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LAND SUITABILITY ASSESSMENT OF SMALL TEA PLANTATIONS FOR SUSTAINABILITY USING ANALYTICAL HIERARCHY PROCESS (AHP) TECHNIQUE: A CASE STUDY OF UDALGURI DISTRICT, ASSAM (INDIA)

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Abstract. Land is one of the most precious natural resources in densely populated regions of the world like India. The ever-increasing population and increasing number of small tea growers (STGs) in Assam and the expansion of settlements have caused difficulties for small tea growers in choosing land, as not every land is suitable for tea cultivation. In Udalguri district, 54.13% are low-lying areas, and more than half the population is engaged as farmers in the district. So, finding land very suitable for tea cultivation is difficult and expensive. On the other hand, farmers are expanding in the northern foothills region of Bhutan and even up to the forest region. So, as suitable land is very scarce, people can also grow in some parts of the low-lying areas. The present study is therefore an attempt to employ the GIS based multi-criterion decision analysis (MCDA) and analytical Hierarchy Process to derive land suitability assessment of Udalguri district for Small Tea Plantations (STPs). Here, 12 factors with the potential to influence land suitability (namely, elevation, slope, groundwater, precipitation, temperature, relative humidity, Soil pH, Soil Nitrogen, Soil Moisture, Soil Organic Carbon, LULC and NDVI) are considered for land suitability assessment of STPs. These criteria are assigned weightages using AHP, wherein elevation has been given the highest criteria followed by groundwater and others. Based on these techniques, land suitability assessment (LSA) of the district is classified into four zones, namely high, moderate, marginal and not suitable. The results, thus validated, imply that the methodology adopted in deriving LSA is highly reliable, which can support the sustainable utilisation, development and management of land resources in the district. Besides the identification and mapping of village wise LSA are very essential for planning of land resource management and agricultural risk mitigation, which ultimately help in sustainable rural development.

Key words: Land Suitability Assessment, GIS, MCDA, AHP, Assam, Small Tea Plantation

Introduction

In the age of dwindling available land resources, there is severe competition among various stakeholders in terms of introducing new cultivars or expanding into under-utilised spaces. Built-up areas and connected infrastructures are expanding while agricultural and pastoral lands are generally shrinking. In this context, optimisation of land use planning and the selection of appropriate plots are valuable endeavours to avoid the wastage of suitable lands for certain usages. Agricultural resources have continued to play an important role in India's economy. Certain commodities require fewer land resources for a higher return, while others are spatially extensive with comparatively little gain. In India's north-east, two crops dominate agriculture: rice and tea. The competition in the agricultural sector is not only between these two highly valued crops but involves all kinds of cultivated and cultivable lands that differ in ecological properties. In addition, the economic potential

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of cultivators and investors might significantly differ when it comes to the cost of converting resources. In India's north-east, the expansion of small tea plantations is a relatively young phenomenon and is taken as a case in point to analyse its growth from the perspective of land suitability. The application of modern methodologies and techniques may improve assessments and reduce the occurrence of failures in land conversion. With this suitable lens, they might support decision-making processes and the selection of plots for tea growing.

Tea (*Camellia Sinensis*) is one of the most widely consumed beverages in the world and plays a vital role in the economies of many countries (Deka, Goswami 2021; Wang *et al*. 2022). As a commercial crop, tea is recognised not only for rising importance on the domestic tea market (Biggs *et al.* 2018) but also for generating large-scale rural employment (Chen *et al.* 2022). In India, tea has a significant position, as the country is the next-largest producer of tea after China (Deka, Goswami 2021). The tea industry is a major part of India's agricultural economy, providing employment to millions of people, including Small Tea Growers (STGs) and plantation labourers (Prokop 2018). Among the tea-growing states, Assam stands out as the largest, accounting for more than 57% of India's total tea production (Biggs *et al.* 2018). Within Assam, Udalguri district in the Bodoland territorial region has emerged as a growing hub for STPs over the past two decades (Directorate of Economics and Statistics, Assam, 2007). Once affected by socio-political unrest, the district has witnessed a steady rise in smallholder tea cultivation as means of livelihood diversification and rural development (*The Telegraph*, 13.3.2008). Many former rice fields and fallow lands have been converted into tea plantations by individual growers, entailing a major shift in land use patterns (Sharma, Barua 2017). Many farmers prefer tea cultivation because it provides income over a longer period compared to traditional crops that can be managed with low-cost labour (Biggs *et al.* 2018). However, since not all areas of Udalguri are equally suitable for tea cultivation, many small tea growers face challenges due to the district's diverse landscape and varying conditions (Deka, Goswami 2021). Moreover, due to a lack of proper knowledge and planning, many farmers have started tea plantations without proper evaluation, which has led to poor results such as low yield and higher maintenance costs (Deka, Goswami 2021). In some cases, failures of STPs have led farmers to give up and return to traditional practices with financial losses (Sarthak 2024). On the other hand, the lack of financial capital, technical guidance and market access often prevents small tea growers from establishing STPs, despite their having suitable land (Bingen *et al.* 2003). Due to the increasing population and economic growth, human activities have continuous impacts on land use, and those impacts lead to a series of complexity toward environment and land resources development (Tong, Qiu 2020). In Udalguri district, the major constraint on tea cultivation is that areas of suitable terrain are limited; this keeps land prices high and the average tea cultivation size small (Evans 1983). It is well known that the rational and sustainable use of irreproducible natural resources such as land is one of the most important indicators of economic growth (Akıncı 2013). With economic development, the rate at which agricultural land is converted to non-agricultural land use has been increasing (Quan 2007). In the changing world climate and growing global and regional food demands, appropriate land-use planning is crucial for sustainable development. It ensures that land is used efficiently for suitable crops and helps to secure food resources for future generations (Rahaman, Aruchamy 2022; Viana *et al.* 2022; Arhin *et al.* 2024). So, maximising tea yield requires identifying ideal land and climate conditions along with sustainably utilising fallow land for cultivation (Das *et al.* 2020). Therefore, the primary objective of this study is to evaluate the potential land for tea cultivation and conduct a quantitative analysis of influencing criteria to ensure the sustainable viability of tea plantations in Udalguri district. These issues highlight the need for a systematic Land Suitability Assessment (LSA) in the district, which helps to identify the most appropriate for tea cultivation by analysing topographic, hydrological, climatic, soil and environmental indicators. This is one of the key processes of land-use planning (Jayasinghe *et al.* 2019; Yu *et al.* 2011), given that finding sites ideal for sustainable agriculture is crucial because suitable farmlands are constantly shrinking (Sathiyamurthi *et al.* 2024). The availability of GIS and Multi-Criterion Decision Analysis (MCDM) like the Analytical Hierarchy Process (AHP) methods allows the combination of knowledge from different sources to support land-use planning and management (Stofkova *et al.* 2022; Karapetsas *et al.* 2024). The LSA approach boosts productivity, conserve resources and promotes sustainable agriculture, making it vital for policymakers and agricultural stakeholders (Karapetsaas *et al.* 2024).

The AHP has advantages over conventional multi-attribute utility methods, consisting of the hierarchical breakdown of the particular decision problem and the use of subjective and verbal expressions to determine the relative importance of the criteria (Sadok *et al.* 2008). So, in order to determine land resources properly, a spatial model for land suitability assessment for tea integrated with geographic information system (GIS) has been developed to segregate which type of land use is most appropriate for a particular location. Land suitability is the fitness of a given type of land for a defined use, and indicates whether land is assessed as suitable or not suitable. To promote sustainable land resource management, the Food and Agriculture Organisation (FAO) developed land-evaluation guidelines that classify land into four categories: highly suitable (S1), moderately suitable (S2), marginally suitable (S3) and not suitable (N).

Study area

Udalguri district, one of the five districts of Bodoland Territorial Region (BTR) in Assam, falls under the North Bank Plain Zone that covers an area of 2013.71 sq. km and lies between 26°39′45″N–26°55′0″N latitude and 92°12′45″E–91°57′ 30″E longitude. The district's agroecological subregion includes parts of Assam and the Bengal Plain and has a hot, humid-to-subhumid climate. The strategic geographical position of Udalguri district holds significant importance because it shares an international boundary with Bhutan and a state boundary with Arunachal Pradesh in the north; the river Pachnoi and Sonitpur district in the east; Darrang district in the south; and Tamulpur district in the west (Fig. 1). The elevation ranges from a minimum of 52 m to a maximum of 672 m above mean sea level (MSL). The annual rainfall of the district is 1971.7 mm. This includes the SW monsoon (Jun–Sep) contributing 1273 mm and the post monsoon/NE monsoon (Oct–Dec) contributing 121.9 mm. Winter (Jan–Mar) contributes 88 mm and summer (Apr–May) brings 488.8 mm. The average temperature is 28°C. Three predominant types of soil are found in the district – sandy loam, clay loam, silty clay loam; among them, clay loam land coverage is highest, at almost 50%.

