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Assessment of Potential Land Suitability for Tea (*Camellia sinensis* (L.) O. Kuntze) in Sri Lanka Using a GIS-Based Multi-Criteria Approach

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Abstract: The potential land suitability assessment for tea is a crucial step in determining the environmental limits of sustainable tea production. The aim of this study was to assess land suitability to determine suitable agricultural land for tea crops in Sri Lanka. Climatic, topographical and soil factors assumed to influence land use were assembled and the weights of their respective contributions to land suitability for tea were assessed using the Analytical Hierarchical Process (AHP) and the Decision-Making Trail and Evaluation Laboratory (DEMATEL) model. Subsequently, all the factors were integrated to generate the potential land suitability map. The results showed that the largest part of the land in Sri Lanka was occupied by low suitability class (42.1%) and 28.5% registered an unsuitable land cover. Furthermore, 12.4% was moderately suitable, 13.9% was highly suitable and 2.5% was very highly suitable for tea cultivation. The highest proportion of "very highly suitable" areas were recorded in the Nuwara Eliya District, which accounted for 29.50% of the highest category. The model validation results showed that 92.46% of the combined "highly suitable" and "very highly suitable" modelled classes are actual current tea-growing areas, showing the overall robustness of this model and the weightings applied. This result is significant in that it provides effective approaches to enhance land-use efficiency and better management of tea production.

Keywords: AHP; DEMATEL; climate; land suitability; soil; tea; topography

1. Introduction

Land evaluation is a foundation for sustainable land resource planning, management and finding optimum land use for each defined land unit [1]. Land cover is the biophysical features of land and the land use refers to the socio-economic functions of land to meet human needs [2,3]. Appropriate land use decisions are vital to achieving optimum land productivity and ensuring environmental sustainability. This requires an effective management of land information on which such decisions should be based [4]. The Food and Agricultural Organization [5,6] recommended a land suitability assessment approach for crops in terms of suitability ratings ranging from very highly suitable to unsuitable based on climatic and terrain data, as well as soil properties. Land suitability evaluation according to FAO standards has been applied in many parts of the world, particularly in the developing countries.

The planting of tea in Sri Lanka has been carried out since 1860 and it has become the mainstay of the island's economy [7]. Of the agricultural land, 40% is used for plantation agriculture—of which 28% is used for tea cultivation [8]. The major constraints of the tea sector in Sri Lanka are the limited area of suitable terrain, which keep land prices high and the average estate size small, and labor shortage [9]. Thus, the selection of land according to its suitability has become increasingly important in making the best use of available land for tea cultivation. Farmers establish tea based on prior knowledge and experience, without the availability of scientific information and validation. So, farmers definitely consider site suitability but using a different set of information. This adversely impacts on tea production and, in the long run, would exacerbate the existing economic, social, and environmental problems related to the tea sector.

Further, land use activity contributes to climate change and the impact of climate and natural disasters has increased in recent decades due to improper land use in Sri Lanka [10]. Tea cultivation in Sri Lanka is clearly vulnerable to climate change and extreme events, and this has resulted in some of the existing tea land area becoming unsustainable for tea cultivation and, by contrast, existing marginal land has been morphed into cultivated land [11]. Other ramifications of climate change are receiving longer dry seasons, uneven rainfall distribution, and erosion of top soil caused by uncharacteristic heavy rainfall patterns, which can lead to negative effects on production. In addition, crop-weed competition, the spread of pests and diseases, drought damage, soil losses and infertility in tea fields fostering the increased use of fertilizers to maintain the soil fertility, resulting in an increase in the cost of production and posing a threat to the tea industry [12,13]. Commercial tea growing in Sri Lanka, limited to a few areas, is at risk due to climate change and its subsequent fallouts. Consequently, the expected production in response to the demand may not be as easy as in the earlier days under given potential constraints on the availability of suitable tea lands [14].

This situation has also aggravated the current status of tea cultivation in Sri Lanka through construction and other human activities and, correspondingly, there is a great risk of a lower return on investment in tea cultivation [15]. For example, forest areas and tea lands in hilly areas have been converted for human settlement and the cultivation of annual crops, which has resulted in soil erosion, soil infertility, landslides and floods. The National Building Research Organization (2015) identified that seven tea-growing districts of Sri Lanka (i.e., Badulla, Nuwara Eliya, Kegalle, Ratnapura, Kandy, Matale and Kalutara) are subjected to severe landslides that demarcate nearly 12,000 km^2 (21%) of the total area of Sri Lanka. Therefore, the extent of the major tea producing area is apparently threatened and not sustainable to produce a high quantity of tea to cater for global demand. Moreover, land use policies in Sri Lanka are not designed to ensure that economies of scale in production and cropping and that farming systems are sustainable in the long run [16]. Also, the productivity of fertile lands has been reduced due to improper land use [10] and this can lead to the mismanagement of natural resources and degradation of the environment with other socio-economic conflicts [17].

Under the current economic trends and the nature of commercialization, tea planters and related companies are more interested in converting the estate bungalows into tourist hotels, cutting down trees in the estates for timber, extracting granite and other mineral resources and selling the land at the end [18]. The public railed against some multipurpose development projects especially implemented in hilly areas (i.e., the irrigation project of Uma oya) for wreaking unsafe levels of environmental damage and thus thousands of acres of tea lands are becoming unusable or less suitable for tea growing [19]. Hence the responsible authorities should shoulder the responsibility to take initiatives to only make use of the unproductive tea lands for the above-mentioned activities, leaving the suitable lands for the long-term sustainability of tea cultivation. Approximately 80% of the population concentrated in the tea plantation sector are Tamil people who immigrated to Sri Lanka from South India during the British colonial era in the 19th century. Most of the workers in the tea estates reside within the estate area itself and work as laborers. The clusters of the labor lines are strategically located in different parts of the tea estate to enable quick labor deployment and to protect the boundary of the tea plantations. But with the increase of population in communities attached to the tea industry, tea plantation workers demand land for constructing their own settlements and fight for their rights for lands as they have no choice [20]. Sometimes they establish their settlements illegally in tea lands, clearing the existing tea cultivation and adjacent forest areas. Thus, it is obvious that immediate steps must be taken to form a national policy and strategy on these circumstances by giving special reference to the land management practices in tea plantations.

In conjunction with the above circumstances, the existing tea-growing areas in Sri Lanka that were identified in the early 1940s may not be suitable for tea anymore or some other areas may have suitable conditions to grow tea. The total land area under tea cultivation was estimated to be approximately 221,969 hectares in 2016 [12], but the area under tea has decreased by 10% from 1946 to 1982 [8]. Based on the figures given by Food and Agriculture Organization (FAO) Statistical Databases [13], we estimate that the tea cultivation area decreased by 2.6% from 1961 to 2016 while other tea producing countries substantially increased their cultivation extent. The land area for tea cultivation in Sri Lanka has not increased compared to other tea producing countries like Kenya, China and India, which creates difficulties in competing in the international market in the future [14]. Therefore, urgent attention has to be drawn to implement proper land use planning and to work on suitability analysis for tea in order to upgrade the productivity and to avoid land use-related problems in tea cultivation [21].

In the global context, a number of studies have been undertaken to assess the land suitability assessment for tea crops. In Kenya, a land use assessment was done for tea, particularly in Kirinyage region using the MaxEnt Species Distribution Model [17], quantitative and economic land suitability has been assessed for tea in Gulian province in Iran using the Square root and the Storie methods [18], and the land suitability assessment was conducted in the Kabarole District of Western Uganda for tea and food crops using a model built in Automated Land Evaluation System (ALES) software by means of decision trees [19]. A comprehensive suitability evaluation was carried out by Bo, Zhang [22] for tea in Southern China using the Geographic Information System (GIS) and modified land ecological suitability evaluation model, providing the scientific basis and reference for the rational distribution of the tea crops, while Gahlod, Binjola [20] carried out an evaluation for tea, cardamom and rubber cultivations in Kerala, making use of environmental and variety of soil physio-chemical parameters. These types of studies provide information on the constraints and opportunities for the use of the land and therefore guide in decision making on optimal utilization of land resources [23].

