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From Biophysical Suitability to Planning-Relevant Rubber Land Evaluation in Hilly Central Vietnam: Evidence from Current Land Use and Fresh Latex Yield

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Abstract

This study evaluated the planning relevance of biophysical land suitability for rubber plantation in a hilly landscape of Central Vietnam. A GIS-based square-root parametric method calculated a land suitability index (LSI) using elevation, slope, annual rainfall, soil depth, soil texture, and soil type. LSI values ranged from 0 to 77.67. Highly and moderately suitable land covered 38.79 ha (0.31%) and 3986.01 ha (31.83%), respectively, with soil depth and texture as important constraints. Overlay with the 2023 land-use map showed that biophysical suitability did not directly indicate practical land availability. Planted forest occupied 38.16 ha, or 98.38%, of the highly suitable class, and no existing rubber plantations occurred in this class. In contrast, 49.27% of existing rubber plantations occurred in the moderately suitable class. After excluding planted forest, paddy rice land, and existing rubber plantations from the 4024.80 ha classified as highly or moderately suitable, only 251.46 ha remained in unused land and annual cropland for further assessment. Data from 45 PB260 plantations showed a positive association between LSI and fresh latex yield after adjustment for the other variables in the multiple regression model, with an adjusted partial regression coefficient of 2.09 kg ha^{-1} year^{-1} per LSI unit (p = 0.016). Thus, suitability maps should not be used as expansion maps without considering current land use, practical land availability, and plantation performance.

Keywords: land suitability evaluation; square-root parametric method; spatial correspondence; rubber plantation; fresh latex yield

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1. Introduction

Land evaluation supports agricultural land-use planning by systematically matching land characteristics with the ecological requirements of specific crops. Its importance is particularly evident in hilly and mountainous regions, where variations in slope, elevation,

soil properties, and microclimatic conditions may strongly influence crop productivity and long-term sustainability. GIS-based approaches have been widely applied to support spatial evaluation and land-use decision making across agricultural and urban contexts [1,2]. In agricultural land evaluation, these approaches can help identify appropriate land-use options, assess potential inconsistencies between land capability and current land use, and support more sustainable land management [2–4]. In land-use planning, suitability maps should be used as decision-support tools rather than as direct recommendations for land allocation. Biophysically suitable areas may not be legally, socially, or economically available for conversion [5].

Many methods have been applied in agricultural land suitability evaluation. The main methods include qualitative classification, multi-criteria decision analysis, fuzzy logic, and parametric methods. Among these approaches, parametric methods convert land characteristics into numerical ratings and integrate them into a single suitability index. The square-root form retains the influence of the most limiting factor while reducing the excessive cumulative effect that may result from direct multiplication [6–8]. Recent empirical studies have also demonstrated the practical application of the square-root method. Azadi et al. (2023) reported R^2 values of 0.62, 0.64, and 0.76 between observed sugarcane yield and the Storie, square-root, and TOPSIS suitability indices, respectively [9]. Kohani et al. (2024) compared the Storie and square-root parametric methods in land-suitability evaluation [10]. This approach is particularly useful when crop requirements can be expressed through measurable environmental thresholds.

Rubber (*Hevea brasiliensis*) is an important commercial perennial crop in tropical Asia. It has played an important role in agricultural commercialization, rural livelihoods, and land-use change across Southeast Asia. In recent decades, rubber plantations have expanded rapidly and become one of the major perennial land-use types in countries such as China, Laos, Cambodia, Thailand, and Vietnam [11,12]. This expansion reflects the high economic value of rubber, but it also raises concerns about natural suitability and sustainability in rubber-growing areas. Some studies have shown that rubber plantations have expanded into areas affected by significant biophysical limitations. For example, Ahrends et al. (2015) [12] estimated that a significant part of rubber expansion in Southeast Asia has taken place in areas affected by limiting factors such as water shortage, erosion, frost, or wind damage. These factors can threaten long-term productivity and livelihood stability. In addition, in some regions, large-scale and unplanned rubber planting can cause serious ecological impacts, including biodiversity loss, forest conversion, changes in ecosystem functions, and lower environmental sustainability [13]. These concerns highlight the need to assess whether existing rubber plantations are spatially consistent with the biophysical suitability of the land. However, land suitability alone does not mean that an area can or should be converted to rubber plantations. In hilly areas, current land use and local management conditions can strongly influence whether biophysically suitable land can actually be used for rubber plantation planning [14].