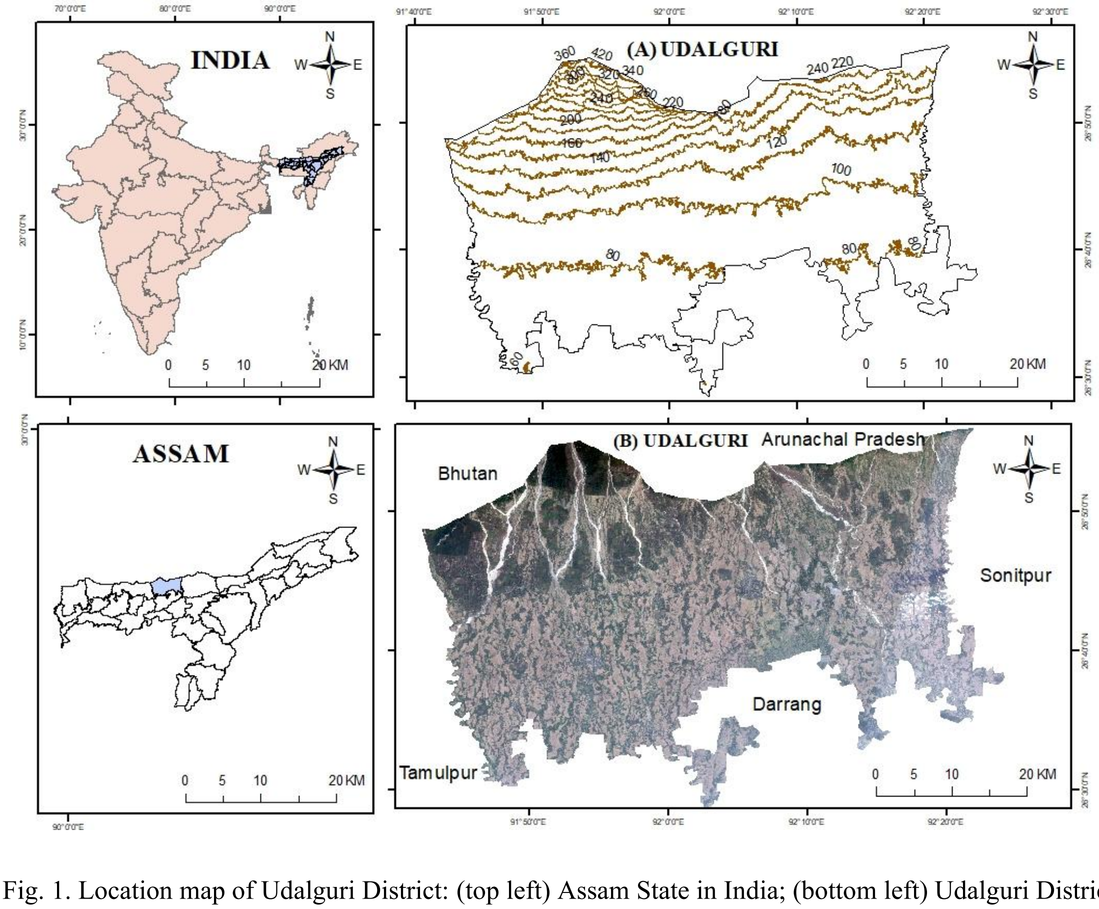

Fig. 1. Location map of Udalguri District: (top left) Assam State in India; (bottom left) Udalguri District in Assam; (top right) Contour Map of Udalguri District; (bottom right) LANDSAT 8 Map of Udalguri District

Materials and methods

Data preparation and parameter selection

The multi-criterion-based land suitability evaluation can be performed by selecting multiple variables and assigning the factors weights based on their influences on tea plantation growth. Based on the extensive literature survey and tea plantation needs according to the specific study region, a total 12 parameters are used to determine land suitability for a sustainable tea plantation. The parameters are broadly classified into five groups: topographic factors (Elevation, Slope), Hydrological factors (Ground Water), Climatic Factors (Rainfall, Temperature, Relative Humidity), Soil Factors (Soil pH, Soil Moisture, Soil Nitrogen, Soil Organic Carbon), and Environmental Factors (LULC, NDVI) (Fig. 2). After preparing all the thematic raster layers, it has been reclassified and converted into the same pixel size of 30-metre resolution and maintained with the same projected coordinate system (UTM WGS 1984, 46°N) in order to enhance output accuracy and minimise potential output errors. The weightage value of each thematic layer has been assigned with the help of MCDM processes, i.e. AHP. Subsequently, the final land suitability for tea plantation was identified using the weighted overlay spatial analysis tool in ArcGIS 10.8 software by giving the weightage value for each.

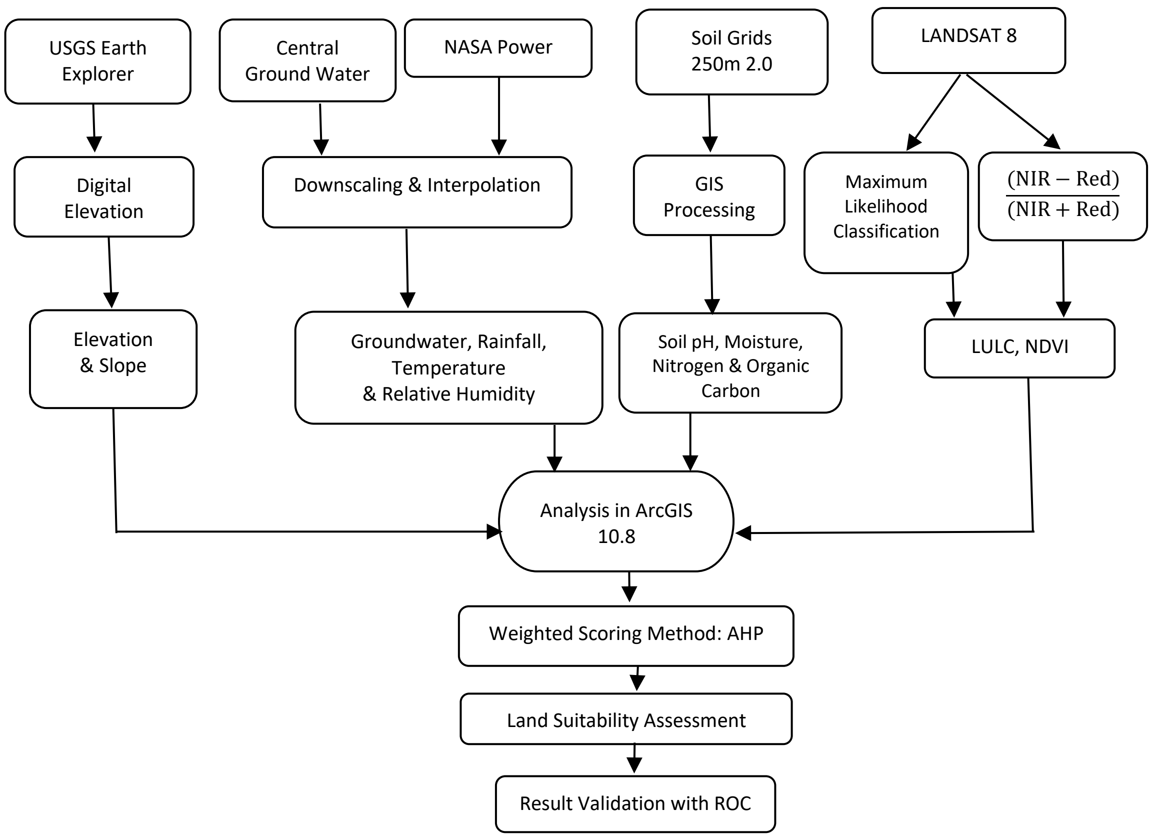

Fig. 2. Methodology used for Land Suitability Assessment

The study involved several datasets in land suitability assessment in Udalguri district (Tab 1). For this purpose, the administrative boundary of the district is first extracted from DIVA-GIS. The topographic maps including elevation and slope were obtained from USGS Earth Explorer. The groundwater map was obtained from the data provided by the Central Ground Water Board. The daily rainfall distribution, temperature and relative humidity map are produced based on the source of NASA Power Access (2021). The soil maps including soil pH, soil moisture, soil nitrogen and soil organic carbon are prepared based on the data of Soil Grids 250 m 2.0. The LULC and NDVI maps are generated based on the LANDSAT 8 satellite imageries of 2021 having 30-m resolution, wherein supervised classification applying maximum likelihood classifier is adopted in ArcGIS.