The present land use pattern in Sri Lanka is a legacy of the land policy of the colonial past, where export-based commercial plantations like tea were superimposed on a traditional subsistence farming system. Today, the tea industry is considered as one of the largest agro-based industries in Sri Lanka and the land suitability assessment will help to achieve maximum sustained production. Until recently, many decisions on land use matters in Sri Lanka were taken on an ad hoc basis, using the local knowledge and intuition of the officers concerned. An inadequate number of studies have been conducted to enable informed decisions on the proper utilization of lands for tea plantation in Sri Lanka, and they have not taken the factors of topography, soil, climate and management into account. The first such attempt was made by Panabokke [24], who identified the main regions for tea and rubber. This gave a general assessment of the land suitability for tea, but no criteria of suitability were given [25]. Jayathilaka, Soni [26] generated crop suitability maps for tea, amalgamating yield maps and climatic factors maps using the Analytic Hierarchy Process (AHP) in multi-criteria analysis under two times frames of 1980–1992 and 1993–2007. The selected study area only covers five agro-ecological zones (AEZs) between the coordinates of 6° and 7°30′N latitude and 79°50′ to 81°E longitude. They only considered climate parameters such as temperature, rainfall, relative humidity and evapotranspiration with yield factors whereas our study addresses climatic as well as topographical and soil parameters in order to study the suitability of land for tea. Land Utilization Committee and Tea Commission of Sri Lanka conducted a comprehensive assessment of the unsuitability of tea plantation lands and the feasibility of rehabilitation and diversification in 1968 considering available data for slope, rockiness, soil depth, drainage, soil erosion, nutrition status, rainfall and temperature. A case study was undertaken to classify and to map the tea-growing areas in Ratnapura District [27], but climatic factors were not taken into consideration for this study.

Also, land use planning for tea by individual site assessment using the traditional method is subjective and a time-consuming procedure [27,28]. Although a few studies have been undertaken [25, 29,30] to map the suitability of lands for tea cultivation, they did not cover the entire tea-growing region of the country. In the given context, no initiative has yet been taken by the Sri Lankan Tea Research Institute to classify land or existing tea-growing areas to varying degrees of suitability.

It is usually difficult to make a detailed and precise analysis because of the inappropriate understanding of evaluation factors and weights in practice [31]. The availability of GIS and Multi-Criteria Decision Analysis (MCDM) methods allows the combination of knowledge from different sources to support land use planning and management [32,33]. The most commonly used MCDM are the AHP, weighted linear combination, ordered weighted averaging, ELECTRE, DEMATEL, PROMETHEE, VIKOR and multiple-objective land allocation [34,35]. 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 [35]. The main drawbacks of the AHP indicated by literature are potential internal inconsistency and the dubious theoretical base of the rigid 1–9 scale, together with the possibility of rank reversal following the introduction of a new alternative [36,37]. Also, the AHP is incapable of finding the interdependence between criteria which does not address the influences and effects that each of them has on other factors. The DEMATEL method is generally used to establish interactive relationships among criteria [38–40]. In addition, this allows to estimate both the importance of criteria and shows the causal relations of factors [41]. This method was originally developed by the Science and Human Affairs Program of the Battelle Memorial Institute of Geneva between 1972 and 1976 [42]. DEMATEL technique has been used in a broad spectrum of fields because of its capacity to handle complex relationships between components of a system [43].

Compared with other MCDMs, the DEMATEL method has many advantages such as it effectively analyzes both direct and indirect effects among different criteria, understands the cause and effect relationships in the decision-making problem, is able to visualize the interrelationships between factors via a causal diagram, and enables the decision maker to clearly understand which factors have mutual influences on one another. The DEMATEL method can be used not only to determine the ranking of alternatives, but also to find out critical evaluation criteria and measure the weights of evaluation criteria [42]. Although the AHP can be implemented to rank alternatives and determine criteria weights, it assumes the criteria are autonomous and their interactions and dependencies are not considered. The DEMATEL technique also has some drawbacks compared to other techniques of MCDMs. It determines the ranking of alternatives based on interdependent interactions between them, but other criteria are not included in the issue of decision-making. It cannot take into account the aspiration level of alternatives or obtain partial ranking orders of alternatives. Therefore, DEMATEL has been incorporated with other MCDM techniques to combine other necessary characteristics in many previous studies [43]. A combined AHP–DEMATEL technique has been used approximately the globe in many land suitability assessments [44–47].

The land suitability assessment for tea is important for identifying the potential areas for maximizing the production and to suggest ameliorating measures for better crop management [20]. The suitability analysis allows recognizing marginal suitable areas which facilitate decision makers to identify limiting factors and enable them to formulate appropriate management decisions (i.e., new planting, replanting, infilling, diversification, and adopting climate-friendly best practices) for increasing the productivity of the land. An exhaustive study needs to be carried out to determine appropriate land use in the unproductive estates giving due consideration to other factors. Also, this allows stakeholders to identify new areas where tea can be planted in accordance with the requirements of the tea crops, emphasizing the qualities of the land unit. Hence, matching crop requirements with available resources through land suitability analysis has become an urgent need to sustain agricultural land productivity in Sri Lanka.

The previous sections show that no comprehensive study has been undertaken in Sri Lanka to look at land suitability for tea cultivation using both physical (soil properties and topography) and climate factors. This shows the need for the rationalization of land use, where the available land should be selected according to the crop requirements and it has become enormously important in making the best use of the land available in Sri Lanka for tea cultivation. Therefore, in this study, an attempt has been made to assess the land suitability for tea in order to ensure the long-term progression in the tea sector towards a sustainable tea production. The geographical information system-based multi-criteria approach was used to identify potential, suitable and unsuitable areas and information about the type of limitation (s) facing the utilization of the land for tea cultivation. The research value and novelty of this study is the simultaneous utilization of the AHP and DEMATEL methods to assess the land suitability for tea crops.

2. Methodology

2.1. Data Sources and General Methodology

2.1.1. Study Area and Climate

The whole of Sri Lanka was considered as the study area. Attention has to be drawn in particular to the effect of rainfall and temperature as they are considered as delimiting and significant factors upon land use in Sri Lanka. The mean monthly temperature range is 25–30 °C in coastal areas and 15–18 °C in the highlands. The Southwest and Northeast monsoons play a major role in annual rainfall in Sri Lanka, which ranges from 900 to 5000 mm per year [48].

Red-yellow podzolic soils (leached lateritic soils) can be found in the Wet Zone and reddish brown earth (nonlateritic loamy soils) is present in the Dry Zone. Reddish brown latosolic soils (partially laterized soils) or immature brown loams (clayey loams) are available in Central Hills. Alluvials occur along the lower courses of rivers and the regosols (sandy soils) occur in the coastal tracts [28].

Guidelines given by Food and Agriculture Organization [5] were used to conduct the land assessment process. Topographic, soil and climatic factors were used to evaluate the suitability of land for tea. Nine criteria were used for land suitability classification for tea crops in Sri Lanka. These were selected based on existing literature and views of local experts. These criteria were basically soil factors (soil type, pH, depth, texture, drainage (permeability)), variables related to topography (slope, elevation and land use) and climatic factors (rainfall and temperature). The existing land use map was used to identify areas with physical limitations for tea cultivation and this allowed us to distinguish potential areas that link ranges and threshold values for other relevant characteristics (i.e., climatic, soil and terrain requirements) to tea crop suitability ratings. The summary of steps used in the land suitability assessment is presented in Figure 1.

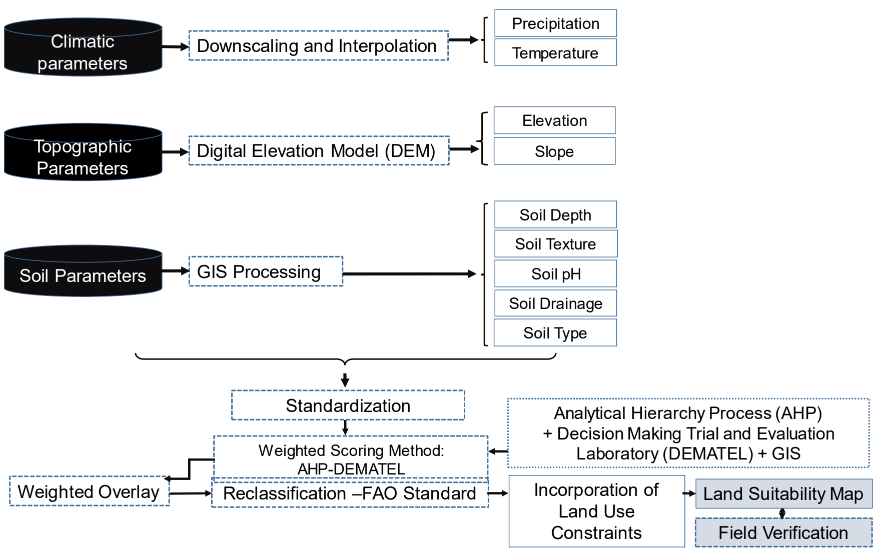

Figure 1. Process for analysis of the suitability of land for tea.

The above set of layers were prepared to assess the suitability of the land for tea cultivation in Sri Lanka. The layers were combined using GIS-based MCDA [32]. This involved five main steps: (1) data acquisition, (2) defining crop requirements for tea in relation to the selected criteria (Table 1), (3) the reclassification of criterion maps using Spatial Analyst Reclassify tool, (4) the weighting of criteria according to importance using the pairwise comparison method using the Analytic Hierarchy Process (AHP) and DEMATEL method, and (5) the standardized criterion maps are combined/aggregated by means of the weighted overlay technique and vector overlay analysis.

