



Oxytenanthera abyssinica (A. Rich.) Munro land suitability evaluation in the Kurar watershed, Abay Gorge, Upper Blue Nile River Basin, Ethiopia

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ABSTRACT

O. abyssinica, known in Ethiopia as lowland bamboo, is a solid-stemmed clump-forming bamboo species widely distributed in the western dry regions of Ethiopia. The versatility of the species means that it has enormous potential for land restoration in arid and semi-arid areas, in addition to bringing socio-economic benefits. It also displays remarkable adaptability, allowing it to thrive in the challenging ecological conditions of areas such as the Abay Gorge. The Abay Gorge, situated within the Upper Blue Nile River Basin of Northwestern Ethiopia is characterized by problems associated with soil erosion and land degradation. This study, therefore, aimed to evaluate and recommend a suitable spatial analysis for the adoption and development of lowland bamboo (*O. abyssinica*). Fifteen primary influencing factors were chosen according to the needs of *O. abyssinica*, the accessibility of data, and the financial implications associated with data analysis, particularly the expenses related to soil laboratory testing. Eight composite soil samples were taken directly by dividing the watershed into two categories (upper and lower catchment areas). These composite soil samples were analyzed. Data analysis was performed via Analytical Hierarchy Process (AHP) in conjunction with Multi-Criteria Decision-Making (MCDM) analysis and the use of Remote Sensing (RS) and Geographic Information System (GIS). The spatial analysis employed in this study was a weighted sum overlay analysis, which was applied by considering the criteria weight assigned to each factor. The analysis revealed that 21.2 % (666.5 ha) of the total area was highly suitable for the growth and development of *O. abyssinica*. About 56 % (1753 ha) of the land was moderately and marginally suitable for the desired land utilization type. However, 23 % (723.8 ha) of the study area was unsuitable for *O. abyssinica*. *O. abyssinica* has the potential to rehabilitate large parts of challenging areas such as the Abay Gorge due to its naturally invasive rhizomes and drought-tolerance. It can also be introduced into agroforestry systems and used as living fences for villages.

1. Introduction

Bamboo is an important forest species that can promote socio-economic growth (Pérez et al., 1999; QiSheng and Bin, 2001; Terefe et al., 2016) and environmental protection (Bystriakova et al., 2004; Thapliyal et al., 2015). Some species can be grown in agroforestry systems and used as edible plants (Abebe, 2005; Jemal & Callo-Concha,

2017), and bamboo in general can be used for constructing houses, animal fodder, soil fertility improvement (Gebrewahid et al., 2019), and as a medicine for the treatment of many types disease (Yuming et al., 2004). The bamboo forest is also a beneficial source of material for furnishings, pulps, particleboard and bio-energy (Embaye, 2003; Gupta and Kumar, 2008; Pang et al., 2022). *O. abyssinica* is a species within the grass family Poaceae, sub-family Bambusoideae (Tewari et al., 2019). It is

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a clump-forming, solid-stemmed bamboo, that has tremendous ecological and economic roles with its fast-growing and easy establishment (Alemayehu and Hido, 2023).

Globally, there are more than 1500 species of bamboo, widely distributed in the tropical, subtropical, and temperate regions of all the continents except Antarctica and Europe (Lobovikov et al., 2007; Soderstrom and Calderon, 1979). They are amongst the most versatile plants. Bamboos are fast growing and have high productivity, have a short harvesting cycle and most can be harvested annually to meet the increasing demands of the human population (Mosissa and Woldegebriel, 2019; Yang et al., 2021). Bamboos are widely distributed in the Asia Pacific, the American, and the African zones (Lobovikov et al., 2007). Bamboo's highest diversity and areal cover is on the Asian continent, followed by America and Africa (Ohrnberger, 1999).

Africa has 1.4 million hectares of bamboo, much of which is distributed over Eastern Africa (Kibwage et al., 2008). Ethiopia's pure natural bamboo forest is the largest in Africa, with over 1 million hectares, and 85 % of this area is covered by *O. abyssinica*, endemic to tropical Africa, and one of Ethiopia's indigenous bamboos.

Ethiopia has two significant indigenous bamboo resources, one being highland bamboo (*Oldeania alpina*) and lowland bamboo (*Oxytenanthera abyssinica* (A.Rich.) Munro) (Gurmessa et al., 2016). *O. abyssinica* is widely distributed in the western dry regions of the country. Ethiopia has five regions that produce bamboo, namely: Benishangul-Gumuz, Oromia, Amhara, Tigray and Gambella (Mulatu et al., 2019). In the Amhara region, based only on altitude approximately 6.9 million ha, close to 44 % of the land area, are deemed suitable for *O. abyssinica* plantations (Anjulo et al., 2022). However, this does not mean that all these lands are ideal for the species as a number of other constraints may limit its potential. *O. abyssinica* constitutes about 85 % of the areal extent of bamboo in the country and is found only under natural stands (Embaye, 2003). The species grows in lowland areas (elevation, 500 – 1800 m.a.s.l) with poor to very poor soils, even tolerating rocky soils, with high mean annual temperatures (average 20 – 35 °C), and mean annual rainfall of 1150 mm. It can endure erratic mean annual rainfall which in some years can be as little as 600 mm (Lemmens, 2023; Mulatu, 2021; Mulatu et al., 2016). This means that it has incredible ecological potential. It readily adapts to poor soil conditions and, owing to its drought resistance, it is often the preferred species for ecological restoration in arid and semi-arid areas (Paudyal et al., 2022).

The characteristics of *O. abyssinica* means that it has the potential to rehabilitate degraded land in the Abay Gorge (in the Upper Blue Nile River Basin Northwestern parts of Ethiopia), an arid area with severe land degradation (including soil erosion and landslides) (Kigomo, 2007) and deforestation (Dessie and Kleman, 2007; Taye and Wale, 2023; Zewdie and Csaplovics, 2016). Every year, an enormous amount of soil is lost to the nearby Abay River (Blue Nile River). This occurs because of the very steep topography, the fragile land-use systems that are in place, and the erodibility of the soil. According to Elnashar et al., (2021), the mean rate of soil loss in the Upper Blue Nile sub-basins is 57.98 t ha⁻¹ yr⁻¹. Other work has suggested that the annual soil loss in one of the watersheds of the Upper Blue Nile River Basin 0 – 511.2 t ha⁻¹ yr⁻¹ with an average of 28.68 t ha⁻¹ yr⁻¹ (Endalamaw et al., 2021; Wolde-mariam et al., 2023; Yeneneh et al., 2022). Bamboo, plantations could provide a green blanket to protect the land from landslides and control soil erosion, as the rhizomes can help stabilize the soil (Anjulo et al., 2022). Bamboo plantations could also reduce erosion arising from raindrop impact and surface flow by intercepting rainfall (Zhang et al., 2015). The litter associated with bamboo can also protect the soil surface from insolation (Ben-zhi et al., 2005). Research in Hunan, China, has found that bamboo leaf litter has a high water retention capacity, and can hold 2.75 times as much water as the dry weight of the litter (Huang et al., 2012).

Globally, GIS and remote sensing have been used in various land-use suitability assessments, including croplands (AbdelRahman et al., 2016; Batool et al., 2023) and forests (Lechner et al., 2020; Mekonnen et al.,

2016), as well as for groundwater potential identification (Abate et al., 2022), and urban green space (Anteneh et al., 2023). These assessments have used different methods, including multi-criteria analysis (Abate and Anteneh, 2024) and fuzzy AHP (Haile and Abebe, 2022; Kahsay et al., 2018). However, previous research on *O. abyssinica* site suitability have not used such methods or species - site suitability matching (Anjulo et al., 2022), and few studies have used multi-criteria parameters. This study addresses this research gap by using many criteria, including soil properties, topography, climate, and other data such as proximity to water sources and land-use land cover types.