Table 1

Sources of data generation used in the study

Thematic Layers	Dataset	Unit of Measurement	Time Periods	Resolu-tion	Sources
Elevation	USGS Earth Explorer	Meter	1/1/2021 to 31/12/2021	30 m	https://earthexplorer.usgs.gov/
Slope	USGS Earth Explorer	Degree	1/1/2021 to 31/12/2021	30 m	https://earthexplorer.usgs.gov/
Ground Water	Central Ground Water Board	Metres Below Ground Level	2019–2020 (March)	-	https://www.cgwb.gov.in/cgwbpnm/publication-detail/61
Rainfall (Daily)	NASA Power Access	mm/day	1/1/2021 to 31/12/2021	55 km	https://power.larc.nasa.gov/data-access-viewer/
Temperature at 2 metres max. (daily)	NASA Power Access	°C/day	1/1/2021 to 31/12/2021	55 km	https://power.larc.nasa.gov/data-access-viewer/
Relative Humidity at 2 metres (daily)	NASA Power Access	%	1/1/2021 to 31/12/2021	55 km	https://power.larc.nasa.gov/data-access-viewer/
Soil pH	Soil Grids 250 m.2.0	pH	2021	250 m	https://soilgrids.org/
Soil Moisture	Soil Grids 250 m.2.0	cubic metres of water per cubic metre of soil (m^3/m^3)	2021	250 m	https://soilgrids.org/
Soil Nitrogen	Soil Grids 250 m.2.0	milligrams of nitrogen per kilogram of soil (mg/kg)	2021	250 m	https://soilgrids.org/
Soil Organic Carbon	Soil Grids 250 m.2.0	grams of organic carbon per kilogram of soil (g/kg)	2021	250 m	https://soilgrids.org/
LULC	LANDSAT 8	30 metres	2021/3/2 2021/1/28	30 m	https://earthexplorer.usgs.gov/
NDVI	LANDSAT 8	30 meters	2021/3/2 2021/1/28	30 m	https://earthexplorer.usgs.gov/

Multi-Criterion Decision-Making process based on Analytical Hierarchical Process in Land Suitability Assessment for Small Tea Plantation

The AHP is a method used in decision-making to help choose the best option when there are many factors to consider and was developed by Saaty in 1970 (Khazaii 2016). The accuracy of the calculated weights is checked by analysing the consistency of expert judgements using a specific formula. The Consistency Ratio (CR) helps to detect any inconsistencies or errors in the priority rankings.

$$CI = \frac{\lambda max - n}{n - 1} \quad (1)$$

$$CR = CI/RCI \quad (2)$$

where:
n – the number of criteria,
CR – the Consistency Ratio,
CI – the Consistency Index,
λmax – the average value of the consistency vector.

The weight for each factor was calculated through a pairwise comparison matrix and the maximum eigen values (λmax) of normalised matrix were computed. The consistency index (CI) was estimated using the formula (Eq. 2). The random consistency index (RCI) was used to determine the degree of consistency or consistency ratio (CR) (i.e., CI/RCI). If the CR value is less than or equal to 0.1, the inconsistency is acceptable, or the pair-wise comparison may be revised (Saaty 1987).

Table 2

Saaty rating scales for criterion weights and ranks (Saaty 1987)

Intensity of importance on an absolute scale	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgement strongly favour one activity over another
5	Essential or strong importance	Experience and judgement strongly favour one activity over another
7	Very strong importance	An activity is strongly favoured and its dominance demonstrated in practice
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent judgements	When compromise is needed

Table 3

Random Consistency Index (RCI) (Jayasinghe *et al.* 2019)

N	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RCI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

The tea land suitability map was generated using the weighted overlay spatial analysis tool in ArcGIS where each criterion was assigned a specific weight. Each raster layer was given a percentage influence based on its importance, which is determined by the average weights from the AHP analysis (Bhuyan, Deka 2022). The weight is a relative percentage, and the sum of the percentage influence weights must add up to 10. Each cell value was multiplied by its percentage influence and then added to create the output raster. The formula used to calculate land unit's suitability index was as follows:

$$Si = \sum Xi \times Wi \quad (3)$$

where:
Xi – values of each criterion,
Wi – weight values of each criterion,
Si – suitability index.

Conditioning factors for Small Tea Plantation in the study area

Total twelve factors were selected based on their direct influence on growth, productivity and sustainability of small tea plantations. Tea plants require specific environmental and soil conditions to grow well, so factors such as elevation, slope, rainfall, temperature and humidity were chosen because they affect climate suitability. Altogether, these factors were selected after reviewing earlier studies on tea suitability and local field knowledge to ensure a comprehensive assessment of area's potential for sustainable tea cultivation.

Topographical Indicators

Small tea plantation is strongly influenced by topography, particularly elevation and slope, which are the key factors that affect development, growth and quality of tea plants (Sahu *et al.* 2023). In Udalguri district, elevation ranges from 52 m in the south to 672 m (Fig. 3) in the north. Based on this variation, elevation is categorized into four suitability classes. First is low-lying areas below 107 m, which are mostly located in the southern region and prone to flooding during rainy season are considered unsuitable for tea cultivation. Next, areas with elevations of 107–163m are classified as marginally suitable (S3), and elevations of 163––258 m are moderately suitable (S2). The most suitable zones, with elevations ranging 258–672 m (S1), are found in the northern parts. Slope refers to the steepness or degree of inclination of a land surface and is expressed in degrees. It represents the degree of change in elevation over a given distance and is a key topographic factor. In the district, the very tilted slope (11°–47°) has been classified as not suitable (N) due to soil erosion, while the gentle slope, i.e. 0°–1° is considered to be the most suitable, and the slope ranges of 1°–3° and 3°–11° are considered moderately and marginally suitable, respectively.

Hydrological Indicator

Accessible and stable groundwater conditions are favorable for tea cultivation (Hajiboland 2017). A large portion of the central and southern parts of the district falls under S1 (highly suitable) category, with groundwater depth ranging from 5.23 to 7.86 meters below ground level (Fig. 3). Surrounding this core, much of the district is classified as S2 (moderately suitable), with groundwater levels between 3.93 and 5.23 meter, withing the acceptable range for STP. The S3 (marginally suitable) areas, where groundwater lies deeper (7.86 to 13.49 m), are mostly concentrated in the north-western and north-eastern regions. These zones face limitations in water accessibility for STP during dry periods. The not-suitable (N) zones, primarily in the north central area and a few isolated places, show shallow groundwater levels (0.80 to 3.93 m).

Climatic Indicators

Tea cultivation in Udalguri district of Assam requires a moderate to high amount of rainfall – ideally between 4.5 to 5.5 mm/day or about 1500 to 2500 mm annually – that is well distributed throughout the year (Jain *et al.* 2012; Duncan *et al.* 2016). The consistent rainfall supports healthy growth, flush cycles and good leaf quality. A significant portion of the western and southern regions of the district (Fig. 3) is highly suitable, with the highest rainfall range (4.99–5.27 mm/day), which is ideal for supporting the water requirements of tea plantations. The central zone falls under S2 category, with rainfall of 4.73––4.99 mm/day. The north-central region is marginally suitable (S3), with slightly lower rainfall (4.43–4.73 mm/day). In contrast, the eastern part of the district falls under not suitable (N), with the lowest rainfall (4.00–4.43 mm/day). The ideal temperature range for tea cultivation lies between 18°C and 25°C (Hajiboland 2017). Tea plants require specific temperature conditions at different growth stages to achieve optimal development and yield. However, an increase in maximum temperature has been observed to potentially reduce tea production across many tea-growing regions worldwide (Jayasinghe, Kumar 2021). The northernmost part of the district falls under the S1 category representing the most favorable temperature range for tea cultivation. The S2 zone (25–27°C) covers a moderate portion of the district. A large portion of the central and south-eastern region is categorized as S3, with temperature ranging from 27 to 28°C. The central core indicates least suitable area (N), where temperature exceed 28°C. At a constant temperature, the moisture content of biological materials eventually reaches an equilibrium with the surrounding relative humidity. This equilibrium occurs when the vapor pressure within the biological material equals that of the ambient air (Chen *et al.* 2014). The northern part of the district is characterized by higher relative humidity levels (73–74.4%), which is classified as S1. The central zone falls within the moderate humidity range (71.93–73%) classified as S2. Meanwhile the southern and south-eastern parts show relatively lower humidity (70.52–71.93%) classified as S3.