2.1.2. Crop Requirements and Classification Procedure

Suitability ratings were established according to FAO [49] classification on the appropriateness of land for defined uses in five different suitability classes defining very highly suitable, highly suitable, moderately suitable, low and unsuitable conditions. Table 1 shows the extent to which a particular factor influences the growth of tea crops directly or indirectly.

The most critical environmental factors for tea are temperature and rainfall as tea growth and productivity are mainly controlled by water availability and temperature [26,50–52]. The tea plant requires a minimum rainfall of 1200 mm per year, but 2500–3000 mm per year is considered optimum [53]. The distribution of rainfall is very important in countries with rain-fed tea production systems, such as Kenya, Sri Lanka and India. Rainfall in Sri Lanka consists of monsoonal, convectional and expressional rainfall. Among them, monsoons play a major role in the share of the annual rainfall [54]. The mean annual rainfall is less than 900 mm in the south-eastern and north-western (driest) parts of the island, and it is over 5000 mm in the western slopes and the central highlands. However, since the distribution of rainfall throughout the year is distinctly bi-modal due to the seasonality of the monsoons, some areas experience a continuous dry period of approximately 2–3 months [55]. In addition, tea-growing areas are expanding rapidly and a large proportion of this expansion is taking place in areas where the main limitation is soil moisture. Hence, the water deficit is and will continue to be a major limiting factor in tea production [56].

The growth of the tea plant is highly affected by temperature ranges. Tea yield is sensitive to increased average monthly temperatures, and sustained periods of higher temperatures reduce tea yield. Tea grows well within an air temperature (Ta) range of approximately 19–23 °C. Air temperatures below 13 °C and above 30 °C have been found to reduce shoot growth [52,57]. Most of the country's central region (i.e., Nuwara Eliya, Badulla, Kandy) has the best temperature for growing tea.

Tea is also grown across a range of elevations, from sea level up to approximately 2200 m above sea level (a.s.m.l). The elevations at which tea grows greatly affects the quality and quantity of tea [53,58]. The difficult climatic conditions found at these extreme altitudes are highly favorable for the development of aromas, as the cold nights and misty peaks slow the growth of the tea plant, resulting in a higher concentration of aromatic oils and richer flavors. The elevation above 2000 m is considered to be moderate areas of suitability, as it involves infrastructure and other practical problems in plucking tea. In addition to that, as the elevation increases above 2000 m, the air gets colder, the soil gets harder and the land gradient makes less rainwater available. These factors inevitably reduce tea crop yield. Low-lying areas ranging from 0 to100 m are considered inappropriate for tea because they flood much more frequently in the rainy seasons [59] and are unfavorable for growth of tea.

The main effect of the slope aspect on surface runoff and erosion is due to differences in the microclimate [60]. Also, Khormali, Ayoubi [60] found that the slope position had a significant impact on soil properties such as soil moisture, clay content, total N, calcium carbonate content and exchangeable Mg. The land with a slope of between 15–25° is considered as very highly suitable class while gentle slope (>5–7°) is regarded as highly suitable for tea. The class of "very steep slope" (more than 35°) is considered as unsuitable for tea. More flatlands and steeper slopes are advisable to be avoided because steeper slopes provide a major risk of soil erosion and landslide while flatlands will increase water-logging conditions, which is undesirable for tea growth [61].

The variety of soil types on which tea is cultivated successfully makes it very difficult to fit the soils into a general classification. This is further complicated by the various descriptive terms and systems used around the world in soil classification. We classified soil into five major classes based on its suitability for tea, according to the literature [28,62]. The Red Yellow Podzolic soils (Ultisol in the U.S. Soil Taxonomy) dominate existing tea lands in Sri Lanka at an altitude of more than 600 a.m.s.l. This soil occurs in a variety of landforms such as undulating, plains, rolling lands, dissected rolling plains, hills with moderately steep slopes, ridge and valley formations, high massive hills, and also steep slopes (i.e., central highlands). Reddish brown latolic soils (partially laterated soils) or immature brown loams (clayey loams) are also suitable for tea growth [28].

Tea is grown in soils that differ from country to country, with soil pH being the most important feature. The pH requirement for the growth of tea is in the range of 4.5–5.5 [20,63]. The optimum soil conditions recommended for tea growth include a well-drained, deep and well-aerated soil with more than 2% organic matter [64]. Other characteristics have to be considered for economic tea production, including field slope, soil gravel percentage in the top 50 cm of the soil layer and rockiness. Soil depths of less than 50 cm, soil gravel of more than 50% in top 50 cm of the soil layer and a rockiness of 20% negatively affect tea growth. Tea plants growing in shallow and compacted soils are likely to suffer from drought and waterlogging during the rainy months [65]. Due to the unavailability of data, organic matter, rockiness and soil gravity were not taken into account in the land suitability assessment.

2.2. Criteria Layers Creation

The vector-formatted world soil data were downloaded from GeoNetwork@fao.org (accessed on 13 November 2018) and then clipped to the Sri Lanka border. Vector files were then converted to raster layers with 30-m cell resolution. Attribute tables were created including pH (5 pH classes), soil type (5 classes where 1 is highly suitable for tea and 5 is not suitable for tea cultivation), texture (1 organic, 2 heavy, 3 medium and 5 light and there is no marginal class, as only 4 classes were available) and depth (5 depth classes).

The 30-m digital elevation data (DEM) were obtained from the global multi-resolution terrain elevation data 2010 (http://lta.cr.usgs.gov/GMTED2010; accessed on 13 November 2018). Slope raster of the study area was derived from the elevation data (both in degrees) using ARC GIS version 10.4.1 [66]. Elevation layer was classified into five classes with regard to the production performance of existing tea cultivation areas, expert advice and previous studies [67]. The slope was also classified into five classes based on tea-growing ability (See Table 1 and Figure 2).

Raster maps for temperature and rainfall were downloaded from WorldClim (1950–2000) (http://www.worldclim.org/; accessed on 13 November 2018). Maps for mean temperature for 12 months were downloaded and annual precipitation was computed. Mean monthly temperature was calculated using the raster calculator and then final maps were clipped and two climate rasters were reclassified according to five classes of suitability as defined in Table 1 and Figure 2.

Land use map 2007 was obtained from the Department of Agriculture, Sri Lanka, and it was used to produce the final land suitability map for tea crops. All raster layers used in this study were projected into the Kandawela Sri Lankan national projection system. All data layers were at 30-m spatial resolution prior to being used in modelling or overlaying to extract statistics.

Table 1. Crop requirements for tea in relation to the selected criteria.

Criteria	Range of Suitability (From Very Highly Suitable (5) to Unsuitable (1))					References
	Very Highly Suitable (5)	**Highly Suitable (4)**	**Moderately Suitable (3)**	**Low Suitability (2)**	**Unsuitable (1)**	[6,68]
Soil Parameters						
Soil depth	50–100	10–50	100–150	>150	<10	[20,63,69]
Soil texture	Loam/Organic	Silt loam/Heavy	Sandy loam/Medium		Clay, sandy/Light	[20,63,69]
Soil pH	4.5–5.5	5.5–7.2	<4.5	7.2–8.5	>8.5	[20,63,69]
Soil drainage	Well drained (28–48)	Moderately well drained (48–58)	Excessively drained (10–28)	Imperfectly drained (58–74) Poorly d rained (74–97)	Water bodies	[63,70]
Soil type	Red-yellow podzolic, Red yellopodzolic soils and mountain regosols, Red-yellopodzolic soil with dark B horizon red yellow podzolic soil	Red-yellow podzolic soils with semi prominent Al horizon, Reddish brown earths and immature brown loams, Reddish Brown Latasolic soils	Red-yellow latosols, red-yellow podzolic soils with soft or hard laterite, red-yellow podzolic soils with strongly mottled subsoil	Immature Brown Loam, Reddish brown earth and low humicgley soils, Reddish Brown Earths and SolodizedSolonetz, Reddish Brown Earths Non-Calcic Brown Soils and low HumicGley soils	Alluvial Soil, Bog and Half-bog soil, Calcic-red yellow Latsols, Erosional remnants, Grumusols, Latosols and Regosols on old red and yellow sands. Non-Calcic Brown soil, Regosols on recent beach and dune sands, Regosols on recent beach sands, Rock knob plains and eroded lands, Solodized on recent marine calcareous sediment, Steep rockland and lithosols	[63]
Climate parameters						
Rainfall (mm)	2500–3000	3000–3500	2000–2500	1500–2000	1000–1500	[26]
Temperature (°C)	19.5–23	23–26.5	16–19.5	26.5–30	30–33, 13.5–16	[26]
Topography parameters						
Slope	≥15–25 (Moderate Slope)	>5–7 (Gentle Slope)	<5 (Very Gentle Slope)	>25–35 (Steep Slope)	>35 (Very steep Slope)	[6,63,71]
Elevation	600–2000 m	300–600 m	2000–2500 m	100–300 m	0–100 m	Own elaboration based on Xin, Youhua [67]

2.3. Determination of Weights

As mentioned in the introduction section, a number of methods exist for the determination of weights for the criteria. In this study, we used the Analytical Hierarchical Process (AHP) and the Decision-Making Trail and Evaluation Laboratory (DEMATEL) methods to calculate the weights. Each of these methods has strengths and weaknesses, and utilizing two methods is expected to give more balanced results.