Although there are rare natural occurrences of *O. abyssinica* at the gorge, assessing and identifying the site requirements for the species is important if the species is to be utilized more widely (Kigomo, 2007). In the study area, development organizations have devoted much finance, time and labour without adequately identifying suitable sites for the species. Suitable environmental conditions (such as soil, temperature and rainfall) for the species have not been assessed or evaluated at the study site. The gorge covers millions of hectares of land, and the soil and other environmental conditions vary throughout it. Consequently, this study aimed to evaluate, validate and recommend suitable land for *O. abyssinica*. Identifying the most suitable sites for the species would bring considerable benefits, including increased carbon sequestration (Atsbha et al., 2019).

2. Research methods

2.1. Description of the study area

The Kurar watershed is located in the northwestern of Ethiopia in the Upper Blue Nile River Basin. It has a wide range of elevations and environments, from highlands (Mt. Choke, 4080 m) to lowlands (Abay Gorge, 1000 m). The watershed covers 3144 ha and is mostly cultivated or bare land (no vegetation). It is located between 38°8'1.851"E to 38°11'50.568"E and 10°9'31.768"N to 10°4'37.511" N (Fig. 1).

2.2. Data collection

Primary and secondary data were collected from a variety of sources, including field soil sample collection and land survey, soil laboratory analysis, satellite data websites, and meteorological agencies (Table 1).

2.3. Methods

2.3.1. Soil sample collection and analysis

The study area was classified into two major landscape classes called Land Mapping Units (LMUs) based on topography (elevation) and some pedological features (physical soil properties, soil color) associated with land capability (Smiraglia et al., 2013). Accordingly, two LMUs (namely the upper and lower catchment) were produced. Hence, soil auger soil samples were collected by zig zag method of soil sampling from a depth of 30 cm. A composite soil sample (CSS) method (Wang et al., 2002) was used to minimize the huge cost of laboratory analysis. Hence, one CSS contains 10–12 soil auger samples points. Then, a one-kilogram composite soil sample (CSS) was taken. A total of eight CSSs were collected using a soil auger instrument and submitted to the soil laboratory for analysis. The original soil laboratory result is shown below in Annex II and Table 2.

Subsequently, due to its advancement, successful prediction and description of geostatistical spatial variability performance in digital soil mapping (Dong et al., 2021; Guan et al., 2017; Martin Bell et al., 2016) isopleth development, and evaluation of the spatial distribution of soil and waste properties, the soil laboratory results were analyzed with kriging interpolation method, which estimates the unsampled locations in the spatial field (Eq. 1). Thus, the nature of the kriging equations has important inferences for the design and implementation of soil surveys (Burgess and Webster, 1980). Its prime purpose for utilization is within

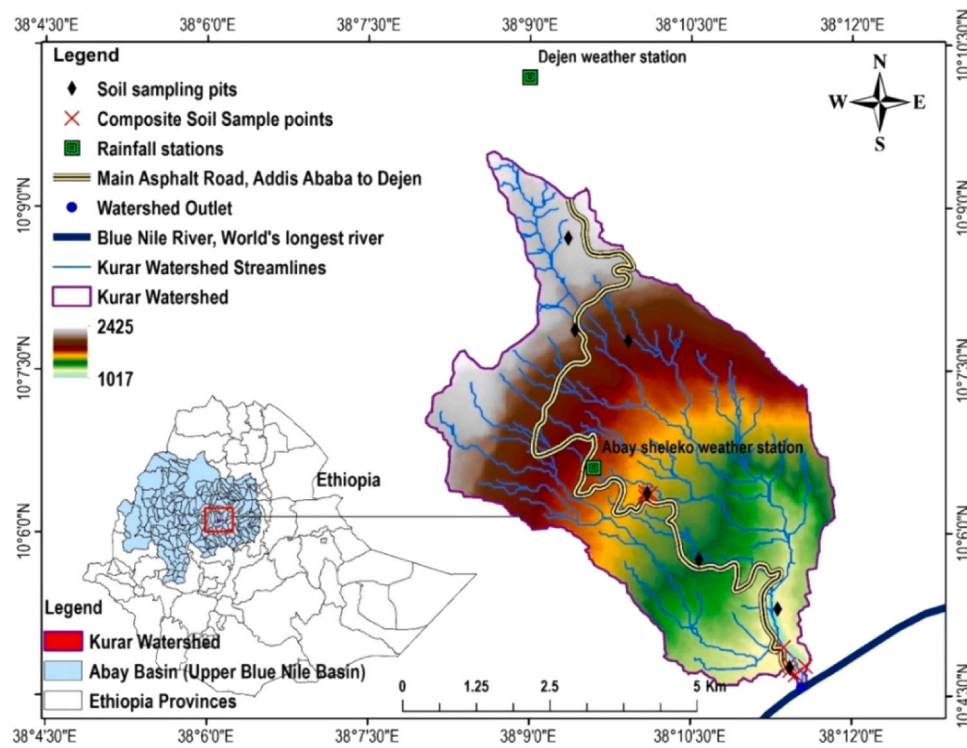


Fig. 1. Location of the study area.

Table 1
Data type, source, and description.

Data type	Data Source	Year	Description	Utilization
Digital Elevation Model (DEM)	ALOS PALSAR DEM data https://search.asf.alaska.edu/#/	2000–02–11–2000–02–22	Digital Elevation Model with 12.5*12.5 m spatial resolution. The finer the spatial resolution, the more detailed the information that is extracted	Slope & elevation
Landsat 8 image	https://usgsEarthExplorer/	023/01/01–2023/04/30	A geographically explicit feature that can be used in different land features (has 30 m spatial resolution). Four consecutive dry months of data was collected.	Preparing NDVI temperature and land use land cover map
Water source data	River data and stream density (generated from the DEM)	2015 and 2000	Rivers and seasonal streams	Proximity to a water source
Rainfall data	Ethiopian Meteorological Agency (Bahir Dar branch, Dejen & Abay Sheleko meteorological stations)	1981–2022	Two rainfall stations (Dejen and Abay Sheleko) of annual rainfall data	Rainfall thematic map
Soil data	Direct field soil sample collected from Kurar watershed and soil laboratory analysis result	2023	Soil physical, chemical properties & soil depth	Soil properties map
Temperature	Landsat 8 image (Thermal Bands)	2022	The minimum and maximum amount of temperature (representative months from four seasons namely: summer (July), autumn (October), spring (April), and winter (January)) with spatial resolution of 30 m.	Land surface temperature map

Table 2
Laboratory soil test analysis results of soil physical and chemical properties.