Soil Indicators

Tea plants generally prefer acidic soils with pH ranging between 4.5 and 5.5 (Yan *et al.* 2020). If the pH moves toward neutral or alkaline (>6.0), nutrient uptake decreases. The northern parts of the district are categorized as highly suitable (S1), having the most acidic soils (0–5.3), which indicate high suitability for tea cultivation, whereas the central belt is moderately suitable (5.3–5.5). In contrast, the southern regions have less-acidic soils making them marginally suitable for tea (5.5–6) due to reduced nutrient availability (Fig. 3). Adequate soil moisture supports vigorous growth and enhances the quality of tea, whereas insufficient moisture can stunt plant development, promote diseases and even halt growth entirely (Huang 2023). Tea cultivation in the Udalguri district of Assam requires soils with good moisture retention and proper drainage, because tea plants are sensitive to both drought and waterlogging. The soil moisture content in Udalguri district of Assam is shown in m^3/m^3 and is categorized into four classes based on moisture content. The highest soil moisture content is categorized as S1 (0.68–0.7 m^3/m^3). Moderate soil moisture content is categorized as S2 (0.66–0.68 m^3/m^3). The marginal suitable of soil moisture content is classified as S3 (0.64–0.66 m^3/m^3). In tea plantation, a continuous supply of nitrogen is necessary to sustain new flushes. Deficiency of nitrogen can lead to stunted growth and to pale and reduced leaf biomass. However, excessive nitrogen application can result in imbalanced growth and reduced quality. Therefore, maintaining optimal nitrogen levels

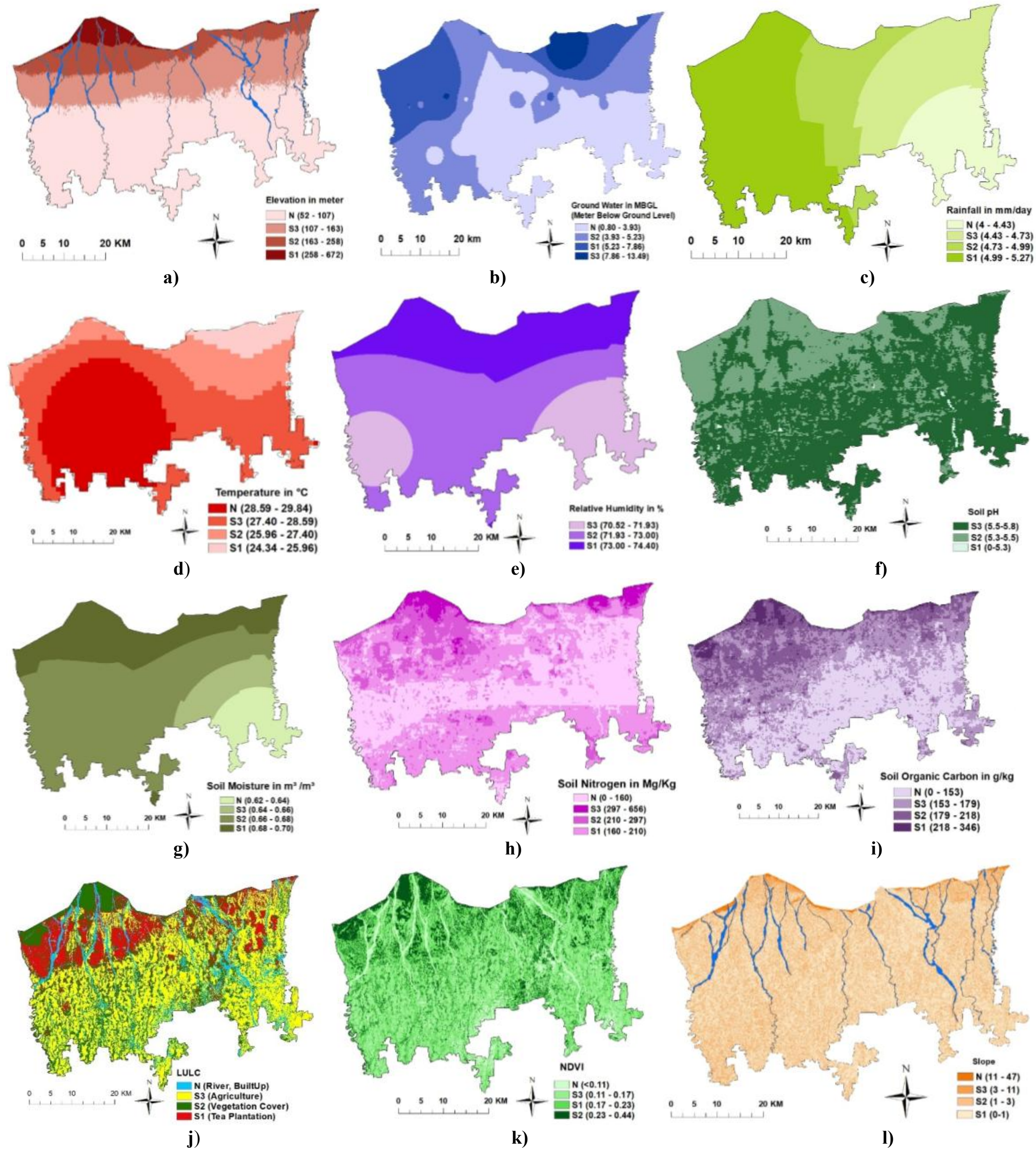

Fig. 3. Thematic layers of different indicators/criteria for Small Tea Plantation in Udalguri District
a – elevation, b – groundwater, c – rainfall, d – temperature, e – relative humidity, f – soil pH, g – soil moisture, h – soil nitrogen, i – soil Organic Carbon, j – LULC, k – NDVI, l – slope

in the soil through appropriate fertilization and organic amendments is crucial for achieving sustainable tea cultivation (Yan *et al.* 2018). The N class (0–160 mg/kg) represents areas with very low nitrogen content and is considered as not suitable for tea cultivation due to insufficient nutrient supply. The S1 category (160–210 mg/kg) signifies highly suitable areas where nitrogen levels are optimal for tea growth. The S2 (210–297 mg/kg) indicates moderately suitable. Lastly, the S3 class (297–656 mg/kg) denotes marginal suitability. Soil Organic Carbon (SOC) is a humic substance formed through long-term humification and exhibits considerable stability, making it a key component of the global carbon cycle. The structural properties of SOC are influenced by factors such as vegetation type, land-use practices and agricultural management, reflecting changes in the soil environment over time (He *et al.* 2021). The N category (0–153 g/kg) indicates low levels of organic carbon signify poor soil health, limited microbial activity and low nutrient holding capacity. S1 (218–346 g/kg) represents rich organic matter presence contributing to improved soil structure and nutrient availability.

Environmental Indicators

LULC refers to the physical characteristics of the earth's surface and the ways in which humans utilize the land, which serve as key indicators for assessing land suitability in Udalguri district. In the present study, LULC has been categorized into four distinct classes. The S1 class represents areas under tea plantation identified as highly suitable for tea cultivation due to their optimal climatic and high topographic conditions. The S2 class indicates vegetation cover areas that are considered moderately suitable due to only partially favourable environmental factors. The S3 class includes agricultural land categorized as marginally suitable. Areas under rivers and built-up areas fall under the N class (Not suitable) category. NDVI is a widely used and measures vegetation health and density, and it was directly derived from Landsat 8 using the formula NDVI=(NIR-RED)/(NIR+RED). NDVI plays a crucial role in land suitability analysis by helping identify areas with strong vegetative growth (Hashim *et al.* 2019; Wang *et al.* 2022). The calculated NDVI value of this study area varies from 0 to 0.44, which is used to measure land suitability for tea cultivation. Low NDVI value (0.11–0.17) classified as having low suitability (S3) for tea cultivation as the land has less capacity to support vegetation cover. Vegetation cover with NDVI values of 0.17–0.23 is considered highly suitable (S1), whereas less than 0.11 is considered not suitable (N), as it has no capacity to support vegetation (Fig. 3).

Results and discussion

The MCDM approach in the spatial AHP was used to evaluate tea plantation suitability criteria and sub-criteria, and weights were assigned based on the influences of individual criteria on the suitability of sites for tea plantations. In this study, the major criteria were further classified into four groups, and weights were assigned to the individual factors; thus 12 sub-criterion weights were calculated. Elevation has the highest weightage (0.16), followed by, temperature (0.11), soil moisture (0.11). slope (0.4), relative humidity (0.5) and NDVI (0.5) was assigned the lowest weights. In this method, each criterion and sub-criterion was compared in pairs based on its relative importance (Tab. 2) for small tea plantation suitability. Methods provided in previous studies (Jayasinghe, Kumar 2021; Mallick *et al.* 2024) were used in conjunction with expert opinions to judge how strongly one factor influences tea cultivation compared to another. First the sub-criteria under each main criterion were compared pairwise based on their relative importance using a 1–9 scale, where 1 indicates equal importance and 9 indicates extreme importance of one element over another. Pairwise comparison matrices were prepared separately for each set of sub-criteria, and individual comparison matrices were combined by calculating the geometric mean to obtain a single aggregated matrix for each group of sub-criteria. Then eigenvector method was applied to each aggregated matrix to derive priority vector were then normalised so that their total sum equalled one. To ensure the consistency of judgements, the maximum eigenvalue (λmax) was computed for each matrix followed by Consistency Index (CI) (eq. 1) and Consistency ration (CR) (eq. 2) was obtained by dividing CI by random index (RI) value corresponding to n. A CR value of less than 0.10 was considered acceptable, indicating that pairwise comparisons were logically consistent. After checking all the comparison results were consistent, the final weight of each sub-criterion was multiplied by the weight of its main criterion to get the overall (global) weight for each sub-criterion. All these calculations were done using Microsoft Excel.