2.3.1. The Analytic Hierarchy Process (AHP)

Weights were allocated for each criterion using the Analytical Hierarchy Process (AHP) introduced by Saaty [72]. The AHP uses a fundamental measurement of 9 points to express individual preferences or judgments [72] and creates a matrix of pairwise comparisons (Table 2). A value of 1 expresses "equal importance" and a value of 9 is given over another factor for those factors which have "extreme importance" (Table 2).

Table 2. Scale of relative importance according to Saaty [73] (Note: 1 is the highest importance and 9 is the least importance).

Intensity of Importance	Definition	Description
1	Equal importance	Two factors contribute equally to the objective
3	Moderate importance of one factor over another	Experience and judgment favor each other slightly
5	Strong or essential importance	Experience and judgement strongly favor one over the other
7	Very strong importance	Experience and judgement very strongly favor one over the other. Its importance is demonstrated in practice
9	Extreme importance	The evidence favoring one over the other is of the highest possible validity
2,4,6,8	Intermediate values	When Compromise is needed

The weight for each factor was calculated through a pairwise comparison matrix and the maximum eigenvalues (λ_{max}) of normalized matrix were computed. The consistency index (CI) was estimated using the formula: CI= (λ_{max}-n)/(n-1) [73]. The random consistency index (RCI) (Table 3) 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 [74]. Accordingly, weights were assigned relevant to the importance of criteria for tea based on expert ideas and literature [75].

Table 3. Random Consistency Index (RCI).

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RCI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

2.3.2. Decision-Making Trial and Evaluation Laboratory (DEMATEL)

The DEMATEL method was used to deal with the importance and causal relationships among the criteria, and to recognize the influential criteria of the land suitability assessment for tea. In this research, the software of MATLAB and Excel 2013 were used to estimate six major measures in the DEMATEL technique. First, three respondents were asked to assess the direct influence between any two criteria. The measurement criteria of 0, 1, 2, 3, and 4 were used to illustrate no influence, very low influence, low influence, high influence and very high influence, respectively [76]. Secondly, the direct-influence matrix was constructed based upon the degrees of relative impact derived from the pair comparisons Equation (1). An initial direct-influence matrix (A) with the directly observed relations was obtained where a_{ij} denotes the degree of impact of the i factor on the j factor [40]. As the third step, the normalized matrix was obtained from Equations (2) and (3) where all the matrix diagonals are equal to zero and the sum of each row and column does not exceed 1. Then, the full relationship matrix (T) was derived from Equation (4). The significance and relationship indicators were estimated summing each column and row using Equations (5) and (6).

$$A = \begin{bmatrix} a_{11}\cdots & a_{1j}\cdots & a_{1n} \\ \vdots & \vdots & \vdots \\ a_{i1}\cdots & a_{ij}\cdots & a_{in} \\ \vdots & \vdots & \vdots \\ a_{n1}\cdots & a_{nj}\cdots & a_{nn} \end{bmatrix} \tag{1}$$

$$X = s.A \tag{2}$$

$$s = min\left[\frac{1}{max_i \sum_{j=1}^{n} \left| a_{ij} \right|}, \frac{1}{max_i \sum_{i=1}^{n} \left| a_{ij} \right|}\right] \tag{3}$$

$$T = X + X^2 + \ldots X^k = T = X(1-X)^{-1} \tag{4}$$

$$D = \left(\sum_{j=1}^{n} Tij \right) = \left[\ d_i \ \right]_{nX1} \tag{5}$$

$$R = \left(\sum_{i=1}^{n} Tij \right) = \left[\ r_j \ \right]_{1Xn} \tag{6}$$

Here, d_i is the sum of each row in T and the rows show the degrees of direct and indirect impact over the other criteria, and r_j is the sum of each column in T where columns indicate the degrees of influence from the other criteria. Numeric algorithm variable d_i, therefore, represents the factors that influence the others, r_j represents the factors that are influenced by others, $d_i + r_j$ represents the strength of relationships between factors, $d_i - r_j$ represents the strength of influences among factors [43]. Subsequently, a threshold value to ignore the minor effects is necessary to isolate the relationship structure of the factors and finally to obtain causal diagram [77]. The threshold value helps in distinguishing some important and unimportant criteria. Only the values greater than the threshold value were highlighted and selected for illustrating the causal diagram.

2.4. Aggregating Criterion Weights and Standardized Criterion Maps

The land adaptation map for tea was created using the "weighted overlay" spatial analysis tool in Arc GIS by assigning a given weight to each criterion. Each raster was assigned a percentage influence depending on its importance as defined by the average weights of the AHP–DEMATEL analysis (Table 10). The weight is a relative percentage, and the sum of the percentage influence weights must add up to 100. 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 Equation (7);

$$S_i = \sum X_i \times W_i \tag{7}$$

where, X_i = values of each criterion, W_i = weight values of each criterion, and S_i = suitability index

As the final step, the constraint criteria were taken into account. The existing land use map of Sri Lanka was used to assess the condition of restrictions on land use for tea growing. The evaluation of land use classes was based on factors affecting the cultivation of tea. Therefore, the existing land use classes were classified in which "1" was for possible appropriate land use classes for tea such as existing tea-growing areas, crop lands, etc., and "0" was where tea could not be grown (i.e., urban, rock, bare lands, open water, wet lands, paddy, roads, etc.). A raster map was then developed. The newly developed land use restriction map was overlaid with the rasterized suitability map.

2.5. Validation of the Results

The validation method used here concerned whether the selected crop had already been produced or grown in the region and a subjective comparison was made [65]. The final suitability map produced from the model was verified to ensure that the model corresponded to the actual conditions in the field. Existing tea-growing areas were extracted from the land use map of Sri Lanka. Using the "geometry intersection" tool in Arc GIS software, each suitability class was intersected with the layer of existing tea-growing area. We calculated the percentage of existing tea-growing areas that were intersected with each of the modelled suitability classes. If a high percentage of modelled "very highly suitable" and "highly suitable" areas fell within the actual tea-growing areas, we assumed that our results were more valid.

3. Results

3.1. Results of the Multi-Criteria Analysis-AHP

The criteria were weighted and scored in terms of their importance for tea cultivation in the preparation of the model. Tables 4 and 5 show the comparison matrix and the calculated weights of the criteria. The overall consistency ratio (CR) of 0.09 was below the 0.10 ratio, suggesting that the judgement had a reasonable level of consistency.

Table 4. Matrix comparing the relative importance of land use requirements for tea cultivation.

Criteria	Temperature	Rainfall	Elevation	Soil Type	Slope	pH	Drainage	Depth	Texture
Temperature	1	$\frac{1}{2}$	2	3	3	5	7	7	7
Rainfall		1	2	3	3	5	7	7	7
Elevation			1	3	3	5	7	7	7
Soil Type				1	3	3	5	5	5
Slope					1	3	5	5	5
pH						1	3	3	3
Drainage							1	3	3
Depth								1	3
Texture									1
Sum	4.9	3.2	6.3	11.3	13.9	23	35.5	38.3	41

(The numbers show the rating of the row factors relative to the column factor). Note: for example, rainfall is more important for tea cultivation than soil texture. (If the soil texture is "a," then the rainfall value can be given as "7a" and the raw value is "7").

Table 5. Analytical Hierarchical Process (AHP) analysis for the assessment of the relative importance of climate, soil and topography parameters; normalized matrix with results.

Criteria	Temperature	Rainfall	Elevation	Soil Type	Slope	pH	Drainage	Depth	Texture	Total	Priority Vector	Influence %
Temperature	0.20	0.16	0.32	0.27	0.22	0.22	0.20	0.18	0.17	1.93	0.21	21.4
Rainfall	0.41	0.32	0.32	0.27	0.22	0.22	0.20	0.18	0.17	2.29	0.25	25.4
Elevation	0.10	0.16	0.16	0.27	0.22	0.22	0.20	0.18	0.17	1.67	0.19	18.5
Soil Type	0.07	0.11	0.05	0.09	0.22	0.13	0.14	0.13	0.12	1.05	0.12	11.7
Slope	0.07	0.06	0.05	0.03	0.07	0.13	0.14	0.13	0.12	0.81	0.09	9.0
pH	0.07	0.06	0.03	0.03	0.02	0.04	0.08	0.08	0.07	0.50	0.06	5.5
Drainage	0.03	0.05	0.02	0.02	0.01	0.01	0.03	0.08	0.07	0.32	0.04	3.6
Depth	0.03	0.05	0.02	0.02	0.01	0.01	0.01	0.03	0.07	0.25	0.03	2.8
Texture	0.03	0.05	0.02	0.02	0.01	0.01	0.01	0.01	0.02	0.18	0.02	2.0

Eigenvalue (λ_{max}) = 10.0, Consistency Index (CI) = 0.13, Consistency Ratio (CR) = 0.09.