CSS No.	Soil pH (H ₂ O)	Soil texture				CECmol+ /Kg	OC	TN	FC	Av. Pppm
		% Sand	% Silt	% Clay	Classes					
CSS–01	6.25	72	16	12	Sandy Loam	12.8	2.2	0.15	39.2838.0739.7637.3739.4940.1236.8940.3	15.05
CSS–02	6.66	76	12	12	Sandy Loam	13.6	1.22	0.11		2.14
CSS–03	6.74	76	10	14	Sandy Loam	11.8	0.55	0.06		2.4
CSS–04	7.09	72	14	14	Sandy Loam	12.6	0.64	0.07		11.3
CSS–05	7.19	74	14	12	Sandy Loam	10.6	0.66	0.07		11.03
CSS–06	7.2	20	22	58	Clay	43.2	3.08	0.28		7.74
CSS–07	7.13	32	28	40	Clay	42.8	1.85	0.17		7.35
CSS–08	7.12	28	20	52	Clay	45.8	1.53	0.14		4.64

Note: CSS-composite soil sample, CEC-cation exchange capacity, OC- organic carbon, TN- total nitrogen, FC- field capacity, PWP- permanent wilting point, Av. P- available phosphorous

the system of samples. It should not be used to extrapolate outside of the boundaries of the sampling area (Barth and Mason, 1984).

$$Z(\text{So}) = \sum_{i=1}^N \lambda_k Z(\text{Sk}) \quad (1)$$

Where:

$Z(\text{Sk})$ = the measured value at the k^{th} location

λ_k = an unknown weight for the measured value at the k^{th} location

So = the predicted location

N = the number of measured values

Multi-criteria decision analysis integrated with the Analytical Hierarchy Process (AHP) was applied to determine ideal locations for *O. abyssinica*. Fifteen lowland bamboo determinant factors/ land use requirements were identified, including slope, elevation, proximity to a water source, rainfall, temperature, land-use type, soil depth, soil organic carbon, soil texture, soil pH, cation exchange capacity, total nitrogen and available phosphorus, field capacity and vegetation cover (Normalized Difference Vegetation Index, NDVI). The weighted sum overlay analysis method within the ArcGIS environment was used to analyze the data. The slope and elevation of the study area were calculated and analyzed from DEM data obtained from ALOS PALSAR (<https://search.asf.alaska.edu/>). Proximity to water sources was computed using the Euclidian distance spatial analysis tool.

2.3.2. Land-use - land-cover analysis/accuracy assessment

The thematic map depicting land use and land cover was created through the utilization of a suitable algorithm to classify the satellite image, followed by validation using Ground Control Points (GCPs). An approach based on maximum likelihood supervised classification was chosen and implemented to perform the analysis of the land use and land cover within the designated study area. The accuracy assessment of the study was conducted with Ground Control Points (GCP) collected by the Global Positioning System (GPS) instrument and data points taken from Google Earth Pro. 309 GCPs were collected (162 by GPS data collection instrument and 147 from Google Earth Pro). As a result, the study's land use/land cover map was validated by the overall accuracy (Eq. 2) and the kappa coefficient (Eq. 3). According to Congalton (2001), the overall accuracy assessment (OvAa) and kappa coefficient (K_{hat}) are calculated as follows, respectively.

$$\text{OvAa} = \Sigma D_{cc} / \text{TNS} * 100 \quad (2)$$

Where; OvAa is the overall Accuracy assessment, ΣD_{cc} , is the sum of correctly classified diagonals, and TNS is the total number of samples (GCPs).

$$K_{\text{hat}} = \frac{\text{To} \sum_{i=1}^{Nr} Y_{ii} - \sum_{i=1}^{Nr} (Y_{i+} * Y_{+i})}{(\text{To})^2 - \sum_{i=1}^{Nr} (Y_{i+} * Y_{+i})} \quad (3)$$

where; To is the total number of observations, Nr is the number of rows in the matrix, Y_{ii} is the number of observations in row i , and column i , and Y_{i+} and Y_{+i} are the marginal totals of row i and column i , respectively.

2.3.3. Rainfall and temperature

Annual rainfall data were obtained from the Ethiopian Meteorological Agency (EMA), Bahir Dar Branch. The inverse distance weight (IDW) method of interpolation was applied to two rainfall stations of Abay Sheleko (a station within the watershed) and Dejen (a nearby station) to determine the rainfall spatial variability (distribution) of the watershed. Land surface temperature (LST) was used as a substitute for air temperature (Kamal et al., 2022). Therefore, an average yearly LST of four seasons (four representative months) namely; summer (July), autumn (October), spring (April), and winter (January) were collected to compute the mean LST using Landsat 8 (2022) satellite data. Top of the atmosphere (TOA) radiance was calculated using the radiance

rescaling factor, thermal infrared digital numbers that are converted into TOA spectral radiance (Rajeshwari and Mani, 2014), using the following relationship:

$$L\lambda = \text{ML} * Q_{\text{cal}} + \text{AL} \quad (4)$$

where $L\lambda$ is TOA spectral radiance (watts m^{-1})

ML is radiance multiplicative band (Band no.)

ALis - radiance add band (Band no.)

Q_{cal} is quantified and calibrated standard product pixel values (DN)

According to Latif (2014), TOA brightness temperature can be calculated from spectral radiance image data, and can be converted to top-of-atmosphere brightness temperature by using the thermal constant values from the metadata file of Landsat 8 data (Eq. 5):

$$Bt = K2 / \ln \left(\frac{K1}{L\lambda} + 1 \right) - 273.15 \quad (5)$$

where Bt is top of atmosphere's brightness temperature ($^{\circ}\text{C}$)

$L\lambda$ is TOA spectral radiance (watts m^{-1})

K1 is a constant band from the metadata (no.)

K2 is a constant band from metadata (no.)

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

Land surface emissivity (PV), an average emissivity value of an element of the surface of the earth, was calculated from the NDVI (Eq. 6):

$$PV = [(NDVI - NDVI_{\text{min}}) / (NDVI_{\text{max}} + NDVI_{\text{min}})]^2 \quad (6)$$

where PV is the proportion of vegetation

NDVI are the DN values from NDVI image

NDVI min is the minimum DN values derived from NDVI image

NDVI max is the maximum DN values derived from NDVI image

$$E = 0.004 * PV + 0.986 \quad (7)$$

where E is LSE

PV is the proportion of vegetation

Finally, the land surface temperature (LST) of the earth was calculated as (Eq. 8) the radiative temperature using top of atmosphere brightness temperature, the wavelength of emitted radiance, and E (LSE) (Eq. 7) (Dash et al., 2002), as follows.

$$LST = \left[\left(\frac{BT}{1} \right) + W * \left(\frac{BT}{14380} \right) * \ln(E) \right] \quad (8)$$

where BT is the top of atmosphere brightness temperature ($^{\circ}\text{C}$)

W is the wavelength of the emitted radiance (Landsat 8 thermal band)

E is the Land surface emissivity

2.3.4. Multi-Criteria Decision-Making (MCDM)

The weights of all the contributing criteria in the map layers differed. Accordingly, a method involving the integration of the Multi-Criteria Decision Method (MCDM) (Malczewski, 1999) and with the Analytical Hierarchy Process (AHP) (Saaty, 1980) was applied. AHP helps in the capturing of objective evaluation metrics and ensures a valuable procedure for confirming whether the evaluations are consistent or not, hence minimizing decision-making bias (Ishizaka and Lusti, 2003). To determine the weight of the decision criteria, AHP used a pairwise comparison matrix, which involved three steps: (1) design and development of a pairwise comparison matrix at each level of the hierarchy, beginning at the top, (2) computation of weights for each element in the hierarchy, and (3) valuation of consistency ratio (C.R) (see Annex III). Lastly, a weighted sum analysis was applied to obtain a suitable site assessment of *O. abyssinica*.

The consistency ratio can be used to assess the inconsistency of judgments in criterion weighting through pairwise comparison (C.R). C.

R. is a metric that determines how far a matrix deviates from consistency, with a C.R. value of 10 % (0.1) or less deemed acceptable (Saaty, 1980).

The Consistency Index (C.I.) can be calculated in Eq. 9 as:

$$C.I = \frac{\lambda_{\max} - n}{n - 1} \quad (9)$$

The C.R. for each matrix in the hierarchy is computed by the following formula:

$$C.R = \frac{C.I}{R.I} * 100 \quad (10)$$

where n is the number of input factors used, R.I is the Random Index, $\lambda_{\max}$ is the biggest eigenvalue and C.R is the consistency ratio.

The Random Index is the average consistency index of a randomly generated comparison matrix. As shown in Annex IV, Saaty's ratio index is not functional for n less than two factors. For example, as the number of input factors is fifteen, the R.I value is 1.58.