The best yields of tea are produced at an altitude of 52–107 m, which was allotted the highest weight 0.16 (16%), indicating its significant impact on land suitability for STP. More than half the area (54.13%) falls in the non-suitable (N) category (52–107 m). Only 3.71% of the area is highly suitable (S1: 258–672 m). Slope has a lower weight (0.04) and influence (4%). However, most of the area (88.74%) is highly suitable (S1: 0–1°, 46.68%). Groundwater availability has a weight of 0.07 (7%). A combined 54.97% of the area is either moderately (S2: 3.93–5.23) or highly suitable (S1: 5.23–7.86). Rainfall has a moderate weight 0.09 (9%), with 44.28% of the area classified as highly suitable (S1: 4.99––5.27). Temperature, with a weight of 0.11 (11%), shows a mixed distribution. While 40.47% of the area is highly suitable (S1: 27–28°C), 34.45% is unsuitable. Relative humidity has the lowest weight (0.05). Nearly half the area (48.07%) is moderately suitable (S2: 71.93–73%), and only 29.09% is highly suitable (74.4%). Among the soil indicators, soil pH (weight: 0.09) demonstrates a strong presence of suitability with 23.64% under S1. Soil moisture (weight: 0.11) emerges as one of the most favorable parameters, with the area categorized as S1. Soil nitrogen (weight: 0.08 rev-

Table 4

Reclassification of criteria for the land suitability evaluation of small tea cultivation

	Class	Sub-Class	Suitability Class	Weight	Influence In %	Area [sq.km]	% of Area
Topographical Indicator	Elevation	52–107	N	0.16	16	1090	54.13
		107–163	S3			559	27.76
		163–258	S2			290	14.4
		258–672	S1			74.71	3.71
	Slope	0–1	S1	0.04	4	940	46.68
		1–3	S2			847	42.06
		3–11	S3			202	10.03
		11–47	N			24.71	1.23
Hydro-logical Indica-tor	Groundwater	0.8–3.93	N	0.07	7	837	41.57
		3.93–5.23	S2			677	33.62
		5.23–7.86	S1			430	21.35
		7.86–13.4	S3			69.71	3.46
Climatic Indicator	Rainfall	4–4.43	N	0.09	9	296	14.7
		4.43–4.73	S3			464	23.04
		4.73–4.99	S2			362	17.98
		4.99–5.27	S1			891.71	44.28
	Temperature	24–25	S1	0.11	11	136	6.75
		25–27	S2			369	18.32
		27–28	S3			815	40.47
		28–29	N			693.71	34.45
	Relative Humidity	70.52–71.93	S3	0.05	5	460	22.84
		71.93–73	S2			968	48.07
		73–74.4	S1			585.71	29.09
Soil Indicator	Soil pH	0–5.3	S1	0.09	9	282	14
		5.3–5.5	S2			1223	60.73
		5.5–5.8	S3			508.71	25.26
	Soil Moisture	0.62–0.64	N	0.11	11	214	10.63
		0.64–0.66	S3			211	10.48
		0.66–0.68	S2			1000	49.66
		0.68–0.70	S1			588.71	29.24
	Soil Nitrogen	0–160	N	0.08	8	765	37.99
		160–210	S1			882	43.8
		210–297	S2			290	14.4
		297–656	S3			76.71	3.81
	Soil Organic Carbon	0–153	N	0.08	8	759.66	37.72
		153–179	S3			766.41	38.06
		179–218	S2			421.22	20.92
		218–346	S1			66.42	3.3
Environmental Indicator	LULC	River	N	0.07	7	257	12.76
		Agriculture	S3			879	43.65
		Vegetation	S2			569	28.26
		Tea Plantation	S1			308.71	15.33
	NDVI	<0.11	N	0.05	5	190	9.44
		0.11–0.17	S3			808	40.12
		0.17–0.23	S1			662	32.87
		0.23–0.44	S2			353.71	17.57

eveals 31.17% being highly suitable (160––210 mg/kg). Similarly, soil organic carbon (weight: 0.08) shows 37.72% of the land as non-suitable and only 25.36% as highly suitable (153––179 g/kg). In terms of environmental indicators, LULC (weight: 0.07) reflects current land utilization patterns. Only 15.31% of the land under tea plantations is rated as highly suitable (S1), whereas a large portion of land under agriculture is rated as highly suitable (43.65%). The NDVI (weight: 0.05), which captures vegetation cover, shows 52.87% of the area as moderately suitable and 17.85% as highly suitable, indicating a moderate overall greenness and biomass condition of the landscape (Tab.4).

Weight assignment using AHP method

In preparing the land suitability assessment (LSA) for tea cultivation, the criteria are weighted and scored based on their relative importance using AHP method. Table 5 and 6 present the paired comparison matrix and the derived weights of the selected criteria. The matrix used in the study shows sufficient internal consistency, which makes it acceptable for decision-making purposes.

Table 5

Pair-Wise Comparison Matrix for tea plantation suitability

Criteria	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
C1	1	3	3	3	2	2	3	2	1	2	2	2
C2	0.33	1	0.5	0.5	0.33	0.33	1	2	1	2	1	2
C3	0.33	2	1	1	3	2	0.33	1	2	2	1	2
C4	0.33	2	1	1	3	2	0.5	1	2	3	3	2
C5	0.5	3.03	0.33	0.33	1	0.25	0.2	0.5	0.33	0.33	2	2
C6	0.5	3.03	0.5	0.5	2	1	1	1	2	2	2	2
C7	0.33	1	1	2	2	1	1	2	2	2	3	2
C8	0.5	0.5	1	1	2	1	0.5	1	3	0.33	2	2
C9	1	1	0.5	0.5	3.03	0.5	0.5	0.33	1	2	2	2
C10	0.5	0.5	0.5	0.33	3.03	0.5	0.5	3.03	0.5	1	2	1
C11	0.5	1	1	0.33	0.5	0.5	0.33	0.5	0.5	0.5	1	1
C12	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	1	1	1
Sum	6.33	18.56	10.83	11	22.39	11.58	9.36	14.86	15.83	18.16	22	21

Table 6

Normalised Matrix with Criterion Wights (Wi), Consistency Index (CI), Random Consistency Index (RCI), Consistency Ratio (CR)

Criteria	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	**Wi**	Lamda
C1	0.16	0.16	0.28	0.27	0.09	0.17	0.32	0.13	0.06	0.11	0.09	0.10	**0.16**	13.16
C2	0.05	0.05	0.05	0.05	0.01	0.03	0.11	0.13	0.06	0.11	0.05	0.10	**0.07**	13.38
C3	0.05	0.11	0.09	0.09	0.13	0.17	0.04	0.07	0.13	0.11	0.05	0.10	**0.09**	13.58
C4	0.05	0.11	0.09	0.09	0.13	0.17	0.05	0.07	0.13	0.17	0.14	0.10	**0.11**	13.51
C5	0.08	0.16	0.03	0.03	0.04	0.02	0.02	0.03	0.02	0.02	0.09	0.10	**0.05**	13.21
C6	0.08	0.16	0.05	0.05	0.09	0.09	0.11	0.07	0.13	0.11	0.09	0.10	**0.09**	13.48
C7	0.05	0.05	0.09	0.18	0.09	0.09	0.11	0.13	0.13	0.11	0.14	0.10	**0.11**	13.43
C8	0.08	0.03	0.09	0.09	0.09	0.09	0.05	0.07	0.19	0.02	0.09	0.10	**0.08**	13.26
C9	0.16	0.05	0.05	0.05	0.14	0.04	0.05	0.02	0.06	0.11	0.09	0.10	**0.08**	13.28
C10	0.08	0.03	0.05	0.03	0.14	0.04	0.05	0.20	0.03	0.06	0.09	0.05	**0.07**	13.52
C11	0.08	0.05	0.09	0.03	0.02	0.04	0.04	0.03	0.03	0.03	0.05	0.05	**0.05**	13.03
C12	0.08	0.03	0.05	0.05	0.02	0.04	0.05	0.03	0.03	0.06	0.05	0.05	**0.04**	13.13
Sum	1	1	1	1	1	1	1	1	1	1	1	1	**1**	13.58

Consistency Index (CI)=0.14, Random Consistency Index (RCI)=1.48, Consistency Ratio (CR)=0.09

The accuracy of the calculated weights is assessed through a consistency analysis. According to the AHP method, if the Consistency Ratio (CR) is less than or equal to 0.1, the level of consistency in the judgements is considered acceptable. A CR value greater than 0.1 suggests the need to revise the subjective judgements. In this study, the overall CR is calculated to be 0.09, which is below the threshold of 0.10, indicating an acceptable level of consistency in the pairwise comparisons (Tab. 5, 6).