3.2. Results of the Multi-Criteria Analysis-DEMATEL

Table 6 presents the ratings assigned to individual pairs of criteria based on the expert participatory method. Then, the normalized direct influence matrix (X) was calculated according to Equation (4) (Table 7) and the matrix of total relations (T) is given in Table 8. DEMATEL has the ability to complete the matrix by obtaining direct and indirect relations from each pair of alternatives. With reference to Table 9, values in the (d_i + r_j) column show the total effect of each main factor on the whole system. Correspondingly, rainfall acquires high influence compared to other criteria. Similarly, values in the (d_i − r_j) column, divide all criteria into cause and effect groups based on their values. The (d_i + r_j) values of all criteria are greater than the threshold value, indicating the importance of these criteria to use in the land suitability assessment process for tea.

Table 6. The initial direct influence matrix (A).

Criteria	Temperature	Rainfall	Elevation	Soil Type	Slope	pH	Drainage	Depth	Texture
Temperature	0	4	3.33	2.33	0	1	0.33	1	0.67
Rainfall	3.67	0	2.67	2.33	1.67	2	2.67	0	0
Elevation	3	2.33	0	2.33	2.33	0.67	0.67	0.33	0.33
Soil Type	0	0	0	0	0	3.33	2.67	2.33	2.67
Slope	0.33	1	3.67	0.67	0	1	1.67	1.33	0.33
pH	1	1.33	1	3.33	0.67	0	1	0.33	1
Drainage	0	0.67	1	2.33	1.33	1	0	1.67	1.33
Depth	0	0	0	2.67	0.33	1.33	2	0	2
Texture	0	0	0	2.33	0	1.67	2.337	2	0

Table 7. The normalized direct influence matrix (X).

Criteria	Temperature	Rainfall	Elevation	Soil Type	Slope	pH	Drainage	Depth	Texture
Temperature	0.00	0.23	0.19	0.13	0.00	0.06	0.02	0.06	0.04
Rainfall	0.21	0.00	0.15	0.13	0.10	0.12	0.15	0.00	0.00
Elevation	0.17	0.13	0.00	0.13	0.13	0.04	0.04	0.02	0.02
Soil Type	0.00	0.00	0.00	0.00	0.00	0.19	0.15	0.13	0.15
Slope	0.02	0.06	0.21	0.04	0.00	0.06	0.10	0.08	0.02
pH	0.06	0.08	0.06	0.19	0.04	0.00	0.06	0.02	0.06
Drainage	0.00	0.04	0.06	0.13	0.08	0.06	0.00	0.10	0.08
Depth	0.00	0.00	0.00	0.15	0.02	0.08	0.12	0.00	0.12
Texture	0.00	0.00	0.00	0.13	0.00	0.10	0.13	0.12	0.00

Table 8. The matrix of total relations (T) and direct–indirect matrix.

Criteria	Temperature	Rainfall	Elevation	Soil Type	Slope	pH	Drainage	Depth	Texture
Temperature	1.38	0.38	0.35	0.36	0.18	0.40	0.26	0.20	0.24
Rainfall	0.40	1.53	0.34	0.31	0.21	0.38	0.46	0.28	0.31
Elevation	0.36	0.23	1.00	0.23	0.21	0.32	0.36	0.30	0.32
Soil Type	0.20	0.22	0.12	0.23	0.11	0.46	0.45	0.78	0.45
Slope	0.10	0.15	0.14	0.16	1.47	0.36	0.13	0.11	0.12
pH	0.18	0.22	0.19	0.40	0.11	0.14	0.15	0.17	0.23
Drainage	0.15	0.34	0.19	0.27	0.09	0.17	0.13	0.17	0.17
Depth	0.11	0.13	0.17	0.37	0.08	0.21	0.13	0.05	0.17
Texture	0.14	0.13	0.14	0.10	0.11	0.11	0.36	0.12	0.11

Table 9. The values of significance and relationship indicators for criteria and their weights.

Criteria	Sum Successive Rows of Di Matrix	Sum of Each Column of the r_j Matrix	Significance Indicator ($d_i + r_j$)	Relationship Indicator ($d_i - r_j$)	Average Rates	Scales
Temperature	3.752	3.008	6.760	0.745	3.752	0.161
Rainfall	4.216	3.325	7.541	0.891	4.216	0.181
Elevation	3.347	2.632	5.979	0.716	3.347	0.144
Soil Type	3.020	2.421	5.441	0.599	3.020	0.130
Slope	2.736	2.570	5.306	0.166	2.736	0.118
pH	1.792	2.547	4.339	−0.755	1.792	0.077
Drainage	1.676	2.436	4.111	−0.760	1.676	0.072
Depth	1.420	2.181	3.601	−0.761	1.420	0.061
Texture	1.313	2.121	3.434	−0.808	1.313	0.056
Threshold value = 0.287					∑ = 23.272	1.00

In Figure 2, the criterion of rainfall has the highest significance indicator value followed by temperature, elevation and slope, indicating that these are the most important criteria for the land suitability assessment for tea in Sri Lanka. The lowest position indicator value is attained by depth and texture. Further, the relationship indicator allows to set a degree of influence of the analyzed parameters on other parameters. In Figure 2, rainfall has the greatest positive value of relationship indicator, which means that it has a dominating, causal influence on the other criteria. The value of d_i-r_j segregated the flexibilities into two groups: cause group and effect group. According to the relationship indicators (Figure 2 and Table 9), rainfall, temperature, elevation and slope belong to the cause group, and have a significant influence over the criteria of pH, soil type, drainage, depth and texture.

The final criteria weights were achieved by calculating each criterion's average weight in both techniques as shown in Table 10 and applied in the land-use suitability for tea crops. Rainfall (21.6%) followed by temperature (18.56%) and elevation (16.69%) highly contributed to the land suitability evaluation than other criteria. The least impact on the evaluation of land suitability for tea was the texture, accounting for 3.8%.

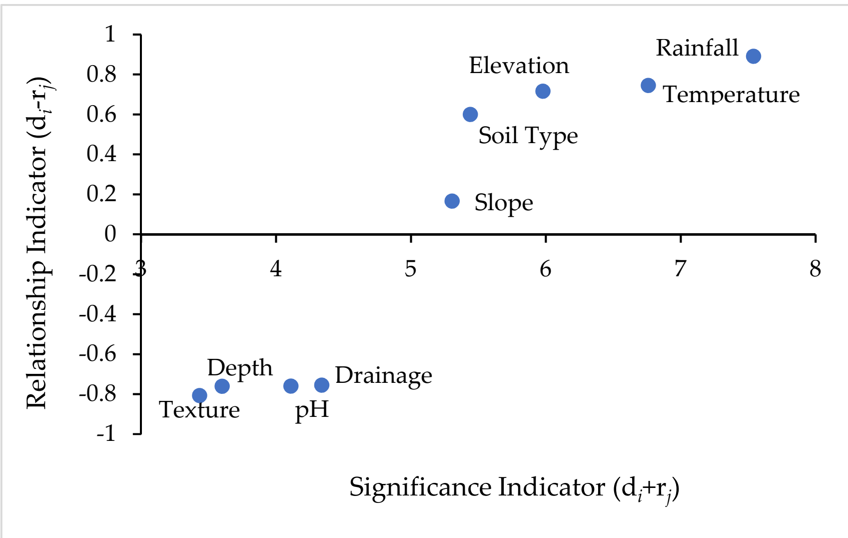

Figure 2. Causal diagram for nine criteria used for the land suitability assessment for tea.

Table 10. The final weights for criteria combining the AHP and Decision-Making Trail and Evaluation Laboratory (DEMATEL) model for the land suitability assessment for tea.