Finally, all thematic map layers were analyzed using the weighted sum overlay analysis tool in ArcGIS 10.8.2 environment based on their weight to provide a suitable site identification for *O. abyssinica* (Eq. 11).

$$OtAsi = \sum_{i=1}^{15} CW_i * PX_i \quad (11)$$

where; *OtAsi*, *O. abyssinica* suitable site identification, CW_i , Weight of criteria (factor weight), PX_i , Assigned reclassified pixel value, and n, number of contributing factors.

2.3.5. Conceptual design

The overall conceptual design/flowchart/ for *O. abyssinica* land suitability assessment is indicated in Fig. 2 below.

3. Results and discussion

3.1. Elevation and slope of the land

O. abyssinica is best suited to grow at elevations below 1800 m a.s.l. The elevation in the Kurar watershed is from 1017 m to 2425 m (Fig. 3a). The elevation or altitude of a given location can influence a variety of climatic variables such as temperature and rainfall, which in turn influence the adaptability and growth of *O. abyssinica* (Chang et al., 2016; Lin et al., 2015; Qing et al., 2014). Slope determines the soil depth and soil structural condition (soil deposition or sedimentation) and the susceptibility to soil erosion (Hopp and McDonnell, 2009). The slope of Kurar watershed ranged from 0 to 65° (Fig. 3b). The slope also has a strong influence on the productivity of bamboo forests (Cheng et al., 2015; Fang et al., 2018).

3.2. Climatic factors (Temperature and rainfall)

Temperature and rainfall are among the major elements of the climate. The rainfall and temperature regimes at a given location can determine the types of vegetation that can grow in an area (Condit et al., 2004; Leigh, 1975; Osland et al., 2017). The Kurar watershed receives an annual minimum rainfall of 1087 mm (Abay sheleko weather station, inside the watershed) and maximum rainfall of 1428 mm (recorded by the nearby highland area, Dejen meteorological station) (Fig. 1 and

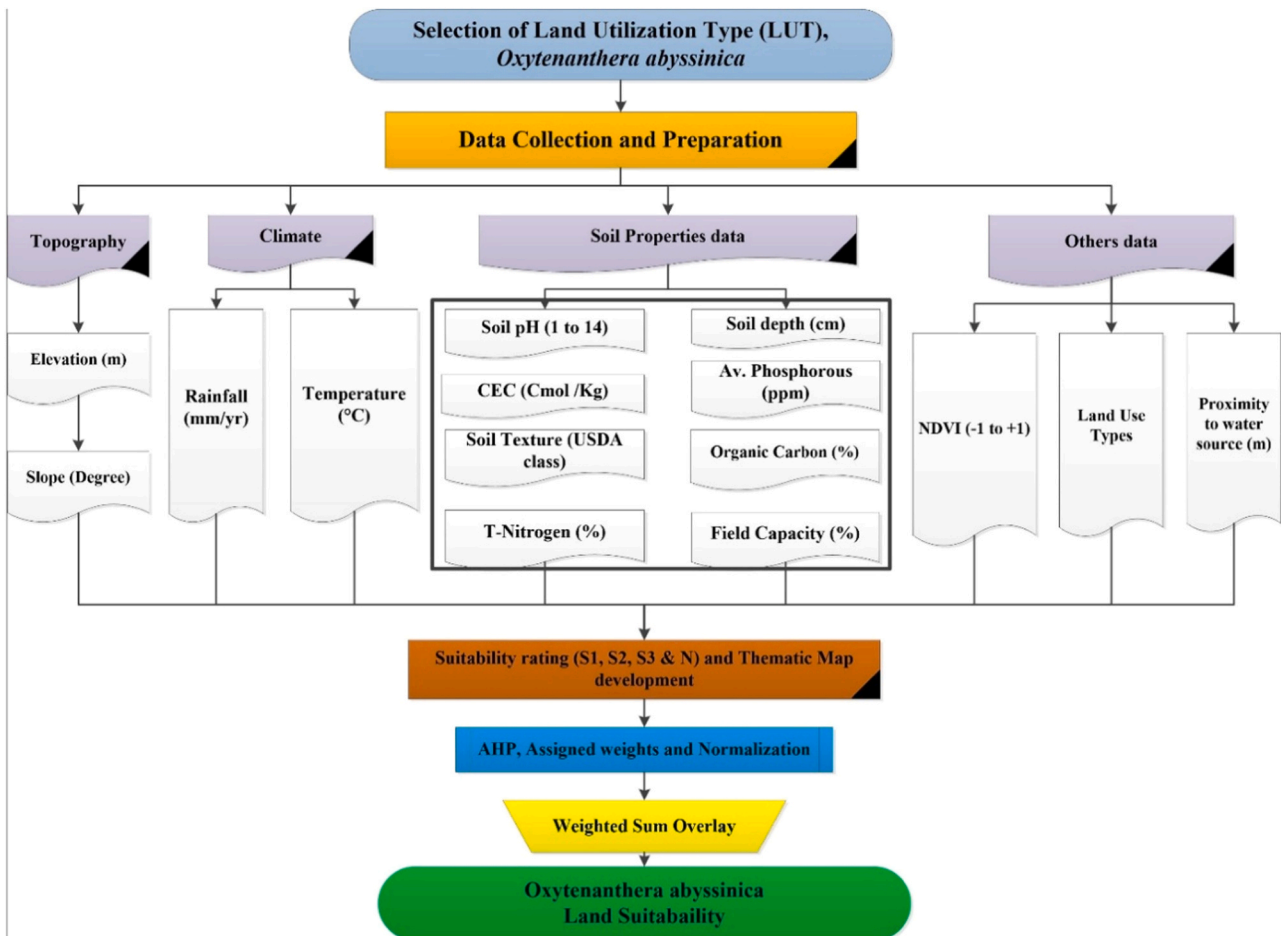


Fig. 2. Flow chart of the study.

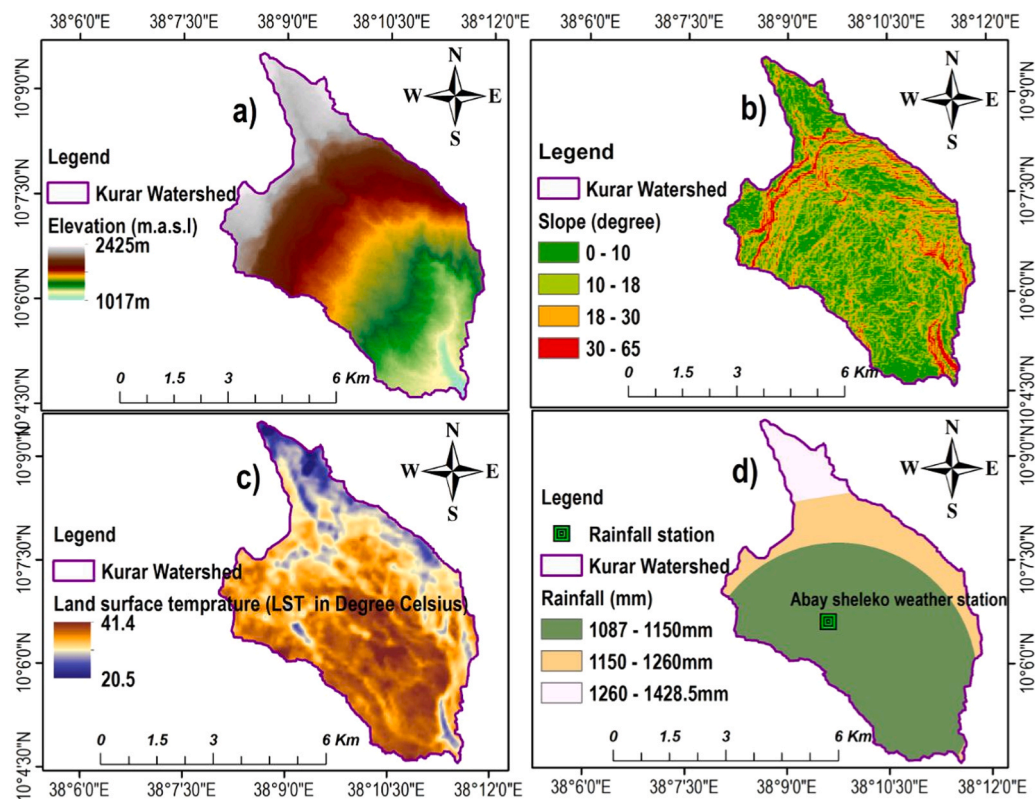


Fig. 3. (a) elevation (b) slope (c) land surface temperature (LST), and (d) rainfall of the Kurar watershed.