In Vietnam, rubber has been promoted in many midland, hilly, and mountainous areas as a perennial crop for economic development [15,16]. However, rubber plantation development has not always been accompanied by systematic evaluation of physical land suitability, despite the strong influence of topographic, climatic, and soil conditions on rubber growth and productivity [17]. In Central Vietnam, previous studies have mainly applied GIS-based multi-criteria and fuzzy approaches to rubber and perennial-crop suitability evaluation. Binh et al. [18] and Tran et al. [19] applied GIS-based Fuzzy AHP to evaluate land suitability for perennial crops in Phong Dien and for rubber plantations in Nam Dong District, respectively. For rubber suitability, Tran et al. considered soil type, soil texture, soil thickness, slope, soil pH, and soil organic matter. They identified soil

thickness as the most influential factor and classified more than 70% of the evaluated agricultural land as currently not suitable [19]. Rubber suitability has also been evaluated using other approaches, including comparisons between fuzzy land evaluation and conventional parametric Storie methods in Thailand [20], as well as GIS-based multi-criteria decision making [21] with AHP weighting of biophysical and socioeconomic criteria. Across these studies, the factors and criteria used vary with environmental conditions and evaluation objectives. For example, Samarappuli et al. [22] considered slope, rockiness, drainage, soil depth, texture, pH, and soil organic carbon, with elevation below 200 m, slope below 20%, soil depth greater than 1 m, and soil pH of 4–6 regarded as favorable conditions for rubber. Hazir et al. [23] identified annual rainfall of approximately 2000–2500 mm as favorable for commercial rubber production in Peninsular Malaysia. These studies illustrate that rubber suitability evaluation commonly classifies individual land characteristics using crop-specific criteria or threshold values before integrating them into an overall suitability assessment. However, many land-suitability studies focus mainly on identifying physically suitable areas and do not consider current land use, practical land availability, or observed crop performance. As a result, suitability maps may overestimate the actual potential for plantation expansion. Previous studies integrating land-suitability assessment with crop-yield information have shown that yield data can improve the practical relevance of suitability results [24]. Therefore, this study integrates three components: a GIS-based square-root parametric LSI, a spatial comparison between LSI classes and current land use, and a field-level assessment of the relationship between LSI and fresh latex yield.

2. Materials and Methods

2.1. Research Site

The study was conducted in the hilly area of Phong Dien Ward, Hue City, Central Vietnam. The approximate geographic center of the study area is located at 107°21′58″ E, 16°32′50″ N (Figure 1). This area lies in the transitional zone between the coastal plain and the mountainous region, where land use is strongly influenced by topographic and climatic conditions. At present, there is no unified official definition of low hilly land in Vietnam. In previous studies, hilly areas have generally been identified mainly based on elevation, although the threshold has varied among authors [25]. For this study, hilly land is defined as areas with elevations ranging from 10 to 200 m above sea level, according to the Thua Thien Hue Gazetteer (2005) [26]. The total area of the hilly region is 27,664 ha. Although special-use forest (8210 ha) and protection forest (2386 ha) are classified as agricultural land, these areas were excluded from the analysis because their conversion to perennial cropland is subject to strict legal restrictions and was therefore not considered a realistic option for rubber plantation development. In contrast, planted production forest is also subject to government regulation but may be considered for conversion to another land use, subject to applicable land-use and forestry planning, approval by the competent authorities, and other statutory procedures. Therefore, planted production forest was retained in the initial suitability assessment to examine its spatial correspondence with the resulting suitability classes. In the land-use dataset used in this study, other categories, including water bodies, residential land, construction land, and transportation land, were classified as non-agricultural land and covered a total area of 4543.51 ha. After excluding special-use forest, protection forest, and non-agricultural land, 12,524.49 ha remained for the land suitability analysis. The study area has a tropical monsoon climate, with a mean annual temperature of approximately 25 °C, summer maximum temperatures reaching up to 40 °C, and winter minimum temperatures of around 10 °C. Meteorological data for the 2020–2024 period, compiled by the Thua Thien Hue Hydro-Meteorological Center, show that annual rainfall ranged from 2000 to 2800 mm, with most precipitation occurring

between September and December [27]. Phong Dien Ward had a population of 27,862 in 2025, approximately 80% of whom depended on agriculture for their livelihoods [28].