Criteria	AHP	DEMATEL	Average Weights of AHP–DEMATEL	Influence %	Rank
Temperature	0.21	0.16	0.19	18.56	2
Rainfall	0.25	0.18	0.22	21.56	1
Elevation	0.19	0.14	0.17	16.69	3
Soil Type	0.12	0.13	0.12	12.49	4
Slope	0.09	0.12	0.10	10.38	5
pH	0.06	0.08	0.07	6.85	6
Drainage	0.04	0.07	0.06	5.60	7
Depth	0.03	0.06	0.05	4.55	8
Texture	0.02	0.06	0.04	3.82	9

3.3. The Land-Use Suitability with Respect to Selected Criteria

All criteria maps were standardized (reclassified) into five classes (very highly suitable, highly suitable, moderately suitable, low suitability and unsuitable). Figure 3 shows the standardized criteria maps for tea suitability. Each of the criteria was separately analyzed for their suitability for supporting tea crops based on its requirements. Most of Sri Lanka's northern, northwestern, north central, and eastern parts do not have suitable rainfall, temperature, and elevation requirements for tea cultivation (Figure 3). Figure 3 shows that, with the exception of the northern parts of the country, many Sri Lankan regions have at least a moderate slope category for tea production. The soil maps of pH, drainage, depth and texture illustrate varying degrees of suitability to grow tea. Overall, soil properties in many parts of Sri Lanka are suitable for tea cultivation.

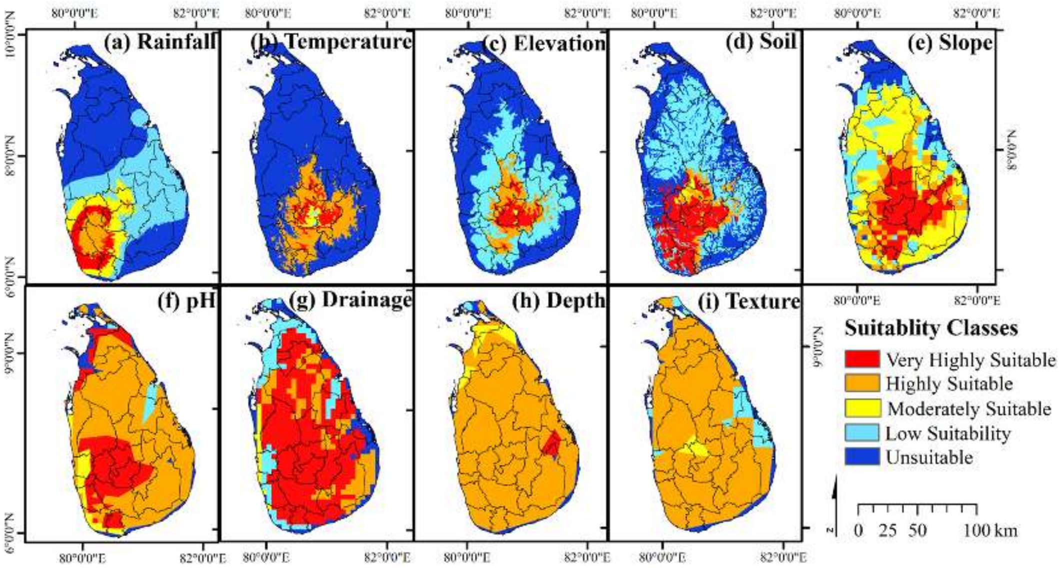

Figure 3. Criteria distribution maps of the study area climatic factors (rainfall (**a**) and temperature (**b**)), elevation (**c**), soil types (**d**), slope (**e**), and other soil characteristics (pH (**f**), drainage (**g**), depth (**h**) and texture (**i**)).

3.4. Overall Land Suitability for Tea in Sri Lanka

Figure 4 shows the map of derived suitability classes of the land for tea cultivation in Sri Lanka and Table 11 shows the potential land area in each suitability class. The land consists of very highly suitable, highly suitable, moderately suitable, low suitable and unsuitable areas as described in Table 2. Nuwara Eliya, Ratnapura, Matara, Galle, Matale, Kandy, Badulla, Kegalle and Kalutara districts show "very highly suitable" or "highly suitable" classes for tea cultivation.

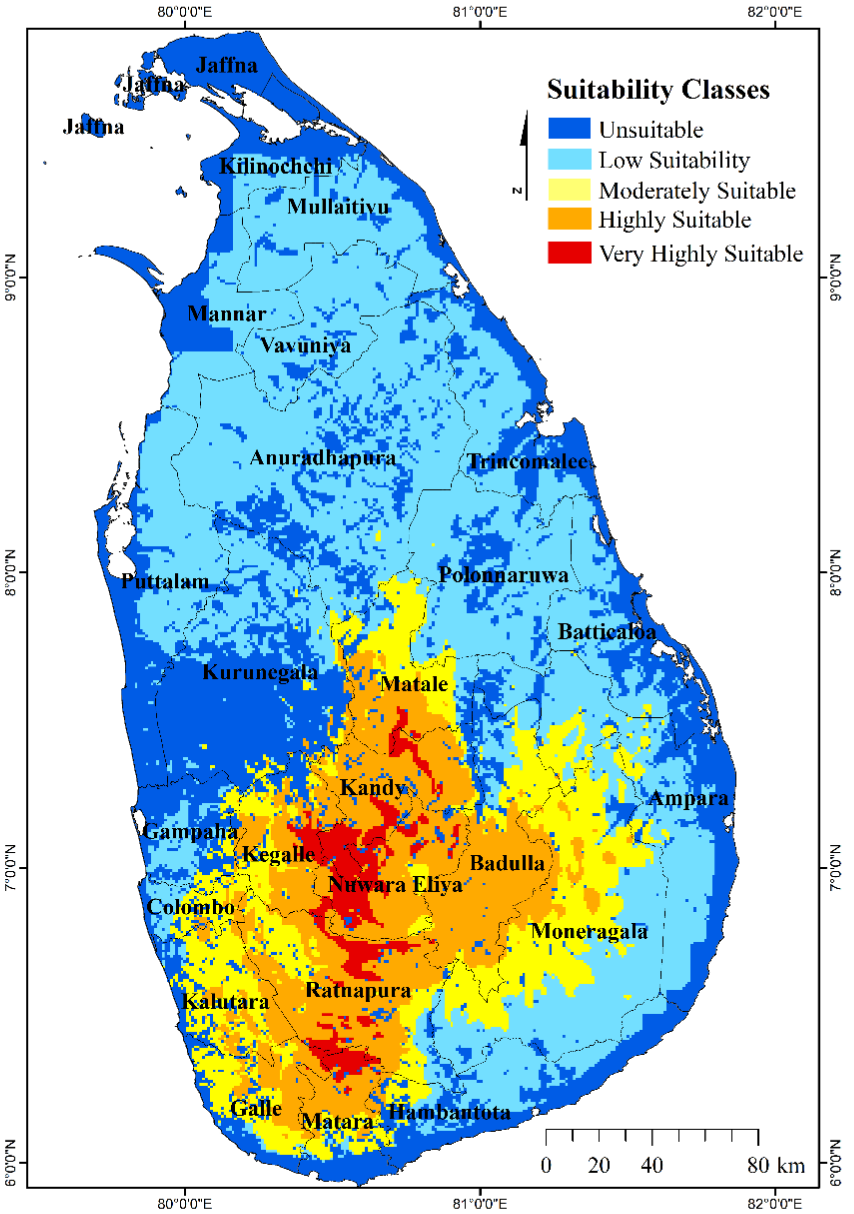

Figure 4. Land suitability classes for tea in Sri Lanka.

Table 11. Potential land area in each suitability class.

Suitability Classes	Total Area (km^2)	Percentage (%)
Unsuitable	18,695	28.5
Low suitability	27,581	42.1
Moderately suitable	8137	12.4
Highly suitable	9498	14.5
Very highly suitable	1627	2.5

The degree of potential land suitability for tea cultivation varies between districts in Sri Lanka (Figure 5). It clearly shows that the existing tea-growing districts are ideal for tea. Among the areas under the very highly suitable category, 29.5% belong to Nuwara-Eliya, 26.2% to Kandy and 21.7% to Ratnapura District. The districts of Ratnapura (52.2%), Kandy (51.4%), Badullla (56.2%), Kegalle (43.1%), NuwaraEliya (48.7%), Matara (38.9%), Matale (32.5%) and Kalutara (25.2%) are clearly classified in the "highly suitable" land category (Figure 5). The highest area under "moderately suitable" is recorded in the Kalutara District, which is approximately 52.0%, followed by Colombo (43.8%), Galle (42.9%) and Moneragala (42.4%). The district of Jaffna (94.9%), Kurunegala (74.1%) and Kilinochchi (70.4%) were dominated by "unsuitable" areas for tea compared to other districts. There are no low suitable areas in the Nuwara Eliya District.