Land Suitability Assessment for tea plantation of Udalguri district

The land suitability assessment of Udalguri district is identified and mapped by the use and integration of multi-influencing land suitability assessment factors (elevation, ground water, rainfall, temperature, relative humidity, soil pH, soil moisture, soil nitrogen, soil organic carbon, LULC, NDVI and slope) in Arc GIS 10.8 utilising AHP techniques. Table 6 lists the criterion weights and consistency ratio for the parameters, and the table lists the normalised weights for the various classes of each parameter. Utilising the overlay analysis, land suitability assessment of Udalguri district is derived. Thus, it is observed that majority of the regions within the district have a marginally suitable LSA. In Fig. 4, S1 (highly suitable) areas are prominently located in the northern part of the district due to optimal conditions such as gentle slope, high NDVI, balanced-pH and nutrient-rich soils, and sufficient moisture. The existing tea plantations were assigned to class S1 (highly suitable) based on factors that together indicate that the land is environmentally capable of sustaining tea cultivation. An alternative field validation method was used. The S2 (moderately suitable) zones are distributed mostly along the transition belt between highly suitable and marginally suitable area due to slightly suboptimal parameters. The S3 (marginally suitable) zones are distributed in the central and southern portion of the district due to some constraints such as lowers soil fertility, steeper slopes or less-favourable moisture and NDVI levels. Zones classed as N (not suitable) are clustered predominately in the south-eastern section due to limitations such as steep slopes, poor soil characteristics or inadequate ground water availability. The forest cover in the north-west distinctly represents ecologically protected zones that are restricted for cultivation (including STP), while the major rivers flowing predominately from north to south help farmers by acting as natural drainage systems.

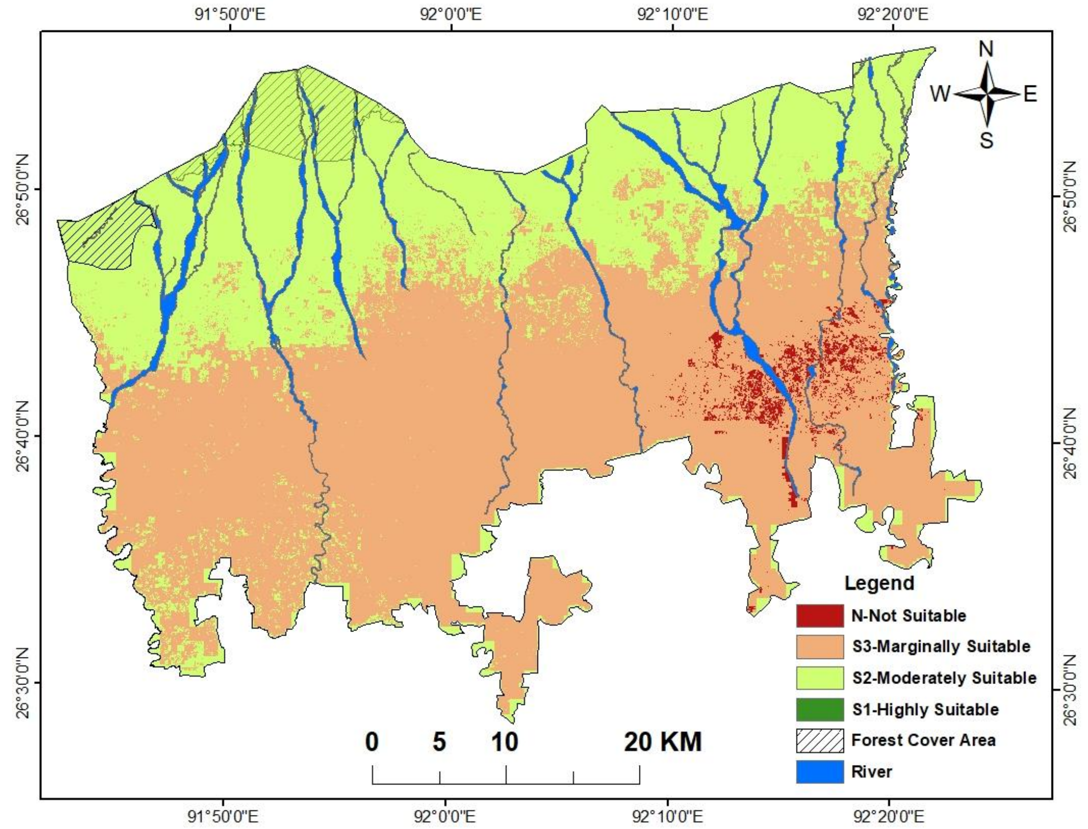

Fig. 4. Land Suitability Assessment for Small Tea Plantation in Udalguri

Table 7

Land Suitability Analysis according to different LULC classes

Suitable Classes \ LULC	Tea	Vegetation	River	Agriculture	Built Up	Total [sq.km]	In %
Not Suitable (N)	0.00	1.06	17.73	12.03	39.84	70.66	3.51
Marginally Suitable (S3)	52.3	314.48	146.54	667.80	29.34	1210.46	60.11
Moderately Suitable (S2)	248.91	224.79	80.81	167.51	10.18	732.2	36.36
Highly Suitable (S1)	0.30	0.10	-	-	-	0.4	0.02
Total	301.51	540.42	245.08	847.33	79.36	2013.7	100

The highly suitable (S1) land is extremely limited, comprising only 0.02% (0.4 sq.km), with only 0.30 sq. km under tea and 0.10 sq. km under vegetation. No agricultural, riverine or built-up lands fall in this category, indicating that ideal conditions for tea cultivation are rare and concentrated in small pockets. Moderately suitable (S2) land constituted 36.36% (732.2 sq. km) of the total area, with tea-growing areas (248.91 sq. km) and vegetation (224.79 sq. km) forming the majority of that area. This indicates a promising zone for potential expansion or intensification of tea cultivation, especially in two categories. The majority of the district 60.11% (1210.46 sq. km) is classified as marginally suitable (S3). Within this class, agricultural lands (667.80 sq. km) and vegetative cover (314.48 sq. km) dominate, indicating that a significant portion of existing land uses are only marginally suitable for tea cultivation. A considerable portion of river (146.54 sq. km) and tea (52.3 sq. km) areas also fall under this class. Not suitable (N) covers only 3.51% of the total area (70.66 sq. km), with built-up areas (39.84 sq. km), river (17.73 sq. km) and smaller segments of vegetation and agriculture.

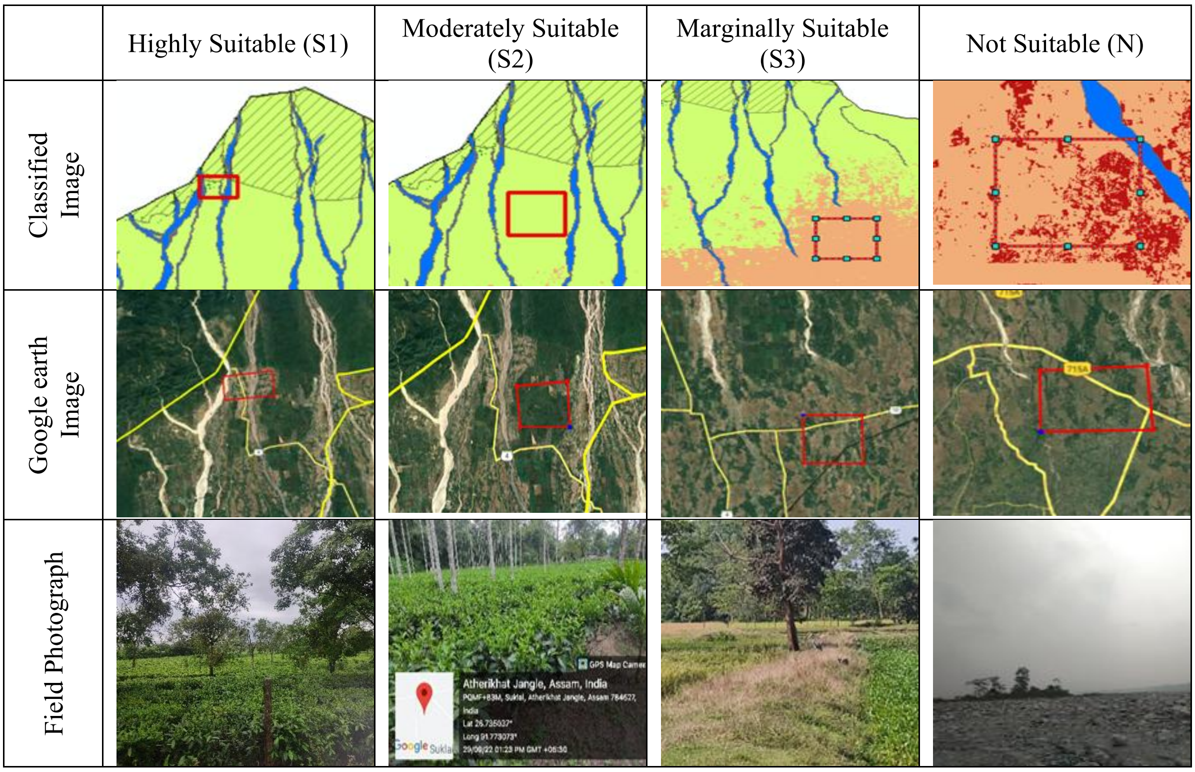

Fig. 5. Comparison of land suitability for Small Tea Plantation with Google Earth Image and ground truth verification for validation

