produced the final suitability map for *C. articulata* in light of the current land use pattern of Uganda (Figure 8). To compare the suitability levels across regions of Uganda, a regions map was used to extract the suitability levels of each region (Central, Eastern, Western and Northern). The mask spatial analyst tool was used in this process. There after the country region maps were converted to vector datasets using the raster to polygon conversion tool. This process is done to enable computation of statistics of the suitability classes. Subsequently, statistics were computed for each suitability class to determine the percentage composition of the suitability classes in each region of the country (Table 5).

Table 5: Percentage distribution of suitability classes across regions of Uganda

Suitability	**Region of the country**			
	Central	Eastern	Western	Northern
Very suitable	22.10	2.58	27.68	0.24
Moderately Suitable	63.95	48.35	58.31	25.90
Marginally Suitable	1.46	36.53	5.17	53.50
Not Suitable	12.49	12.54	8.84	20.36
Total	100.00	100.00	100.00	100.00

3. Results and Discussion

3.1 Environmental requirements for production of *C. articulata*

3.1.1 Climatic factors

Annual rainfall in the country ranges from 534-1852 mm with the highest rainfall recorded around the Lake Victoria basin (Figure 3a). On the other hand, the lowest rainfall is registered in the North eastern part of the country. Spatial data revealed that the plant occurred in areas with generally high annual rainfall ranging from 1240.14 to 1741.98 mm as shown in Table 2, thus rendering areas that receive annual rainfall within this range as suitable for production of *C. articulata* (Figure 3) in the country. Notwithstanding, low rainfall levels usually have negative impacts on the productivity of many plants (Nieuwolt, 1982). This therefore implies that the Northeastern part of the country which is generally characterized with low rainfall amounts may not favor production of *C. articulata.* Therefore, this may call for further interventions or land modification in case this plant species is to be grown in such areas. The role of water regimes in plant growth and development cannot be overemphasized. In this regard, expert opinion rated rainfall as one of the critical factors in the production of *C. articulata* bearing a weight of 0.094 (9.4%) as shown in Table 4.

The annual relative humidity of the country ranges from 50-75% (Figure 3c). The highest relative humidity values are observed in the central and southwestern regions and a small portion of Northwestern sub region in an area neighboring the Democratic Republic of Congo (DRC). Consequently, the lowest relative humidity levels are observed in the Northeastern part of the country. *C. articulata* occurrence as outlined in Table 2 is observed in areas with high relative humidity presenting an average of 69.71± 3.16%. This observation is supported by the fact that some species in Rutaceae family thrive in areas with very high humidity (Zabihi et al., 2015). In this regard, we identified areas with relative humidity levels of above 69% as most suitable for production of *C. articulata* as indicated in Figure 3b. This therefore renders the Northeastern part of country unsuitable for production of *C. articulata* because this part of the country generally has low humidity compared to other regions of the country.

As shown in Figure 3c, the annual maximum temperature of the country ranges from 24.2°C to 32.2°C. The highest temperatures are mainly observed in the Northern region of the country, while the lowest temperatures are recorded around the Lake Victoria basin, Southwestern and highland areas of Mountain Rwenzori and Elgon. Spatial data indicated that *C. articulata* occurred in areas with an average annual maximum temperature of 27.68±1.31 °C with individual occurrences between 26.23-29.73 °C as indicated in Table 2. Therefore, based on this observation, areas in the country with annul high temperatures within this range should be suitable for production of *C. articulata*. This implies that *C. articulata* has potential of thriving in areas with moderate temperature. Important to note is that very high temperature has been reported to be one of the leading causes of water deficiency and stress on a plant thus affecting its productivity (Zabihi et al., 2015). Therefore, very high temperatures may not favor the productivity of *C. articulata.* Consequently, the very high temperature stricken Northeastern sub region of the country may not favor the production of *C. articulata*. It should be noted that temperature is known to have a significant effect on all thermo-sensitive cellular metabolic processes in a plant (Hatfield and Prueger, 2015; Hughes and Dunn, 1990). Thus, the expert opinion could not agree more, hence rated temperature as one of the critical factors in the productivity of *C. articulata* bearing a weight of 0.104 (10.4%) as shown in Table 4.