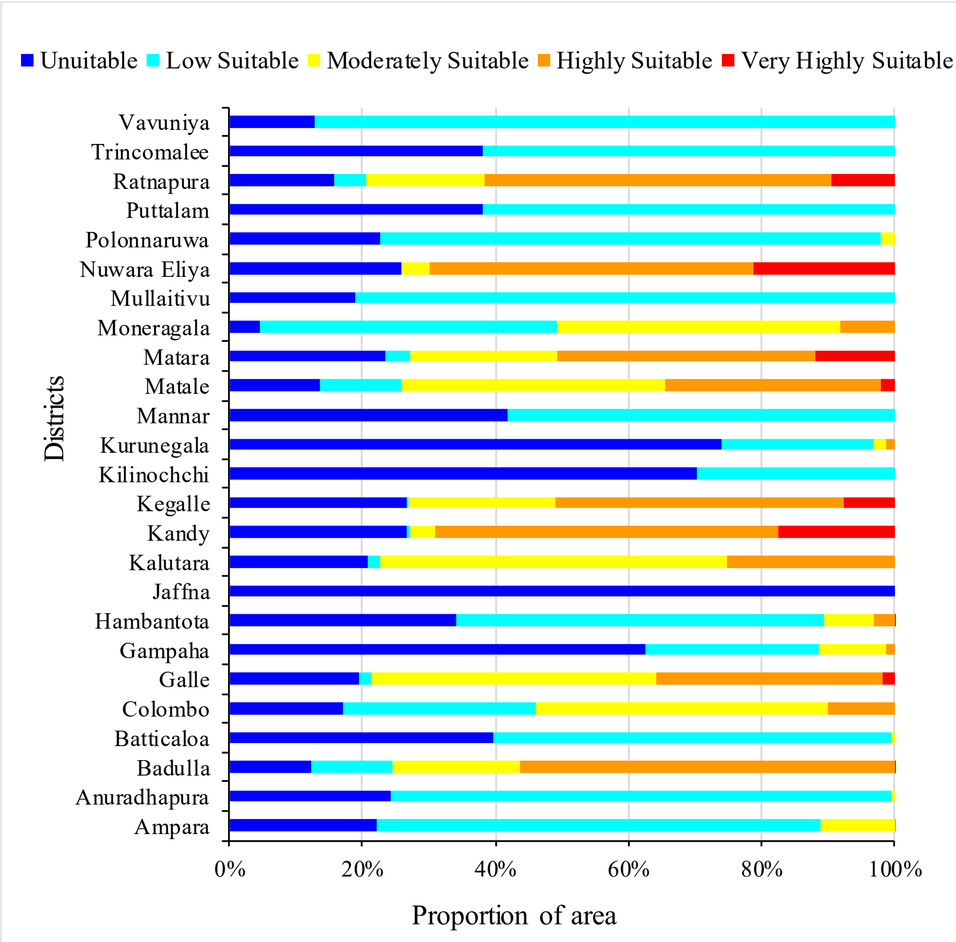

Figure 5. Land suitability assessment according to district basis.

3.5. Measures of Model Performance

The coordinates of modelled very highly and highly suitable areas were within the range of the coordinates of existing tea-growing areas (Figure 6). The latitudes of existing tea cultivation areas range from 5.9991 to 7.59550, where the coordinates of modelled highly tea-growing areas ranged from 6.2473 to 7.4508. This showed that most of the existing tea-growing areas range from 80.0489 to 81.3026, where the longitude of the modelled very highly and highly suitable area ranged from 80.4531 to 80.9239 (Figure 6).

Most of the modelled "highly suitable" class aligns with existing tea-growing areas, accounting for 62.45%, while the "very highly suitable" class accounts for 30.01% of existing tea cultivation (Figure 6 and Table 12). The moderately suitable class accounts for 7.10% of existing tea lands, while the lowest percentage of existing tea land classified as "low suitability" was 0.36% (Figure 6 and Table 12). Further, 0.08% of the current tea-growing areas were modelled as unsuitable areas.

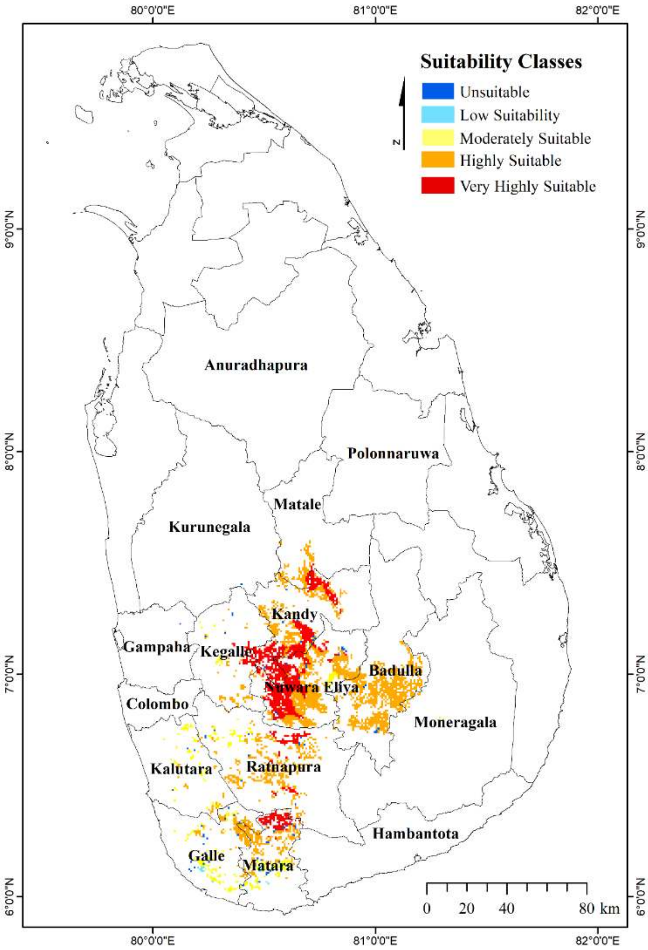

Figure 6. Coordinates of highly suitable modelled areas and existing tea cultivation areas.

Table 12. The percentage of existing tea-growing areas intersected with each of the modelled suitability classes.

Suitability Classes	Modelled Area under Existing Tea Land Cover (km^2)	Percentage (%)
Unsuitable	1.84	0.08
Low suitability	8.3	0.36
Moderately suitable	163.4	7.10
Highly suitable	1437.28	62.45
Very highly suitable	690.56	30.01

4. Discussion

Selecting the most rational algorithm for assessing the land suitability is crucial for current and future land use planning for tea cultivation. A key step in the land suitability assessment for crop production is to determine the weight of each factor affecting the land suitability [77]. The presence of different and multiple criteria complicates the assessment of land suitability because factors affecting land suitability are of unequal significance [78]. The AHP and DEMATEL methods have been widely reported in literature [40,43,46,79,80]. In this study we used an integrated multiple criteria decision-making (MCDM) technique that combines the AHP and DEMATEL. Our decision to integrate the DEMATEL approach with the AHP was because one of the weaknesses of the AHP is the fact that it does not allow for evaluating interrelations and influences between the elements that compose the decision-making process. Application of the DEMATEL method allows not only the description of the structure and interrelationships between the criteria, but also allowed us to identify the key criteria influencing tea with regard to land suitability [43]. Further, the results of the AHP are often taken into consideration when making short-term decisions. The DEMATEL technique, on the other hand, evaluates both the importance of criteria and shows the causal diagram which could assist in enhancing the long-term impacts of choices. The integration of the AHP and DEMATEL techniques thus offers the decision maker comprehension to enhance efficiency from either short-term or long-term points of view [79]. The integrated approach of GIS and the AHP–DEMATEL technique in this study has great potential to classify the land suitability of tea plantations. No previous studies have been conducted in Sri Lanka and the holistic approach of GIS and the AHP–DEMATEL technique are hence used for the first time to determine the suitability of tea lands. This study represents the efficacy of the AHP and weighted overlay model for the land suitability analysis of tea resulting in a CR value less than 0.1 (Table 5). The paired comparison matrix used in this study therefore appears to have sufficient internal consistency to be considered acceptable. Furthermore, the DEMATEL technique confirmed the importance of the criteria chosen from the AHP analysis to use in the tea suitability assessment process.

The soil, topography and climate factors are critical and necessary for successful tea cultivation [27]. All criteria which are considered as relevant for a land suitability decision are compared against each other in a pair-wise comparison matrix which is a measure to express the relative preference among the factors (Table 10). On the basis of the results, the total suitability of rainfall and temperature were given a high average weight in the AHP–DEMATEL technique compared to the total suitability of the other topographic and soil factors since these variables were the most restrictive factors for the assessment of land suitability for tea [26,48,52]. The climate is the most important factor that determines the land suitability of tea [26,81]. Rainfall in fact influences all other meteorological elements, including temperature, and the present agricultural land use of Sri Lanka already underlines the effects of rainfall upon land use [4,51]. Therefore, in matrix comparison AHP and DEMATEL, rainfall is considered as equally or moderately important than temperature (Tables 4, 9 and 10).