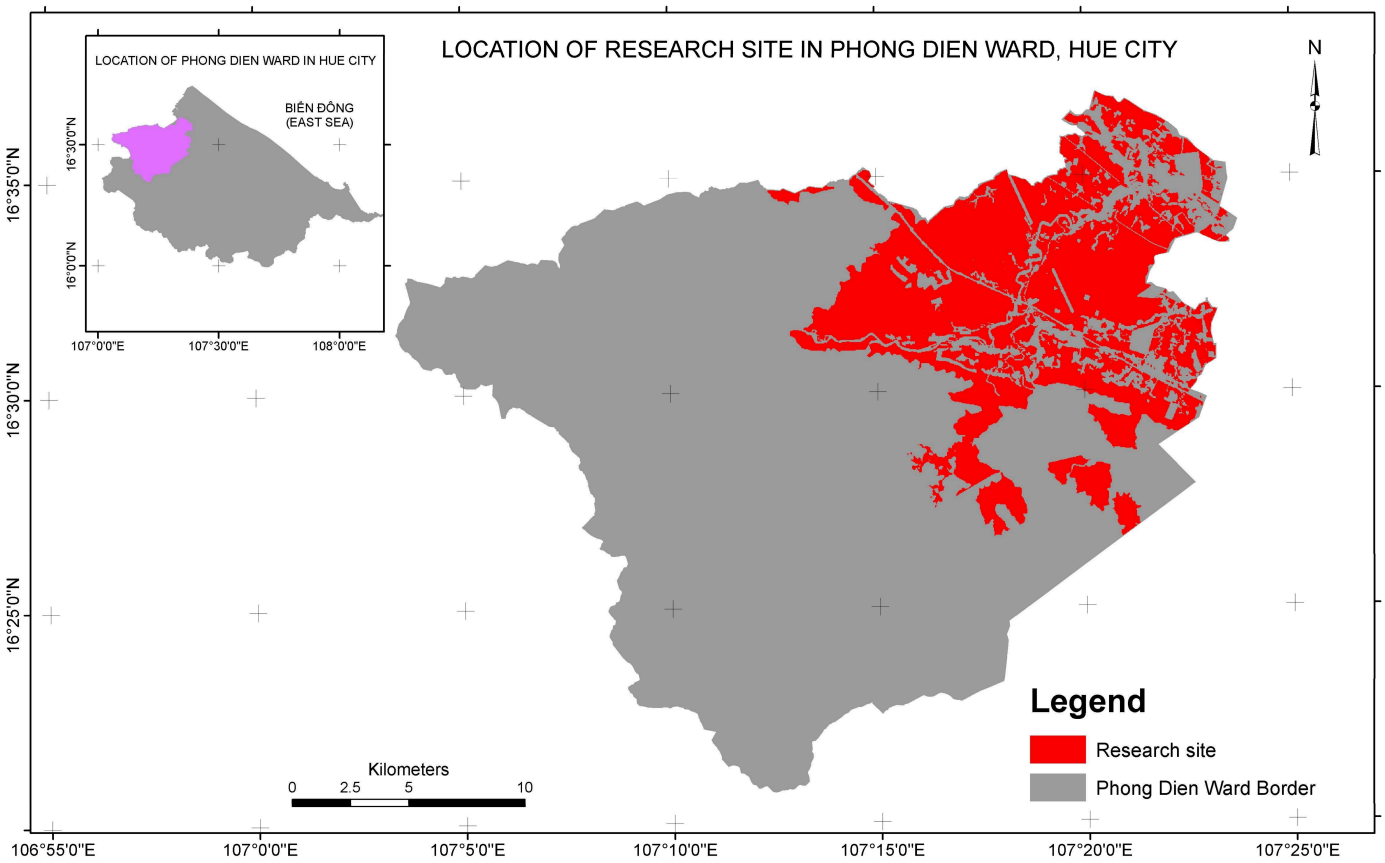


Figure 1. Location of the study area in Phong Dien Ward.

2.2. Materials

The land-suitability evaluation used six biophysical factors relevant to rubber growth: elevation, slope, annual rainfall, soil depth, soil texture, and soil type. Together, these factors represent the principal topographic, climatic, and soil conditions affecting rubber growth [19,22,29,30]. Monthly precipitation data representing the 1970–2000 climatic baseline were obtained from WorldClim version 2.1 at a spatial resolution of 30 arc-seconds [31]. WorldClim was used for the spatial suitability analysis because it provides a spatially continuous long-term precipitation surface across the entire study area, which is required for the raster-based LSI calculation. In contrast, the local meteorological dataset used in this study covered the 2020–2024 period and was derived from only two monitoring stations; therefore, it was used only to describe recent climatic conditions rather than to generate the spatial rainfall layer for the LSI analysis. The 12 monthly precipitation layers were summed to derive mean annual rainfall. Within the study area, the WorldClim mean annual rainfall ranged from 2303 to 2487 mm year^{-1}. Therefore, all raster cells fell within the 2250–2500 mm rainfall interval used in the suitability scoring. The resulting raster was reprojected to and aligned with the common 30 m analysis grid used for spatial overlay. These data represented long-term average rainfall conditions relevant to rubber growth. Elevation data were obtained from the 30 m Shuttle Radar Topography Mission (SRTM) DEM downloaded from the USGS website [32]. The DEM was used as the elevation layer, while the slope layer was derived from it using terrain-analysis tools in QGIS. Data on soil type, soil depth, and soil texture were extracted from the 1:100,000 soil map of Thua Thien Hue Province (2005) [33], whereas the 2023 land-use data were obtained from the

official digital vector GIS database prepared by the Department of Natural Resources and Environment [34]. This land-use map was developed based on cadastral maps and represents land use at the individual parcel level. For spatial analysis, the vector layer was subsequently rasterized to a spatial resolution of 30 m. All datasets were processed in QGIS Version 3.44 Solothurn, projected to WGS 84/UTM Zone 48N (EPSG:32648), and aligned with a common 30 m analysis grid.