3.1.2 Soil

Soil physical factors

Soil texture is a significant soil parameter that largely influences soil characteristics that affect plant development. Uganda is characterized by varying soil textures ranging from clay to sandy loam (Figure 4a). Spatial data indicated that *C. articulata* majorly occurred in areas with clay and clay loam soils. Thus, areas with such soil texture are potentially very suitable for production of *C. articulata* as indicated in Figure 4a. The fact that sandy soils are generally characterized with very low nutrients and organic matter content may limit the productivity of this plant (Buol et al., 2003). Thus, areas in Uganda dominated by sandy soils may not generally support the productivity of *C. articulata*.

Soil bulk density shows the ability of soil to support soil aeration, structural support, water and solute movement to plants (USDA, 2008). The country's bulk density is in the range of 593-1700 kg/m^3 and is relatively distributed in the country (Figure 4b). Occurrence of *C. articulata* was mainly in areas with average bulk density of 1302.52±50.53 kg/m^3 (Table 2). Basing on this result, areas with moderately high bulk density are deemed appropriate to support production of *C. articulata* (Figure 4b). On the other hand, very low bulk density constituted the unsuitable areas because excessively low bulk density is known to limit productivity of the plants (Houlbrooke et al., 1997; Stirzaker et al., 1996; USDA, 2008).

Soil drainage is a natural process by which water moves through soil as a result of the force of gravity (Fausey, 2005). Good drainage is very vital in sustaining agricultural production and management of water supply in many agroecosystems (Abd-Elmabod et al., 2017). Uganda is generally characterized with well drained soils as shown in Figure 4c. Spatial data indicated that *C. articulata* majorly occurred in areas with well drained soils. Thus, areas with good soil drainage are potentially very suitable for production of *C. articulata* (Figure 4c).

Soil chemical factors

Soil pH of Uganda is in the ranges of 4.7 and 8.1 (Figure 5a). The somewhat alkaline soils are concentrated in the Northeastern part of the country whereas the moderately acidic soils are located in the Western and Central regions of the country. As stipulated in Table 2, *C. articulata* occurred in areas with an average pH of 5.24±0.20. This is an indication that this plant thrives in moderately acidic soils. Thus, areas in Uganda with moderately acidic soils are considered most suited to support agricultural production of *C. articulata* (Figure 5a). Clearly, most micronutrients are more available to plants in acidic soils compared to neutral-alkaline soils, thus facilitating plant growth and development (Lončarić et al., 2008). In this study experts rated pH as the most critical factor in production of *C. articulata* bearing a weight of 0.111(11.1%). This decision is supported by other studies (Gentili et al., 2018; Neina, 2019) which emphasize that soil pH significantly influences other soil proprieties and processes that affect plant growth and development. For instance, soil microbial activity, nutrients solubility and availability all largely depend on soil pH.

Uganda as a country has a varied distribution of soil phosphorus as indicated in Figure 5b with exceedingly high levels of phosphorous occurring mainly in the mountainous areas of Mountain (Mt) Rwenzori in Southwestern and Mt Elgon in the Eastern region. Nevertheless, soils in the largest portion of the country are characterized with moderately low levels of phosphorus. As stipulated in Table 2, *C. articulata* occurred in areas with an average soil phosphorus concentration of 333.81± 83.63 mg/kg. This gives an indication that this species potentially occurs in areas with moderately low levels of phosphorus when compared with other parts of the country (Figure 5b). Worth noting is that *C. articulata* is mainly restricted to tropical forests in Uganda. Soils underlying tropical forests are known to have moderate to low levels of phosphorus (Turner et al., 2018). Thus, this could explain the occurrence of this species in areas with moderately low levels of phosphorus. Additionally, some species in Rutaceae have been shown to thrive in low phosphorus levels thus very high phosphorus may have undesirable effects on their plant growth (De Villiers, 2007). For instance, excessive soil phosphorus may reduce the plant's ability to take up essential micronutrients, such as iron and zinc thus deterring plant development (Malhotra et al., 2018; Stapanian et al., 2016).

Potassium is a vital nutrient for plant growth and development primarily by activation of numerous enzymes, and protection of electrical potential gradients in cell membranes (Çalişkan and Çalişkan, 2019). Potassium levels in Uganda range from 72-1566 mg/kg as indicated in Figure 5c. Excessively high levels of potassium are concentrated in the Northeastern part of the country while the largest portion of the country is covered with moderately low potassium levels. As indicated in Table 2 *C. articulata* occurred in areas with an average Potassium concentration of 153.04±16.16 mg/kg. Thus, indicating that this species occurs in areas with moderately low levels of potassium when compared with other parts of the country (Figure 5c). Furthermore, the fact that *C. articulata* is a tropical forest species, this increases its likelihood of occurring in areas with low potassium levels. Tropical forest soils are known to have low mineral content due to their highly weathered nature and lashing rains that leach soil nutrients (Park, 2002; Place, 2001).