The actual spatial variation of crop cultivation is often modified by different types of soil with varying physical, chemical and biological properties and thus determining the land suitability for tea [81]. In the analysis of the land suitability for tea, slope is another key determinant [60] which is given high priority compared to other soil characteristics (Table 10). The lack of reliable country-specific soil data can significantly hamper interventions to assess land suitability. There is no clear and detailed coverage of point-based soil profile data in Sri Lanka. Since there are no country-specific data available at the desirable scale, data were extracted from the Harmonized World Soil Database which is readily available on FAO soils portal (Figure 3). Land suitability mapping can only be used as a first step in spatial planning, since the actual suitability can only be assessed on the basis of a detailed investigation [82].

Despite some of the above limitations, the majority of existing tea-growing areas is classified into "very highly suitable" and "highly suitable" classes in the modelling, implying that the results are robust (Figure 4). Therefore, our assessment of land suitability is considered to be sufficiently accurate as it aligns with the current tea-growing regions. In line with the results of previous research conducted by others [26,27,81], this study shows that tea-growing areas are clustered in the central hills and SW quarter of Sri Lanka. Apparently the most suitable land masses for tea are clustered in Nuwara Eliya, Ratnapura, Matara, Galle, Matale, Kandy, Badulla, Kegalle and Kalutara districts. Soil types in these regions are mainly red yellow Podzolic which are suitable for the cultivation of tea crops, and soil textures are mainly sandy loam and loamy sand. If the environment is relatively stable and no natural disasters occur, these regions typically show a high yield of tea crops. Therefore, this type of region should be protected as a key tea ecological protection region and the suitability classes for tea will pave the way in determining policies for the optimal utilization of land in a sustainable manner for the future.

The analysis showed that the largest part of the land is occupied by a low suitability class, with 27,581 km^2 (42.1%), and an area of 18,695 km^2 (28.5%) has unsuitable land cover. An area of 8137 km^2 was moderately suitable and an area of 9498 km^2 was highly suitable for tea cultivation. The area of land that is very highly suitable for tea cultivation was 1627 km^2 (Table 11). The highest proportion of "very highly suitable" areas in the Nuwara Eliya District, which is approximately 25 percent, indicates that climate, topographic and soil factors are desirable for tea cultivation in the Nuwara Eliya District. An area of approximately 477.5 km^2 (29.5%) of the very highly suitable class was recorded in the Kandy District, while Matara (465.1 km^2), Galle (508.1 km^2), Kegalle (820.6 km^2) and Ratnapura (1935.9 km^2) districts were also recorded as highly suitable tea-growing areas.

The coastal belt and the northern, western, eastern and north central regions are not suitable for tea cultivation (Figure 4). It is known, for example, that considerable stretches of the coastal belt in the south western part of Sri Lanka (Galle, Matara, Kalutara and Colombo etc.) are partially or totally unsuitable for tea, not because of the climate, but mainly due to the poor soil types, namely grumosols, sandy regosols, non-calcic brown soils, etc. On the other hand, it is apparent that under suitable soil conditions, it is the climate and its temporal and spatial variations that delimit the possibilities and potential of agriculture in Sri Lanka [81]. Although tea is not currently grown in some areas, they are found to be of moderate or low suitability (Figures 4 and 5). This implies the possibility for future tea cultivation in these potential areas. In the Ampara, Moneragala and Kurunegala districts, for instance, there are moderately suitable areas where the cultivation can be expanded, despite the fact that they are not currently very renowned for tea cultivation.

A very small proportion of very highly suitable areas is reported in the Badulla district, which accounts for only 0.16%, although it is one of the major tea-growing areas in Sri Lanka [11]. It can possibly be due to changing climatic conditions and other physical, chemical and soil-related biological limitations. The Kurunegala, Kegalle and Moneragala districts are known to contribute to tea production in Sri Lanka. The present study also shows that the Kurunegala, Kalutara, and Moneragala districts have "highly suitable" tea-growing areas, resulting in 1.35, 7.79, and 8.23% respectively.

Jaffna District is totally unsuitable for growing tea. The Kilinochchi District is also highly unsuitable for tea cultivation. Moreover, most other parts of Sri Lanka, such as the northern, central, north-western and eastern parts are shown as likely to be unsuitable as the topographical, climatic and soil factors are not favorable for tea cultivation, resulting in a higher proportion of "unsuitable" or "low suitable" categories (Figure 5).

For Sri Lanka, in particular, climatic indices such as the ratio between rainfall and evaporation seems to be of great practical use for delimiting the potential growing areas of the tea plant. With regard to water balance, the potential tea-growing areas are limited roughly to the south-west quarter of Sri Lanka, including the Central Highlands [81]. Interestingly, some parts of the Nuwara Eliya District are also unsuitable for tea production, as some lands are located on a much higher elevation, where the favorable environment for tea growth is limited. In particular, the upper limit of the highlands represents the boundaries of a warmth deficit as a result of temperature reduction with a higher altitude above sea level [83]. This temperature deficit can have a severe impact on tea bushes by accelerating frost damage. Many parts of the highly grown tea fields (>1900 m) are heavily affected by "frost burning" and this may result in some areas of Nuwara Eliya being unsuitable for tea cultivation. Taking into account the specific slope requirements of the tea plants, the slope is highly correlated with sunshine hours.

According to the Tea Research Institute of Sri Lanka, the current main tea-growing areas are Nuwara Eliya, Ratnapura, Matara, and Kalawana [84,85], while the Galle and Kalutara districts and some parts of the Ratnapura, Kandy, and Matale districts are partly contributing to tea production [85]. The results were verified by comparing the modelled suitability sites with the existing tea cultivation locations (Figure 6 and Table 12). If the majority of suitability classes exist in a region, it reflects the results in a logical and acceptable way, and then the findings become more viable [78]. Correspondingly, the results of this study show that the existing tea-growing areas represent a higher percentage of "very highly" and "highly" suitable modelled classes, implying that our modelling was robust and the weightings that were used were appropriate. The high overlay in the very high and highly suitable class (92.46%) with existing tea-growing areas validates selection procedures of farmers and planters but also shows that the methodology used here is valid.

This study's findings provide insights into recognizing those areas that are irreplaceable in terms of existing and future production and can therefore be used as a focus for more detailed planning. It is important for the tea sector to identify very highly and/or highly suitable land areas for tea as these areas can be used to further expand tea cultivation and to prevent it from being allocated for other non-agricultural purposes. An area of 685.8 km^2 under the very highly suitable category is recorded in Ratnapura, Nuwara Eliya, Kegalle, and Matara districts that can potentially be brought into tea production in the future, while an area of 7261.7 km^2 is also registered as a highly suitable area in the Moneragala, Kalutara and Matale districts and the other major existing tea-growing regions. In addition, the highly suitable potential lands can also be focused on for more detailed planning to help ensure sustainable tea production. Appropriate measures and resources should be properly placed in moderately suitable areas to maximize the land use for tea cultivation. This study allows the easy identification of low suitability and unsuitable tea lands, providing a sound impetus to utilize these lands for other management and development activities (i.e., construction, urban planning, ecosystem conservation, and agricultural purposes).

Furthermore, it is strategically important to understand the prevailing reality of the land suitability classes to tackle the socio-economic as well as environmental consequences of existing tea-based land use systems [86]. The information provided in the maps (Figures 4 and 5) can be used to identify more productive regions and tea lands for replanting, crop diversification, forestry and urban amenities, etc. Growers can also improve the suitability of available lands for tea crops by adopting appropriate agronomy measures relevant to the limitations indicated. A more detailed analysis for tea still requires more data, for example in terms of soil chemical properties and socio-economic factors. This study has provided information not only to the tea plantation sector and tea small holding sector, but also to the other investors planning for tea tourism. This helps stakeholders to easily identify the suitable blocks for tea cultivation and also the limiting factors, if any.

5. Conclusions

The analysis of land suitability for tea is important information for the development and future planning of the tea sector in Sri Lanka. This research used GIS processing and analysis in conjunction with the AHP–DEMATEL technique to assess land suitability for tea production. This is the first study that used climatic as well as topographic and soil factors in modelling land suitability for tea cultivation in Sri Lanka. The spatial land suitability for tea crops was obtained after analyzing selected evaluation criteria such as soil characteristics, topographic and climatic factors. As per the land characteristics and crop requirements, the potential areas for tea crops fall into very highly suitable (2.5%), highly suitable (14.5%), moderately suitable (12.4%), low suitability (42.1%) and unsuitable (28.5%) classes. The model validation results showed that 92.46% of the combined "highly suitable" and "very highly suitable" modelled classes are actual current tea-growing areas, showing the overall robustness of this model and the weightings applied. The land suitability assessment that was utilized in this study provides a useful decision-making approach to help tea growers and decision makers to carry out suitability assessment for tea crops. It should be noted that socio-economic and cultural factors that enable policy makers to make better decisions must be taken into account in making final decisions.

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