2.3. Parametric Land Suitability Evaluation

The method was selected because it combines several land characteristics into a single quantitative suitability index. The square-root transformation moderates the cumulative reduction caused by direct multiplication while retaining the influence of the most limiting factor. Comparative studies suggest that the square-root method produces less restrictive and more differentiated suitability scores than the Storie method, particularly in heterogeneous environments [6,8]. The square-root parametric method is expressed as follows:

$$LSI = S_{min} * \sqrt{\prod_{i=1}^{n-1} \frac{S_i}{100}} \quad (1)$$

where LSI is Land Suitability Index; S_{min} is minimum score among all factors and S_i is score of the i^{th} remaining land characteristic after excluding the factor with the minimum score; and n is number of evaluated factors. Because all factor scores range from 0 to 100, the resulting LSI also ranges from 0 to 100 and cannot exceed the minimum individual factor score. A higher LSI value indicates greater physical suitability of the land unit for the evaluated land-use type. The resulting LSI values were classified into four physical land-suitability classes: highly suitable (S1: $75 \leq$ LSI ≤ 100), moderately suitable (S2: $50 \leq$ LSI < 75), marginally suitable (S3: $25 \leq$ LSI < 50), and not suitable (N: $0 \leq$ LSI < 25). The class boundaries at LSI values of 75, 50, and 25 follow the conventional land-index classification used in parametric land evaluation and adopted in previous applications of the square-root method [6]. These LSI class boundaries were specified independently of the field-yield analysis; the 45 plantation observations were used to evaluate the relationship between continuous LSI and fresh latex yield rather than to calibrate the class thresholds.

2.4. Selection and Scoring of Evaluation Factors

The selected biophysical factors were scored according to the ecological requirements of rubber and evidence from previous land-evaluation studies [19,22,35]. Higher scores indicate more favorable conditions, while lower scores indicate stronger limitations. The ratings were based on previous studies and consultation with local agricultural experts (Table 1). This factor-by-factor matching approach is commonly applied in GIS-based agricultural land evaluation [36,37].

Table 1. Scoring functions and spatial distribution of the biophysical factors used to evaluate land suitability for rubber plantation.

Factor	Value Range	Suitability Class	Formula/Method	Score Range	Area (Ha)	Sources
Elevation (m, a.s.l)	$0 \leq E_i \leq 100$	S1	$S_E = 100 - 0.25 \times E_i$	[100–75]	10,519.56	[22,38]
	$100 < E_i \leq 200$	S2		(75–50]	2004.93	
Slope (Degrees)	$0 \leq SL_i \leq 10$	S1	$S_{SL} = 100–2.5 \times SL_i$	[100–75]	10,017.54	[19,22]
	$10 < SL_i \leq 20$	S2		(75–50]	1866.06	
	$20 < SL_i \leq 25$	S3	$S_{SL} = 150 – 5 \times SL_i$	(50–25]	333.36	
	$SL_i > 25$	N	$S_{SL} = 0$	0	307.53	
Annual rainfall (mm)	$2000 \leq AR_i \leq 2250$	S1	$S_{AR} = 75 + 0.1 \times (AR_i - 2000)$	[75–100]	0	[23,29]
	$2250 < AR_i \leq 2500$	S1	$S_{AR} = 100 – 0.1 \times (AR_i - 2250)$	(100–75]	12,524.49	
Soil depth (cm)	≤50	N	Delphi method	0	3634.20	[19,30]
	(50–70]	S3		25	1017.81	
	(70–100]	S2		50	1824.48	
	(100–130]	S1		75	4396.59	
	>130	S1		100	1651.41	
Soil texture	Loam	S1		100	4412.79	[22,30]
	Sandy loam	S1		75	6840.81	
	Clay	S2		50	865.62	
	Sand	N		0	405.27	
Soil type	Ferralsols	S1		100	313.11	[19,22]
	Acrisols	S1		90	9015.66	
	Fluvisols	S2		60	1029.69	
	Anthrosols	S2		60	820.89	
	Leptosols	N		0	907.47	
	Arenosols	N		0	437.67	

Note: the E_i, SL_i, AR_i represent elevation, slope, and annual rainfall at the location i while S_E, S_{SL}, S_{AR} represent their corresponding suitability scores.