As stipulated in Figure 5d total nitrogen in the country ranges from 667-12532 mg/kg. Generally high levels of nitrogen are observed in mountainous areas of the country, this includes Mt. Rwenzori and Mt. Elgon areas. Spatial data revealed that *C. articulata* occurred in areas with an average total nitrogen concentration of 2064.23±215.62 mg/kg as shown in Table 2. This implies that this species thrives in areas with moderate levels of nitrogen when compared to other parts of the country (Figure 5d). Hence areas in the country with moderate levels of soil total nitrogen were deemed sufficient to support production of *C. articulata.* It is worth noting that excessively high level of soil nitrogen has been linked to alteration of biogeochemical cycling of essential plant nutrients (Gilliam et al., 2016). Thus, this may negatively impact the productivity of the plant. This coupled with the localization of exceedingly high levels of nitrogen in unreachable areas (mountain peaks) rendered these areas unsuitable for ex-situ production of *C. articulata*.

Cation exchange capacity (CEC) is a measure of the ability of soil to retain positively charged nutrient ions called cations (Olofsson, 2016). It is worth noting that soils with very low CEC are more susceptible to losing cations such as magnesium and potassium ions among others through leaching. On the other hand, soils with high CEC are less susceptible to lose these cations through leaching (Crouse, 2018). As shown in Figure 5e cation exchange capacity of the country ranges from 6-58. The country is mainly dominated with soils of low CEC. As indicated in Table 2 *C. articulata* occurred in areas with an average cation exchange capacity of 10.04±2.57 cmolc/kg. This indicates that the plant generally grows in areas with moderately low CEC. The fact that *C. articulata* is mainly restricted to tropical forests in Uganda; yet, tropical forest soil systems have been reported to have low cationic exchange capacity (Aprile and Lorandi, 2012; Tagami et al., 2012) could explain the occurrence of this species in areas with moderately low levels of CEC. Furthermore, the fact that *C. articulata* thrives in somewhat acidic soils, could further explain the occurrence in moderately low CEC since soil pH is positively correlated with soil CEC (Sonon et al., 2014).

Soil organic carbon (SOC) is a major component of soil organic matter (SOM) that plays an important role in plant productivity (Lefèvre et al., 2017). SOC encompasses remains of plants, animals and microbial biomass and their byproducts (Lal, 2016). Nevertheless, high amounts of

SOC have been associated with an increase in plant available water (Clay et al., 2014). Maintaining a healthy level of SOC is essential to overall soil health. Soil organic carbon of the country ranges from 3-150 g/kg with high levels of SOC mainly observed in the Western region of the country and low levels are mainly observed in the Eastern region of the country (Figure 5f). *C. articulata* occurred in areas with SOC between 23.00 and 40.00 g/kg with a mean of 31.88± 3.61 g/kg as indicated in Table 2. Thus, areas in Uganda with SOC within this range of are potentially suitable for *C. articulata* production (Figure 5f).

3.1.3 Topography

Elevation of the country is in the range of 608-5193 m with very high altitudinal areas mainly observed in the Western and Eastern border regions of the country. The Northern region is generally situated at low altitudes (Figure 6a). As stipulated in Table 2, *C. articulata* occurred in areas with an average elevation 1209.31±124.06 m. This implies that *C. articulata* thrives in areas with relatively moderate elevation. Thus, areas in the country with relatively moderate elevation are considered very suitable for agricultural production of *C. articulata* as shown in Figure 6a. Needless to say, elevation is known to have a direct influence on temperature, humidity and distribution of soil nutrients thus affecting plant productivity (He et al., 2016; Jiang et al., 2019; Xu et al., 2017).