Fig. 3d). *O. abyssinica* can grow in areas receiving less than 1000 mm rainfall, but good production of lowland bamboo obtained when it exceeds 1000 mm (Kigomo, 2007). It is well-adapted to the temperatures experienced in the Kurar watershed (minimum temperature of 20°C and maximum temperature 41°C (Fig. 3c)) (Battisti et al., 2019; Worku et al., 2023).

3.3. Soil physical and chemical properties

The growth and development of lowland bamboo is significantly influenced by soil physical and chemical properties. Bamboo plantations affect soil properties differently based on species, with variations observed in water-holding capacity, pH, electrical conductivity, bulk density and organic carbon (Gogoi, 2019). Depending on the species used, soil fertility under bamboo agroforestry systems can be maintained, with no significant depletion observed in nutrients like organic carbon and total nitrogen (Kleinhenz and Midmore, 2001). Additionally, mulch treatments using bamboo leaves and organic fertilizers enhance soil nutrient availability, biochemical traits, and ultimately promote bamboo shoot productivity, highlighting the importance of organic materials in improving soil quality for optimal bamboo growth (Fan et al., 2021).

In this investigation, different soil physical properties such as the soil depth, soil texture, and field capacity were tested. Soil physical properties such as soil depth have great influence on the development of lowland bamboo rhizomes (Kigomo, 2007). The soil textural class has also an impact on the root penetration of ratoon crops. For instance, *O. abyssinica* grows much better in loams than in clay soils. However, the nutrient content of a clay soil is much better than a sandy loam (Blanco-Canqui and Wortmann, 2020). Plants require similar essential plant macro-nutrients for their growth and development (Ericsson, 1994; Vallicrosa Pou et al., 2021). Species such as *O. abyssinica* also need fertile soil because of their fast growth rates and high productivity (Gebrewahid et al., 2019). In this study, soil chemical properties such as

soil pH, cation exchange capacity, organic carbon, total nitrogen, and available phosphorus were analyzed in the laboratory, and results are shown in Table 2 below. (Figs. 4 and 5)

3.4. Land-use type, NDVI, and proximity to water source

The land-use/ land-cover map of the Kurar watershed was developed with an overall accuracy of 90 % and a Kappa coefficient (K_{ha}) of 0.88 (See Annex I). As the Abay Gorge area is semi-arid (Ayele et al., 2022), each land-use/ land-cover type has its own importance in protecting the evaporation rate (Kayitesi et al., 2022), and preventing soil drying (Lozano-Parra et al., 2018). As indicated in Fig. 6(m), seven land-use types were identified, namely construction and sandy beaches near the rivers (which had similar satellite image reflectance values and were therefore classified as one category), barelands, farmland (cultivated land), grasslands, forest lands, shrublands and sparse forest.

The NDVI values in the study area ranged from +0.999 to −0.348 (Fig. 6n). NDVI values can be used as an indicator of the best ecological environment for forest management in a specific area (Meneses-Tovar, 2011; Právalie et al., 2022). Higher NDVI zones are favoured for the cultivation of lowland bamboo due to improved vegetation health, superior soil conditions, sufficient water resources, stable microclimates and reduced erosion susceptibility, all of which play a critical role in facilitating optimal bamboo growth and environmental sustainability (Guo et al., 2023) (Liu et al., 2023; Mesquita et al., 2023). Such areas offer nutrient-rich soils, consistent moisture content, and a balanced ecosystem that can help prevent pest infestations and diseases, thereby fostering vigorous bamboo development, increased yield, and positive contributions to climate change mitigation endeavours. Consequently, higher NDVI zones can ensure favourable growth conditions for bamboo plantations while also benefiting the surrounding environment (Georgiou and Akçit, 2017).

Proximity to a water source plays a crucial role in shaping the growth of lowland bamboo forests (Ford et al., 2011). The proximity to a water

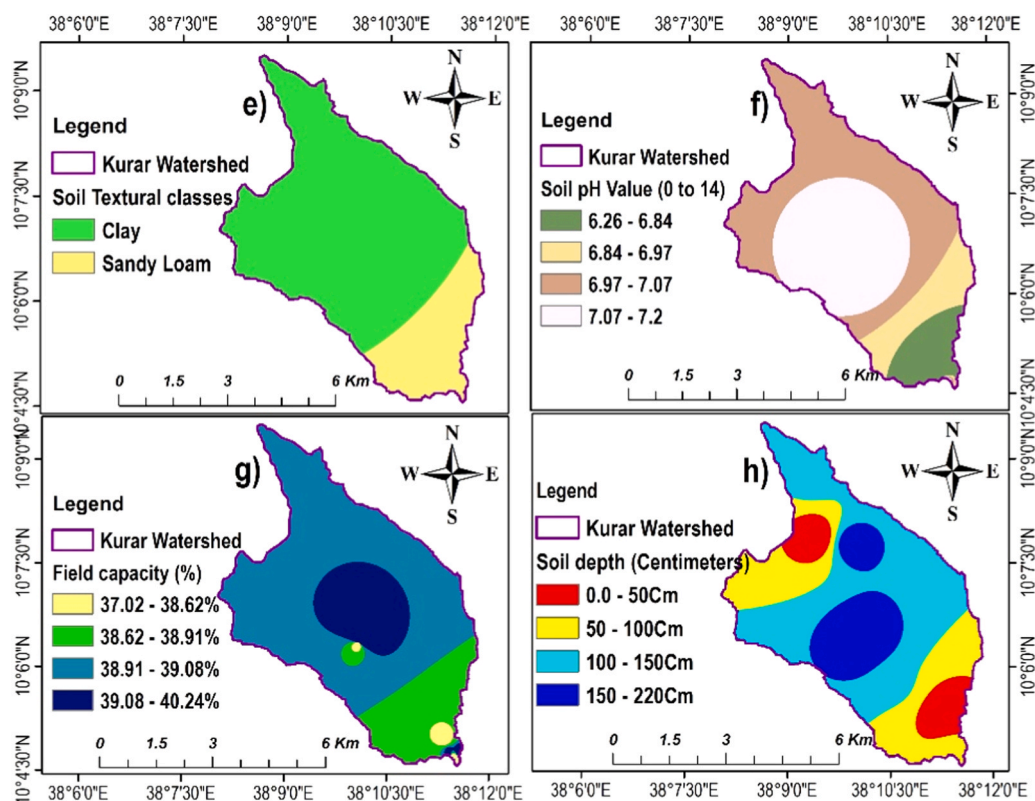


Fig. 4. (e) soil textural class (f) soil pH range (g) soil field capacity and (h) soil depth of the Kurar watershed.