In Table 1, the suitability scores for elevation and slope were inversely related to the corresponding pixel values. For example, within the elevation range classified as highly suitable (S1), a score of 100 was assigned to an elevation of 0 m, whereas a score of 75 was assigned to an elevation of 100 m. Similarly, within the slope range classified as highly suitable (S1), a score of 100 was assigned to a slope of 0°, whereas a score of 75 was assigned to a slope of 10°. For annual rainfall, the adopted scoring function assigned the maximum suitability score of 100 at 2250 mm year^{-1}. Scores increased linearly from 75 to 100 between 2000 and 2250 mm and decreased linearly from 100 to 75 between 2250 and 2500 mm. Because the WorldClim mean annual rainfall values within the study area ranged from 2303 to 2487 mm year^{-1}, only the 2250–2500 mm branch of the scoring function was applied in the spatial analysis. In contrast, categorical variables, including soil type, soil texture, and soil-depth classes derived from the soil map, were assigned fixed suitability scores. The scores assigned to the categorical factors were reviewed by four scientists from Hue University of Agriculture and Forestry with expertise in soil and crop sciences and six experienced rubber farmers. Each farmer managed at least 1 ha of rubber plantation area and had at least 10 years of farming experience. A three-round

Delphi process was conducted. In the first round, participants independently reviewed the preliminary scores derived from published studies. In the subsequent rounds, anonymized summaries of the responses were provided, and participants were invited to reconsider their ratings. A final score was accepted when at least 70% of the participants—seven of the ten participants—agreed on the proposed score. Specifically, for soil type, the assigned scores were 100 for Ferralsols, 90 for Acrisols, 60 for Fluvisols and Anthrosols, and 0 for Arenosols and Leptosols. For soil depth, the assigned scores were >130 cm (100), 100–130 cm (75), 70–100 cm (50), 50–70 cm (25), and ≤50 cm (0). For soil texture, the assigned scores were 100 for loam, 75 for sandy loam, 50 for clay, and 0 for sand. Because soil type, soil depth, and soil texture were derived from the same soil map, the potential association among their suitability-score rasters was examined using pairwise Spearman's rank correlation coefficients (ρ). Spearman's correlation was used because the analysis focused on the ranked suitability scores assigned to these soil characteristics rather than on the original soil categories. The absolute values of ρ were classified as follows: 0.00–0.10, negligible; 0.10–0.39, weak; 0.40–0.69, moderate; 0.70–0.89, strong; and 0.90–1.00, very strong [39]. To assess the sensitivity of the LSI to the simultaneous inclusion of these soil-related factors, a leave-one-factor-out analysis was also conducted by recalculating the square-root LSI after separately excluding soil type, soil texture, and soil depth [40]. The same suitability scores and LSI classification thresholds were retained in all alternative specifications.

2.5. Assessment of Spatial Correspondence Between Land Suitability and Current Land Use

To assess the spatial correspondence between land suitability and existing rubber plantations in 2023, the suitability map was overlaid with the 30 m land-use raster derived from the parcel-based vector database. This analysis distinguished physically suitable land from areas already occupied by existing land uses and was used to calculate the suitability-by-consistency index (SbC). In this study, the SbC index was defined as the proportion of the total existing rubber plantation area located within the highly and moderately suitable classes. Similar overlay-based approaches have been used to compare land-suitability results with existing land-use patterns in Vietnam and other regions [14,41,42]. The SbC index was calculated using Equation (2):

$$SbC(\%) = \frac{(A_{S1} + A_{S2})}{A_{Total}} \times 100 \quad (2)$$

where A_{S1} and A_{S2} are the areas of existing rubber plantations located in the highly and moderately suitable classes, respectively; A_{Total} is the total area of existing rubber plantations.

Because no generally accepted classification thresholds have been established for the SbC index, it was used only as a continuous descriptive measure rather than to classify spatial or planning consistency as low, moderate, or high. Accordingly, the SbC value was reported as the percentage of the existing rubber plantation area occurring within the highly and moderately suitable classes. This ratio provides local authorities with a descriptive overview of the current spatial correspondence between rubber plantations and the two higher suitability classes.

2.6. Assessment of the Relationship Between LSI and Fresh Latex Yield

Field surveys were conducted from September to December 2025. Forty-five households with at least 10 years of experience in rubber production were randomly selected. One rubber plantation was surveyed for each selected household, resulting in 45 plantation-level observations. The survey locations provided broad spatial coverage of the areas currently under rubber plantations in the study area. LSI values and suitability classes were not considered during sample selection. All surveyed plantations were planted with the

PB260 clone, a commonly cultivated rubber clone in Phong Dien, and contained trees aged 8–10 years. The households had two to three laborers. Fresh latex yield data were obtained from farmers' sales records. These records included the amount of fresh latex sold after each tapping cycle. Annual fresh latex yield was calculated by dividing the total annual latex production of each surveyed plantation by its surveyed area. Yield was expressed as kg ha^{-1} $year^{-1}$. Tapping tree density was calculated by dividing the number of trees being tapped by the surveyed plantation area. The yield measurement referred only to the surveyed plantation and not to the household's total rubber plantation area.