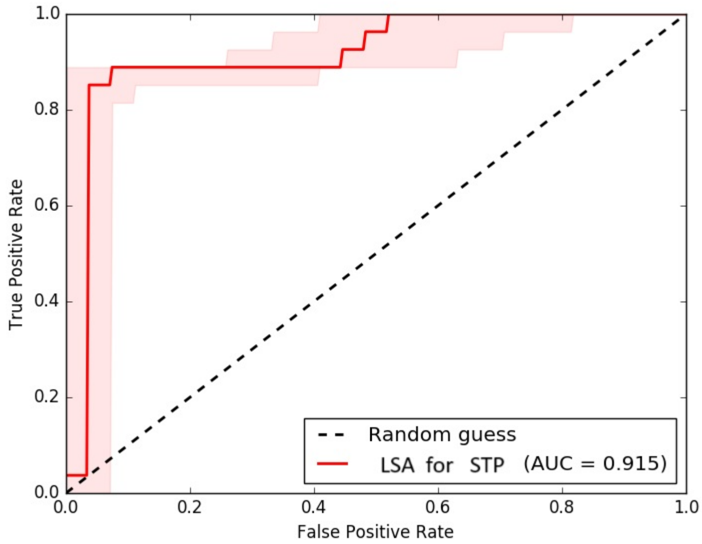

Fig. 6. ROC Curve Model

Ground truth verification of land suitability classes

To ensure the reliability and practical applicability of the generated land suitability and classified land use maps, the present study employed three validation techniques: 1) comparison with Google Earth Imagery, 2) verification through ground truth data and 3) performance classification using the Receiver Operating Characteristics (ROC) curve. As shown in Figure 5, areas identified as highly suitable (S1) for tea cultivation correspond well with existing tea plantations, which are clearly visible in both Google Earth images and ground truth photographs. Similarly, moderately suitable areas (S2) also align with actual plantation sites and are often associated with partial vegetation cover observed on the ground. Marginally suitable areas (S3) are primarily located in low-lying regions where rice cultivation is common, which is consistent with wetland features and terrain visible in the ground imagery. In contrast, areas classified as not suitable (N) are predominately riverine zones and built-up areas, as confirmed through both satellite and on-site observations.

The ROC (Receiver-operating characteristics curve) is used in a land suitability assessment model for tea cultivation. The ROC curve illustrates the model's diagnostic ability to distinguish between suitable and unsuitable land based on elevation weighting. The red line represents the model's performance, while the shaded area around it indicates the confidence interval or variability across multiple runs or folds. The model achieves an area under the curve (AUC) value of 0.915, which indicates a high level of accuracy. An AUC of 0.915 suggests that there is a 91.5% chance that the model will correctly distinguish between a randomly chosen suitable site and an unsuitable one. This performance reflects that LSA for STP is a significant predictor in evaluating land suitability for tea cultivation.

Conclusion

There has been literature (Chen *et al.* 2014; Jayasinghe *et al.* 2019; Das *et al.* 2020; Jayasinghe, Kumar 2021; Chen *et al.* 2022; Rahaman, Aruchamy 2022; Sahu *et al.* 2023; Karapetsas *et al.* 2024; Mallick *et al.* 2024) on land suitability for tea plantations, but most focuses on large tea estates. However, in Udalguri district, small tea growers have limited land and fewer resources, and they face more challenges in choosing the right land for cultivation. While several studies have evaluated land suitability for tea plantations broadly, they overlook the unique ecological and socio-economic factors that affect growers. Udalguri district has witnessed a notable shift from traditional agriculture to STP, and STGs operate under different constraints and opportunities compared to large estates. These constraints include limited landholdings, financial resources and access to expert guidance. A localised, criterion-based assessment using AHP not only ensures a more nuanced understanding of land potential for STGs but also contributes to sustainable planning and policy support. This study will provide tea growers with better ideas about where to grow tea, which can help them use their land wisely and earn more. The assessment of land suitability for small tea plantations (STPs) in Udalguri district has provided valuable insights into the spatial dynamics and agricultural potential of the region. It is evident based on the GIS generated suitability map that, while certain parts of the district hold significant promise for tea cultivation, a substantial portion remains either only marginally suitable or not suitable at all. From the map (Fig. 4, 5), it is clear that only a very limited area of the district falls under the S1 (highly suitable) category indicated by red zones, and these are mostly concentrated along the river basins where water availability, soil conditions and microclimatic factors likely support favourable tea growth. In contrast, a significant portion of the district is categorised under S3 (marginally suitable), which is shown in light brown colour. These areas may support tea cultivation but would require heavy input investment such as soil amendments and other management as these zones are primarily low-lying areas that are highly prone to seasonal flooding and waterlogging – especially during the monsoon months. In these flood-affected areas, the soil texture is often clayey and compact, which prevents proper drainage. Tea requires well-drained, slightly sloped terrain and a low-lying location makes the root system vulnerable. The moderately suitable areas (S2) shown in light green show moderate potential and cover a relatively broader belt in the northern and central zones. These regions may already be under partial cultivation or transitioning toward small tea plantation development, because there are opportunities for cultivation of STP in scattered patches of fallow land if the lands are slightly elevated, well-drained and underutilised. Land ownership and financial capacity are two major challenges for STGs in the district. Many indigenous and marginal farmers lack legal land documents, which prevents them from accessing institutional support like loans and subsidies. Even where land is moderately suitable, the high initial investment needed for tea cultivation, such as in the costs of saplings, fencing, irrigation and maintenance makes it difficult for resource-poor growers to start or sustain plantations. However, a few financially capable growers are overcoming these constraints by purchasing low-lying land and raising its elevation through soil filling. The map indicates a dense river network, which plays a vital role in determining tea suitability. The areas close to rivers have better soil moisture conditions. For districts like Udalguri where land pressure is high and economic opportunities are limited, expanding small tea plantations in a planned and scientifically guided manner can catalyse inclusive rural development. The value of such a detailed land suitability assessment lies in its practical application. The map serves as a decision-support tool for both policymakers and farmers. However, the effectiveness of this map depends on frequent ground truthing, updating with remote-sensing data and incorporation of climatic trends and socio-economic factors like land tenure and market access. The map should thus not be viewed as a static product but as a dynamic tool that evolves with changing land-use patterns and agro-climatic conditions. The forest covered areas in the north-west are critical ecological zones and should be kept out of agricultural conversion, as these areas serve as important carbon sinks and biodiversity corridors and help regulate the regional microclimate. The expansion of tea plantations into forest zones, as is sometimes seen in frontier villages, could pose serious ecological threats. Therefore, any further plantation expansion must strictly follow the land-use zone guidelines and be monitored using satellite-based forest-change-detection techniques. Applying these methods could be a valuable step in supporting decision-making and selection of plots for the implementation of a value-adding approach to utilise limited agricultural resources for a better future of the farming communities.

References

Akıncı H., Özalp A.Y., Turgut B. 2013. Agricultural land use suitability analysis using GIS and AHP technique. *Computers and Electronics in Agriculture* 97: 71-82. https://doi.org/10.1016/j.compag.2013.07.006

Arhin I., Yeboah E., Liu X., Liu A., Chen X., Li X. 2024. Integrating farmers' perception of sustainable agricultural technologies towards the development of sustainable tea production in China. *International Journal of Agricultural Sustainability* 22(1). https://doi.org/10.1080/14735903.2024.2303886

Bhuyan M.J., Deka N. 2022. Delineation of groundwater potential zones at micro-spatial units of Nagaon district in Assam, India, using GIS-based MCDA and AHP techniques. *Environmental Science and Pollution Research* 31: 54107-54128. https://dx.doi.org/10.1007/s11356-022-24505-4

Biggs E.M., Gupta N., Saikia S.D., Duncan J.M.A. 2018. The tea landscape of Assam: Multi-stakeholder insights into sustainable livelihoods under a changing climate. *Environmental Science & Policy* 82: 9-18. https://doi.org/10.1016/j.envsci.2018.01.003

Bingen J., Serrano A., Howard J. 2003. Linking farmers to markets: different approaches to human capital development. *Food Policy* 28(4): 405-419. https://doi.org/10.1016/j.foodpol.2003.08.007

Chen A., Chen H.Y., Chen C. 2014. Use of Temperature and Humidity Sensors to Determine Moisture Content of Oolong Tea. *Sensors* 14(8): 15593--15609. doi:10.3390/s140815593