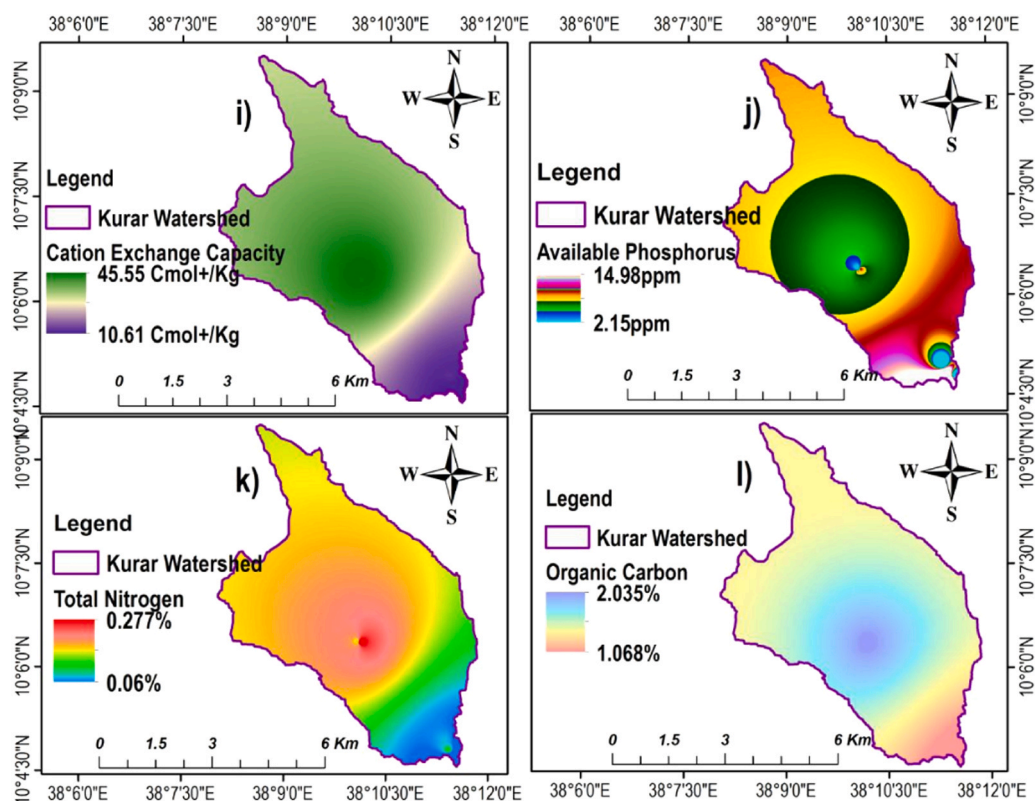


Fig. 5. (i) cation exchange capacity (j) available phosphorus (k) total nitrogen and (l) organic carbon of the Kurar watershed.

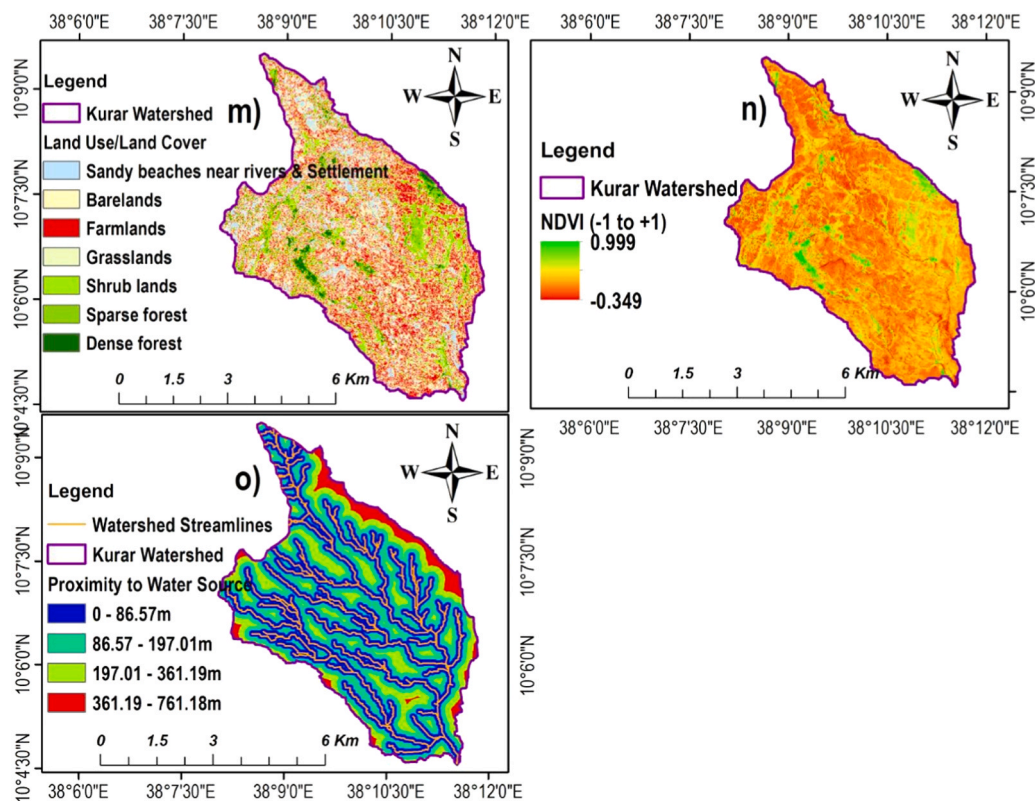


Fig. 6. (m) land use/land cover (n) NDVI (o) proximity to water sources/ streams of the Kurar watershed.

source in the Kurar watershed ranged from 0 m to 761 m (Fig. 6o). Studies conducted on *Bambusa rigida* Keng & Keng.f. in Peru and Brazil underscore the significance of water availability for the sustainability of bamboo ecosystems (Chen et al., 2020; Fitmawati et al., 2023; Louton et al., 1996).

The soil textural classes in the study area include clay and sandy clay loam types. The soil pH ranged from 6.25 to 7.19 and CEC ranged from 10.6 to 45.8 $\text{Cmol}^+ \text{Kg}^{-1}$. The organic carbon content, total nitrogen, and field capacity of the soil in the Kurar watershed ranged from 0.55 to 3.08, 0.06–0.28, and 36.89–40.3, respectively. The available phosphorous content of the study area was from 2.14 ppm to 15.1 ppm (Table 2).

3.5. Reclassification of land utilization types

In this study, 15 main land utilization criteria were identified and reclassified based on literature review and expert opinions (Table 3). Each factor or criterion had its unit of measurement. For instance, slope was measured in degrees, temperature in degrees celsius, and elevation in metres above sea level. The selected main criterion also had its prioritization scores (as 1, 2, 3, and 4) and suitability ratings, based on highly suitable, moderately suitable, marginally suitable, and not suitable.

3.6. Criteria and sub-criteria for suitability analysis

The fifteen selected land-use requirements or input factors/criteria for the *O. abyssinica* pairwise comparison matrix are shown in Table 4. Elevation, proximity to water source/ streams, rainfall, soil pH and organic carbon rank from one to fifth, respectively, and are the top five influencing factors for the potential growth and development of *O. abyssinica*. The computed criteria weight (CW) of all factors for *O. abyssinica*, ranged from 0.03 (3 %) to 0.143 (14.3 %). The calculated λ_{max} (the average biggest eigenvalue) and the Consistency Index (CI) value were 15.695 and 0.0496, respectively. The input contributing factor (F) for the suitability for *O. abyssinica* was 15 and its Random

Index (RI) value was 1.58 (Annex IV). This led to a calculated Consistency Ratio (C.R) value of 0.0314, which is less than 0.1, and deemed acceptable (Thakkar, 2021).

3.7. Land suitability of *O. abyssinica*

Highly suitable land accounts for 21.2 % (667 ha of land see Table 5) and is characterized by better soil physical and chemical properties, gentle slope, deeper soil depth, good soil textural classes (such as sandy loam and clay) are highly suitable for *O. abyssinica* (Fig. 7). Most downslope (gentle slope) lands associated with the nearest water source and good soil fertility in the centre of Kurar watershed are highly suitable for the growth of lowland bamboo.