Production conditions of the surveyed plantations were summarized using the mean, standard deviation, range, and coefficient of variation of tree age (TA), household labor (HL), total rubber plantation area of each surveyed household (RA), tapping tree density (TTD), and annual tapping frequency (ATF). The locations of the 45 survey points were overlaid on the LSI map, and the Sample Raster Values tool in QGIS was used to extract the LSI value corresponding to each survey point. This analysis was used to examine whether the LSI had field-level relevance for observed rubber plantation performance [24]. The relationship between LSI and fresh latex yield was analyzed using the following multiple linear regression model:

$$Yield_i = \beta_0 + \beta_1 * LSI_i + \beta_2 * TA_i + \beta_3 * HL_i + \beta_4 * RA_i + \beta_5 * TTD_i + \beta_6 * ATF_i + \varepsilon_i \quad (3)$$

where $Yield_i$ is the fresh latex yield (kg/ha/year) at survey point i^{th}, β_0 is intercept; β_1 to β_6 are the regression coefficients; ε_i is the random error term.

To assess the potential influence of the control-variable specification, a sensitivity analysis was conducted using alternative control-variable specifications, in which TA and TTD were excluded individually and jointly while the other explanatory variables were retained. The overall significance and goodness of fit of the model were evaluated using the F-test, the coefficient of determination (R^2), and the adjusted coefficient of determination (R^2-Adj) [43]. The distribution of the residuals was examined using the Shapiro–Wilk test [44], whereas heteroscedasticity was assessed using the Breusch–Pagan test [45]. Multicollinearity among the explanatory variables was evaluated using the variance inflation factor (VIF) [46], with VIF values below 5 indicating no serious multicollinearity [47]. Influential observations were identified using Cook's distance [48], with values approaching or exceeding 1 considered potentially strongly influential [49]. Spatial autocorrelation of the regression residuals was assessed using Moran's I based on a row-standardized symmetric four-nearest-neighbor spatial weights matrix constructed from the geographic coordinates of the 45 sampled plantations. Statistical significance was evaluated using 9999 random permutations [50]. All statistical tests were conducted at a significance level of $p < 0.10$, corresponding to a 90% confidence level. Data processing and statistical analyses were performed using R version 4.4.2 within the RStudio environment.

3. Results

3.1. Spatial Distribution of Physical Land Suitability for Rubber Plantation

The spatial distribution and characteristics of the six biophysical factors are presented in Table 1 and Figure 2. The results show that elevation, slope, and rainfall conditions across most of the study area were generally favorable for rubber plantation. Areas with soil depths below 50 cm covered 3634.20 ha, accounting for 29.02% of the study area, whereas areas with depths exceeding 130 cm covered 1651.41 ha, or 13.19%. Loam, which received the maximum score of 100, covered 4412.79 ha or 35.23% of the study area, while sandy loam, assigned a score of 75, covered 6840.81 ha or 54.62%. Regarding soil type, Acrisols

were the dominant soil type, covering 9015.66 ha or 71.98% of the study area, and received a suitability score of 90.