As specified in Figure 6b, the country's slope angle ranges from 0-76 degrees with high slope angles suited along mountainous areas of the country. As indicated in Table 2 *C. articulata* occurred in areas with an average slope angle of 4.13±2.39 degrees. This indicates that gentle slope areas favor the occurrence of this plant species. Therefore, areas with gentle slopes are deemed most suitable for agricultural production of *C. articulata* (Figure 6b). Nonetheless very steep areas may not be suitable for production of *C. articulata,* because such areas may result in shallow soils that are very prone to erosion. Slope angle has a significant effect on amounts of soil organic carbon and soil nutrients such as nitrogen by altering the rate of soil accumulation in an area (Kapolka and Dollhopf, 2001; Xue et al., 2018). In this regard experts rated slope as a critical factor in production of *C. articulata* bearing a weight of 0.102 (10.2%) as indicated in Table 4.

3.2 Land suitability

As indicated in Figure 8, only 13.0% (31495.77 km^2) of the country is very suitable to support natural production of *C. articulata,* whereas the largest proportion 45.6% (110075.82 km^2) of the country is moderately suitable and only 13.5% (32503.48 km^2) of the country area is not suitable for production of *C. articulata*. Important to note is that, the Western (27.68%) and Central (22.10%) regions of the country had the largest composition of very suitable land for production of *C. articulata* (Table 5). This may be attributed to the fact that these regions of the country are characterized with moderately acidic soils, high annual rainfall (Figure 3a and 5a) and also endowed with a considerable tropical forest cover (Obua et al., 2010; Plumptre, 2002) which provide a natural habitat for *C articulata*. Thus, these factors collectively provide ideal conditions for production of *C. articulata*. Only 0.24% of the northern region of country is very suitable for production of *C. articulata* (Table 5). This area is mainly observed in the West Nile (Northwestern) sub region in the present Zombo District, an area neighboring the Democratic Republic of Congo (DRC). The fact that Zombo District experiences largely tropical climate due to her location within the eastern topographical rainfall zone (Pierre-Charles, 2016) and additionally having moderately acidic soils (Figure 5a), gentle slopes (Figure 6b) and moderate temperature (Figure 3c) may explain occurrence of very suitable land in this part of the country, because these factors as elucidated above favor productivity of *C. articulata*. On the other hand, the Northern region also had the largest proportion (20.36%) of unsuitable land for production of *C. articulata*. The fact that the Northeastern part of the country is characterized by high temperatures, moderately alkaline soils and a semiarid nature (Echeverría et al., 2016; Osaliya et al., 2019), these may not naturally support productivity of *C. articulata*. Therefore, may require interventions such as soil amendments to suit production of *C. articulata.*

Examining the potential areas for productivity of *C. articulata* indicated that 76.4% (24062.77 km^2) of very suitable land is situated outside protected areas (Figure 8). This result demonstrates presence of potential sites for commercial production, domestication and ex-situ production of *C. articulata*. Given the fact that the current stocks of *C. articulata* are mainly restricted to protected areas of the country (MTWA, 2018), cultivating this species outside protected areas will provide alternatives sources of the plant product harvest. This will aid to relieve current pressures on the wild populations of *C. articulata*. In any case, the increasing depletion of forest resources implies that the natural habitats may not be able to match supply to the growing market for medicinal plant products (Bhattacharjee et al., 2020; Schippmann et al., 2002; Wiersum et al., 2006). Therefore, cultivation of this plant species will be a valuable step taken in meeting its increasing demand.

4. Conclusions

This study has pristinely demonstrated that the application of Multi-criteria evaluation (MCE) in land suitability evaluation is a valuable approach in identifying potential ex-situ production sites for the world's threatened flora. Findings revealed that *C. articulata* has potential of thriving in well drained, moderately acidic soils and pleasantly warm regions endowed with moderately high precipitation and humidity. In this regard, Uganda is characterized with varying levels of land suitability for natural production of *C. articulata* with a small portion being highly suitable for its production and this is predominantly situated in the western region of the country. The fact that an immense proportion of the suitable land is situated outside protected areas presents an opportunity for cultivation of *C. articulata*. However, if cultivation of this species is to be undertaken in marginally suitable and unsuitable areas, then a number of land modifications may be required to achieve appropriate productivity of this species under the current climatic conditions. The findings of this study further provide information valuable to aid decisions and precise ex-situ production efforts of threatened *C. articulata* at both local and regional scale. With the medicinal potential of many plant species yet to be profoundly explored, adopting domestication and commercial cultivation of medicinal plants will help to relieve pressure on wild flora, a phenomenon that has threatened many floral species to the verge of extinction.

Data Availability

Datasets used in this study will be made available by the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no competing interests

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