Chen P., Li C., Chen S., Li Z., Zhang H., Zhao C. 2022. Tea Cultivation Suitability Evaluation and Driving Force Analysis Based on AHP and Geodetector Results: A Case Study of Yingde in Guangdong, China. *Remote Sensing* 14(10): 2412. https://doi.org/10.3390/rs14102412

Das A.C., Noguchi R., Ahamed T. 2020. Integrating an Expert System, GIS, and Satellite Remote Sensing to Evaluate Land Suitability for Sustainable Tea Production in Bangladesh. *Remote Sensing* 12(24): 4136. https://doi.org/10.3390/rs12244136

Deka N., Goswami K. 2021. Economic sustainability of organic cultivation of Assam tea produced by small-scale growers. *Sustainable Production and Consumption* 26: 111-125. https://doi.org/10.1016/j.spc.2020.09.020

Directorate of Economics and Statistics, Assam. 2023. Statistical handbook of Assam. Government of Asam. Online: https://des.assam.gov.in/sites/default/files/swf_utility_folder/departments/ecostat_medhassu_in_oid_3/menu/document/statistical_handbook_assam_2023.pdf

Duncan J.M.A., Saikia S.D., Gupta N., Biggs E.M. 2016. Observing climate impacts on tea yield in Assam, India. *Applied geography* 77: 64-71. https://dx.doi.org/10.1016/j.apgeog.2016.10.004

Evans A.W. 1983. The Determination of the Price of Land. *Urban Studies* 20(2): 119-129. https://doi.org/10.1080/00420988320080271

Hajiboland R. 2017. Environmental and nutritional requirements for tea cultivation. *Folia Horticulture* 29(2): 199-220. DOI: 10.1515/fhort-2017-0019

Hashim H., Abd Latif Z., Adnan N.A. 2019. Urban vegetation classification with NDVI threshold value method with very high resolution (VHR) Pleiades imagery. The International Archives of the Photogrammetry. *Remote Sensing and Spatial Information Sciences* 42: 237-240.

He S., Zheng Z., Zhu R. 2021. Long-term tea plantation effects on composition and stabilization of soil organic matter in Southwest China. *Catena* 199: 105132. https://doi.org/10.1016/j.catena.2020.105132

Huang Y. 2023. Improved SVM-Based Soil-Moisture-Content Prediction Model for Tea Plantation. *Plants* 12: 2309. https://doi.org/10.3390/plants12122309

Jain S.K., Kumar V., Saharia M. 2012. Analysis of rainfall and temperature trends in northeast India. *International Journal of Climatology* 33(4): 968--978. DOI: 10.1002/joc.3483

Jayasinghe S.L., Kumar L. 2021. Potential Impact of the Current and Future Climate on the Yield, Quality, and Climate Suitability for Tea [*Camellia sinensis* (L.) O. Kuntze]: A Systematic review. *Agronomy* 11(4): 619. https://doi.org/10.3390/agronomy11040619

Jayasinghe S.L., Kumar L., Sandamali J. 2019. Assessment of Potential Land Suitability for Tea (Camellia sinensis (L.) O. Kuntze) in Sri Lanka Using a GIS-Based Multi-criteria Approach. *Agriculture* 9(7): 148. doi:10.3390/agriculture9070148

Karapetsas N., Gobin A., Bilas G., Koutsos T.M., Pavlidis V., Katragkou E., Alexandridis T.K. 2024. Analysis of Land Suitability for Maize Production under Climate Change and Its Mitigation Potential through Crop Residue Management. *Land* 13(1): 63. https://doi.org/10.3390/land13010063

Khazaii J. 2016. Analytical Hierarchy Process (AHP). *Advanced Decisions Making for HVAC Engineers:* 73-85. https://doi.org/10.1007/978-3-319-33328-1_9

Mallick M., Krishnaiah Y.V., Panja K., Das D., Rai D., Hati M., Chakma A. 2024. Land suitability assessment for tea cultivation in Jalpaiguri district of West Bengal, India, using AHP and DEMATEL techniques. *Environment, Development and Sustainability*. https://doi.org/10.1007/s10668-024-05711-1

Prokop P. 2018. Tea plantations as a driving force of long-term land use and population changes in the eastern Himalayan piedmont. *Land Use Policy*, 77: 51-62. https://doi.org/10.1016/j.landusepol.2018.05.035

Quan B., Zhu H.J., Chen S.L., Romkens M.J.M., Li B.C. 2007. Land Suitability Assessment and Land Use Change in Fujian Province, China. *Pedosphere* 17(4): 493-504. https://doi.org/10.1016/S1002-0160(07)60059-9

Rahaman S.A., Aruchamy S. 2022. Land Suitability Evaluation of Tea (*Camellia sinensis L.*) Plantation in Kallar Watershed of Nilgiri Bioreserve, India. *Geographies* 2(4): 701-723. https://doi.org/10.3390geographies2040043

Saaty R.W. 1987. The analytic hierarchy process-what it is and how it is used. *Mathematical Modelling,* 9(3-5): 161-176. https://doi.org/10.1016/0270-0255(87)90473-8

Sadok W., Angevin F., Bergez J.E., Bockstaller C., Colombo B., Guichard L., Reau R., Dore T. 2008. Ex ante assessment of the sustainability of alternative cropping systems: implications for using multi-criteria decision-aid methods. A review. *Agronomy for Sustainable Development* 28(1): 163-174. https://doi.org/10.1051/agro:2007043

Sahu N., Das P., Saini A., Varun A., Mallick S.K., Nayan R., Aggrawal S.P., Pani B., Kesharwani R., Kumar A. 2023. Analysis of Tea Plantation Suitability Using Geostatistical and Machine Learning techniques: A case of Darjeeling Himalaya, India. *Sustainability* 15(13): 10101. https://doi.org/10.3390/su151310101

Sarthak G. 2024. Facing losses, tea producers use idle land for alternate crops. *The Times of India*. https://timesofindia.indiatimes.com/city/kolkata/tea-producers-opt-for-alternative-crops-amid-losses/articleshow/110410135.cms?

Sathiyamurthi S., Saravanan S., Karuppannan S., Balakumbahan R., Sivasakthi M., Kumar S.P., Ramya M., Hussain S., Tariq A. 2024. Agricultural land suitability of Manimutha Nadhi watershed using AHP and GIS techniques. *Discover Sustainability* 5(270). https://link.springer.com/article/10.1007/s43621-024-00471-4?fromPaywallRec=true

Sharma C.K., Barua P. 2017. Small Tea Plantation and Its Impact on the Rural Landscape of Contemporary Assam. International Journal of Rural Management 13(2): 140-161. https://doi.org/10.1177/0973005217725454

Stofkova J., Krejnus M., Stofkova K.R., Malega P., Binasova V. 2022. Use of the Analytic Hierarchy Process and Selected Methods in the Managerial Decision-Making Process in the Context of Sustainable Development. *Sustainability* 14(18): 11546. https://doi.org/10.3390/su141811546

Tea Brews Success for Youths. 2008. *The Telegraph Online*, March 13. https://www.telegraphindia.com/

Tong Q., Qiu F. 2020. Population growth and land development: Investing the bi-directional interactioons. *Ecological Economics* 169: 106505. https://doi.org/10.1016/j.ecolecon.2019.106505

Viana C.M., Freire D., Abrantes P., Rocha J., Pereira P. 2022. Agricultural land systems importance for supporting food security and sustainable development goals: A systematic review. *Science of the Total Environment* 806. https://doi.org/10.1016/j.scitotenv.2021.150718

Wang W., Han J., Pu Y., Wang X. 2022. Tea (Camellia sinensis): A Review of Nutritional Composition, Potential Applications, and Omics Research. *Applied Sciences* 12(12): 5874. https://doi.org/10.3390/app12125874

Wang H., Muller J.D., Tatarinov F., Yakir D., Rotenberg E. 2022. Disentangling Soil, Shade, and Tree Canopy Contributions to Mixed Satellite Vegetation Indices in a Sparse Dry Forest. *Remote Sensing* 14(15): 3681. https://doi.org/10.3390/rs14153681

Yan P., Shen C., Fan L., Li X., Zhang L., Zhang L., Han W. 2018. Tea planting affects soil acidification and nitrogen and phosphorous distribution in soil. *Agriculture, Ecosystems and Environment*, 254: 20-25. https://doi.org/10.1016/j.agee.2017.11.015

Yan P., Wu L., Wang D., Fu J., Shen C., Li X., Zhang L., Zhang L., Fan L., Wenyan H. 2020. Soil acidification in Chinese tea plantations. *Science of the Total Environment* 715: 136963. https://doi.org/10.1016/j.scitotenv.2020.136963

Yu J., Chen Y., Wu J. 2011. Modelling and implementation of classification rule discovery by ant colony optimisation for spatial land-use suitability assessment. *Computers, Environment and Urban Systems* 35(4): 308-319. https://doi.org/10.1016/j.compenvurbsys.2010.12.003