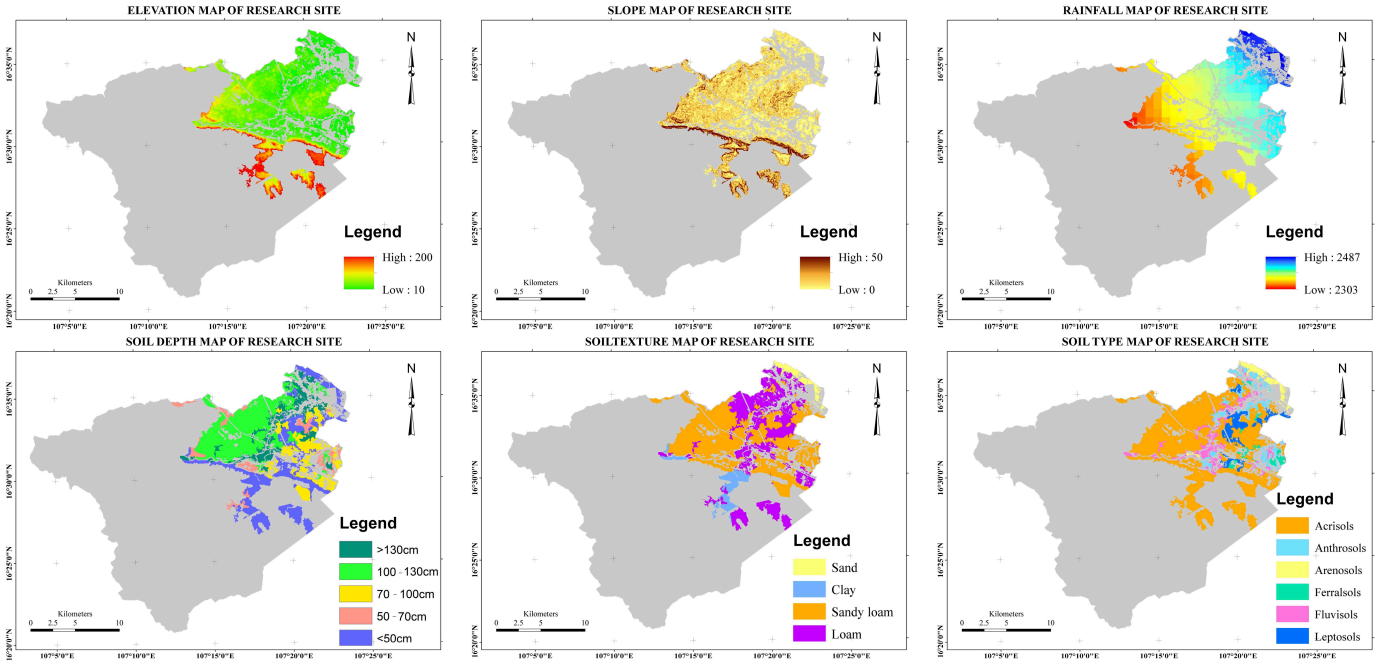


Figure 2. Spatial distribution of elevation, slope, annual rainfall, soil depth, soil texture, and soil type in the study area (The factors are presented from left to right, top to bottom).

The resulting Land Suitability Index ranged from 0 to 77.67. Areas with LSI values of 75 or higher covered 38.79 ha, accounting for 0.31% of the study area. Land with scores ranging from 50 to below 75 occupied 3986.01 ha, equivalent to 31.83% of the total area, while areas scoring from 25 to below 50 covered 3736.17 ha, representing 29.83%. The remaining area received scores below 25. Overall, 4024.80 ha were classified as highly or moderately suitable for rubber plantation. The spatial pattern of suitability suggests that soil-related factors, particularly soil depth, were important biophysical constraints. The maps depicting the suitability scores of individual factors for rubber plantation are presented in Figure 3, while the Land Suitability Index and Land Suitability Classification map for rubber plantation in the study area are shown in Figure 4. Spatially, the highly suitable areas were very limited and fragmented, whereas moderately suitable areas were more widely distributed across the study area. The distribution of marginally suitable and not suitable areas appeared to be associated mainly with shallow soil depth and less favorable soil texture. These results describe the biophysical suitability pattern of the study area and provide the basis for the subsequent assessment of current land-use correspondence and observed latex yield.

Pairwise Spearman's rank correlations among the soil-related suitability-score rasters were generally low. The correlation between soil depth and soil texture was 0.389, whereas those between soil depth and soil type ($\rho = -0.020$) and between soil texture and soil type ($\rho = -0.025$) were negligible. These results indicate that the three soil-related score rasters did not show strong spatial similarity across the study area. The leave-one-factor-out sensitivity analysis showed that the suitability classification was affected by the choice of soil factors (Table 2). The combined S1 + S2 area increased from 4024.80 ha in the original model to 5350.68 ha when soil type was excluded, 5152.77 ha when soil texture was excluded, and 7810.38 ha when soil depth was excluded. The largest change occurred when soil depth was omitted, indicating that soil depth had the strongest influence on the resulting suitability classification.