About 28 % of the study area was found to be moderately suitable for the growth and development of lowland bamboo. However, most of the margins of the study area are high-elevation areas and unsuitable for *O. abyssinica*. Unsuitable lands included those with shallower soil depths, high elevation (>1800 m.a.s.l), farthest from seasonal and permanent water sources (streams), bareland, very steep slopes and sandy beaches. These were all either marginally suitable or unsuitable for the development of *O. abyssinica*. Even if land had some positive qualities, it did not guarantee a classification of being highly suitable. Most highly suitable lands in the study area were cultivated lands and were characterized by high soil fertility capacity, deeper soils, flat to gentle slopes, and located near settlements. This suggests the possibility of introducing *O. abyssinica* as a system of agroforestry and fences near villages.

Suitable land for lowland bamboo growth and development should ideally have characteristics such as sandy clay loam or shallow lateritic soil mixed with fine sandy clay, as indicated in a study on Malaysian bamboo species (Boissière et al., 2020). Additionally, degraded and marginal landscapes like Abay Gorge could be restored effectively by planting bamboo (Othman, 2001). In India, bamboo has been identified as a potential species for ravine lands due to its extensive fibrous root system, dense foliage, and high stemflow, making it well-suited for

Table 3

Main criteria and sub-criteria with their respective standardization scores and factors suitability rating.

Main Criteria	Units of measurement	Reclassification values	Prioritization	Suitability rating
Slope	Degree	1 – 10	1	High
		10 – 18	2	Moderate
		18 – 30	3	Marginal
		30 – 65	4	Not suitable
Elevation	metres above sea level	1017 – 1500	1	High
		1500 – 1800	2	Moderate
		1800 – 2000	3	Marginal
		2000 – 2425	4	Not suitable
Temperature	Degrees Celsius (°C)	37 – 41.36	1	High
		35 – 37	2	Moderate
		32 – 35	3	Marginal
		20 – 32	4	Not suitable
NDVI	Values of –1 to +1	–0.35–0.17	4	Not suitable
		0.17–0.27	3	Marginal
		0.27–0.41	2	Moderate
		0.41 – 1	1	High
Rainfall	mm yr ⁻¹	1260–1428.5	1	High
		1150–1260	2	Moderate
		1087–1150	3	Marginal
		0–86.57	1	High
Proximity to water/streams	Metres	86.57–197.01	2	Moderate
		197.01–361.19	3	Marginal
		361.19–761.18	4	Not suitable
		Dense forest, sparse forest	1	High
Land-use type	Land-use type	Shrubland, grassland, farmland	2	Moderate
		Sandy beaches near to river	3	Marginal
		Barelands	4	Not suitable
		>200	1	High
Soil depth	Centimetres	100 – 200	2	Moderate
		50 – 100	3	Marginal
		0 – 50	4	Not suitable
		6.26–6.84	1	High
Soil pH (H ₂ O)	pH value 1–14	6.84–6.97	2	Moderate
		6.97–7.07	3	Marginal
		7.07–7.2	4	Not suitable
		clay	3	Marginal
Soil texture	Textural class	Sandy loam	2	Moderate
		37.37–45.55	1	High
		30.23–37.37	2	Moderate
		20.93–30.23	3	Marginal
Cation Exchange Capacity	Cmol ⁺ Kg ⁻¹	10.61–20.93	4	Not suitable
		1.78–2.03	1	High
		1.63–1.78	2	Moderate
		1.45–1.63	3	Marginal
Organic Carbon	Percent	1.07–1.45	4	Not suitable
		0.17–0.28	1	High
		0.15–0.17	2	Moderate
		0.12–0.15	3	Marginal
Total Nitrogen	Percent	0.06–0.12	4	Not suitable
		9.04–14.98	1	High
		7.23–9.04	2	Moderate
		5.67–7.23	3	Marginal
Av. Phosphorus	ppm	2.15–5.67	4	Not suitable
		39.08–40.24	1	High
		38.91–39.08	2	Moderate
		38.62–38.91	3	Marginal
Field capacity	Percent (%)	37.02–38.62	4	Not suitable

Source: Adapted from (Anjulo et al., 2022; Bahru et al., 2015; Darcha et al., 2015; Mulatu et al., 2019).

hydrological interventions in degraded gully lands (Nfornkah et al., 2023). An economic evaluation of bamboo plantations in ravine systems has highlighted the financial benefits and sustainability of bamboo-based interventions in such areas (Krishna Rao et al., 2018).

4. Conclusions

Land suitability analysis is a key factor for the success and failure of all plantations. It has the potential to reduce development failures in marginal areas such as the Kurar watershed, where there are high temperatures and accessibility problems. *O. abyssinica* has the potential to rehabilitate such semi-arid areas in Ethiopia due to its naturally invasive rhizomes and drought tolerance. The application of remote

sensing and GIS technologies can help the assessment of land suitability for lowland bamboo plantations. Use of such technology can reduce time and save costs, thereby helping to reduce the frequency with which plantation projects fail.

Ethics approval

The authors respected all the ethics of the journal for publication

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Table 4
Pairwise comparison matrix of input contributing factors for *O. abyssinica*.

	Sl	Elev	Temp	Rf	NDVI	S_depth	LULC	P _{rox} .WaS	S_pH	S_tex	CEC	TN	OC	Av. P	FC	WSv	CW
Sl	1	0.25	1.25	0.5	1.25	1.5	1.5	1	0.5	0.75	0.5	0.5	0.5	0.5	0.25	0.690	0.044
Elev		1	3	1.5	5	2.5	3	1.5	2	3	2	2	2	2	5	2.250	0.143
Temp			1	0.5	2	0.75	2.5	0.5	1.5	0.5	0.75	1.5	0.5	0.5	3	0.920	0.058
Rf				1	3	1.5	3	0.75	1.5	1.5	1.5	0.75	0.75	0.75	2	1.275	0.081
NDVI					1	0.5	1	0.25	0.5	0.75	0.5	0.5	0.75	0.5	1.25	0.529	0.034
S_depth						1	2	0.75	0.75	1	0.5	0.5	0.5	0.75	2	0.830	0.053
LULC							1	0.25	0.5	0.5	0.5	0.4	0.5	0.75	1	0.505	0.032
P _{rox} .WaS								1	1.25	2	1.25	1.25	1.25	1.5	3	1.497	0.096
S_pH									1	1.5	1.5	1.5	1.5	1.5	2	1.203	0.077
S_tex										1	0.5	0.5	0.5	0.5	1	0.776	0.049
CEC											1	1	1	1	1.5	1.109	0.071
TN												1	1	1	1.5	1.140	0.073
OC													1	1	1.5	1.180	0.075
Av. P														1	1.5	1.133	0.072
FC															1	0.662	0.042
Sum of CW value																	1.000

Note: Sl- slope, Elev-elevation, Rf- rainfall, NDVI- normalized difference vegetation index, S_depth-soil depth, LULC- land use land cover, P_{rox}.WaS- proximity to water source/ streams, S_pH- soil pH, S_tex- soil texture, CEC- cation exchange capacity, TN- total nitrogen, OC- organic carbon, Av.P-available Phosphorous, FC- field capacity, WSv- weighted sum value, CW- criteria weight.

Table 5
Land-suitability classes for *O. abyssinica* in the Kurar watershed, Upper Blue Nile River.

	Highly suitable (ha)	Moderately suitable (ha)	Marginally suitable (ha)	Not suitable (ha)	Total
Area (ha)	667	887	866	724	3144
Area (%)	21.2	28.2	27.6	23.0	100

Authors contribution

All authors contribute to the success of the manuscript

Consent for publication

We, the authors request the Journal of Advances in Bamboo Science to permit us to go through the requirements for publication.

CRedit authorship contribution statement

Birhanie Alemayehu Ambaye: Formal analysis. **Simeneh Gedefaw Abate:** Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal

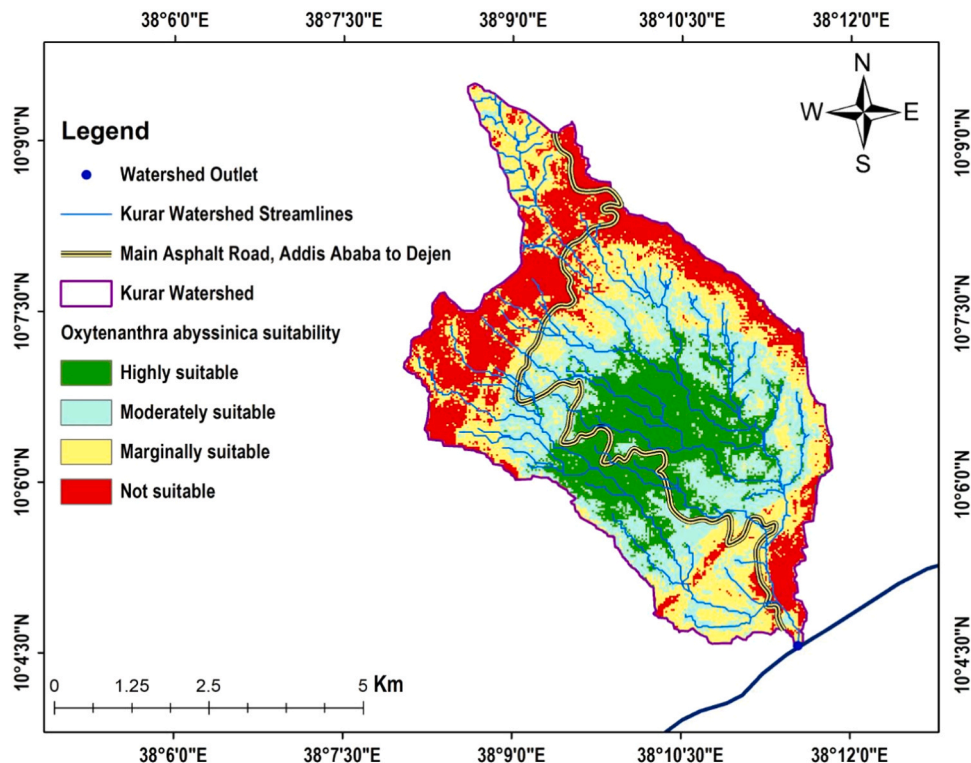


Fig. 7. *O. abyssinica* suitability map of the Kurar watershed, Upper Blue Nile basin.

analysis, Data curation, Conceptualization. **Tsedenya Adinew Bekele:** Project administration, Funding acquisition. **Mebrate Belachew Tir-
uneh:** Writing – review & editing, Funding acquisition. **Demisachew
Shitaw Cherie:** Project administration. **Alemayehu Kefalew Shembo:**
Validation, Resources, Methodology, Investigation, Formal analysis,
Data curation. **Abreham Mulu Belay:** Supervision.

Declaration of Competing Interest

There is no conflict of interest of the research paper.

Data Availability

Data will be made available on request.

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Annex I. : Error matrix of land use land cover classification map of Kurar watershed

Error matrix										
	FoL	SpVeg.	ShL	GrL	FrmL	BrL	Cons	GCPs	UA	EC
FoL	37	1	2	1	0	2	0	43	86.05	13.95
SpVeg.	1	38	0	0	1	0	0	40	95	5
ShL	1	1	48	1	0	1	0	52	92.31	7.69
GrL	0	2	4	22	0	0	0	28	78.57	21.43
FrmL	1	0	0	0	59	2	2	64	92.19	7.81
BrL	0	0	0	2	3	39	0	44	88.64	11.36
Cons	1	1	0	0	1	0	35	38	92.11	7.89
Total	41	43	54	26	64	44	37	278		
PA	90.24	88.37	88.89	84.62	92.19	88.64	94.59			
EO	9.76	11.63	11.11	15.38	7.81	11.36	5.41			
Overall accuracy	88.97									
Kappa Coefficient	0.88									

Note: FoL - Forest land, SpVeg - Sparse Vegetation, ShL - Shrub land, GrL - Grass land, FrmL - Farm land, BrL - Bare land, Cons - Construction, UA - User Accuracy, PA - Producer Accuracy, EC - Error of Commission, EO - Error of Omission.

Annex 2. : Soil laboratory test results



ΔΥΠΤΕΡ ΓΕΩΤΕΧΝΙΚΗ ΕΠΙΧΕΙΡΗΣΗ
ΑΡΧΙΤΕΚΤΟΝΙΚΗ
ΓΕΩΛΟΓΙΚΟ ΕΡΕΥΝΗΤΙΚΟ ΚΑΙ ΤΕΧΝΙΚΟ ΛΕΓΟΜΕΝΟ

Lihiket Design & Supervision Corporation
Laboratory Service
Soil Chemistry & Water Quality Section

Soil Analysis of Laboratory Report
Client : Abreham Mulu (DMU)

Sr. No.	Lab. No.	Client Code	pH (H ₂ O)	EC dS/m	%Sand	%Silt	%Clay	Classess	Ex.Ca	Ex.Mg	Ex.Na	Ex.K	CEC	OC	TN	FC	PWP	Av.P
									Cmol (+)/Kg				%					
									ppm									
1	0547/23	CSS-01	6.25	0.17	72	16	12	Sandy Loam	11.72	0.54	0.05	5.89	12.80	2.20	0.15	39.28	28.71	15.05
2	0548/23	CSS-02	6.66	0.08	76	12	12	Sandy Loam	12.47	0.37	0.19	2.89	13.60	1.22	0.11	38.07	23.32	2.14
3	0549/23	CSS-03	6.74	0.11	76	10	14	Sandy Loam	12.49	0.38	0.22	2.63	11.80	0.55	0.06	39.76	29.32	2.40
4	0550/23	CSS-04	7.09	0.16	72	14	14	Sandy Loam	12.50	0.82	0.10	4.22	12.60	0.64	0.07	37.37	26.19	11.30
5	0551/23	CSS-05	7.19	0.18	74	14	12	Sandy Loam	17.67	1.03	0.07	3.28	10.60	0.66	0.07	39.49	29.89	11.03
6	0552/23	CSS-06	7.20	0.19	20	22	58	Clay	30.34	1.70	0.22	4.04	43.20	3.08	0.28	40.12	23.43	7.74
7	0553/23	CSS-07	7.13	0.11	32	28	40	Clay	27.90	0.68	0.19	2.50	42.80	1.85	0.17	36.89	27.91	7.35
8	0554/23	CSS-08	7.12	0.13	28	20	52	Clay	20.50	1.02	0.16	3.62	45.80	1.53	0.14	40.30	23.77	4.64

Name of Chemist Gedaneh Desalegn Checked by Gedaneh D. Approved by Ababa Birhanu
 Date 12/11/2015 Date 12/11/2015 Date 12/11/15
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Annex III. : The fundamental scale of absolute numbers in AHP (Saaty, 2008)

Importance intensity	Explanation of importance
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong or demonstrated importance
9	Extreme importance
Reciprocals of above	If factor <i>i</i> has one of the above non-zero numbers assigned to it when compared with activity <i>j</i> , then <i>j</i> has the reciprocal value when compared with <i>i</i>
1.1–1.9	If the factors are very close

Annex IV. : RI value of consistency index for various number of input factors (F) used developed by (Saaty, 2008)

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

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