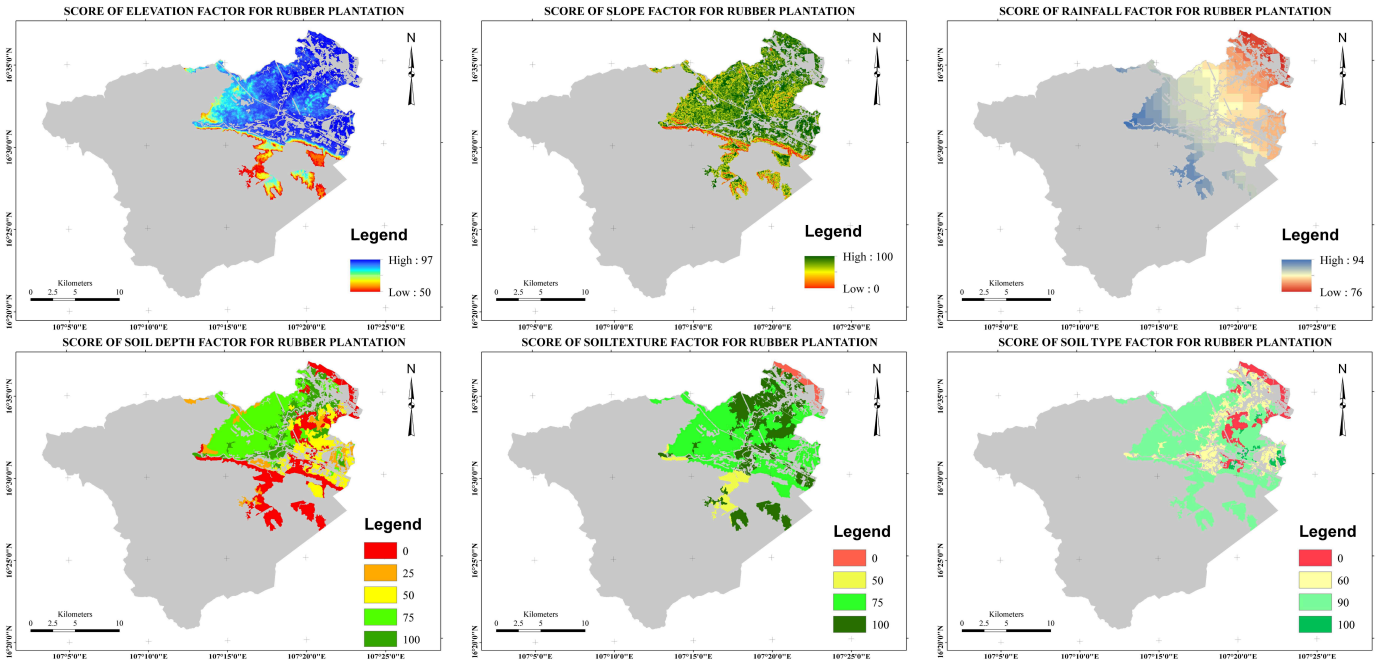


Figure 3. Suitability-score maps of the six biophysical factors evaluated for rubber plantation.

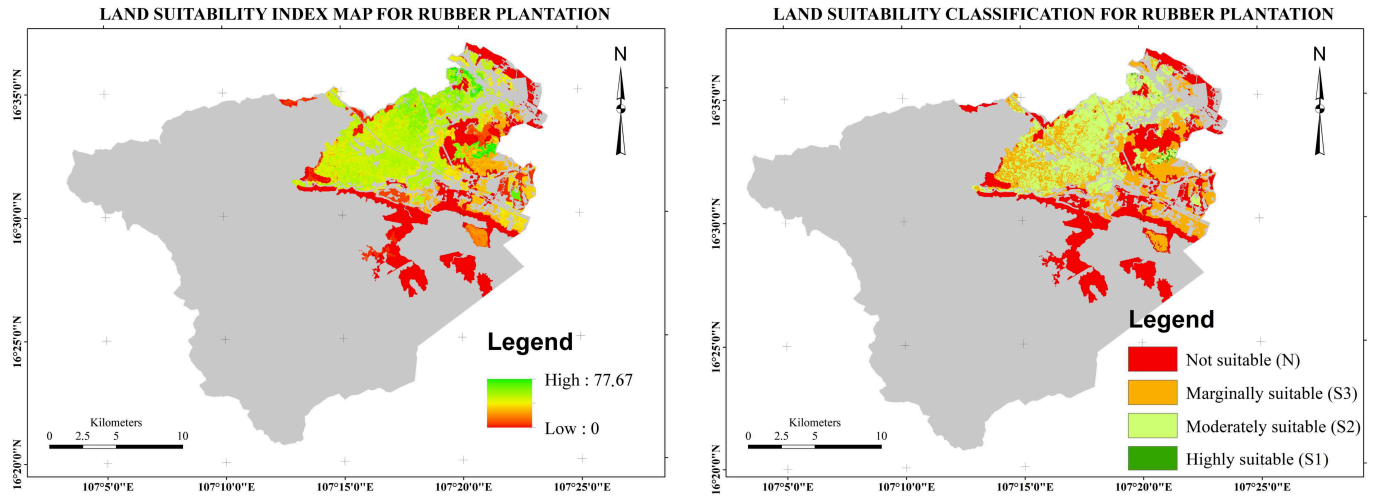


Figure 4. Land Suitability Index and physical land-suitability classification for rubber plantation in the study area.

Table 2. Sensitivity of the land-suitability classification to alternative soil-factor specifications.

Model	Max LSI	S1 (ha)	S2 (ha)	S3 (ha)	N (ha)	S1 + S2 (ha)
Original	77.67	38.79	3986.01	3736.17	4763.52	4024.80
Excluding soil type	87.76	1046.25	4304.43	2464.11	4709.70	5350.68
Excluding soil texture	80.76	93.15	5059.62	2646.00	4725.72	5152.77
Excluding soil depth	81.08	499.23	7311.15	2924.10	1790.01	7810.38

3.2. Spatial Correspondence Between Existing Rubber Plantations and Land Suitability

The 2023 land-use map of Phong Dien Ward (Figure 5) shows that rubber plantations covered 2016.63 ha within the study area. Rubber plantations were mainly concentrated in the central part of the ward, where the terrain is relatively flat and favorable for latex harvesting and transportation. Existing rubber plantations showed partial spatial correspondence with the suitability classification, as they were distributed across the moderately

suitable, marginally suitable, and not suitable classes, while none occurred in the very small highly suitable area. A substantial proportion occurred in the moderately suitable class. The absence of rubber plantations in the very small highly suitable area should be considered together with its existing planted forest cover.

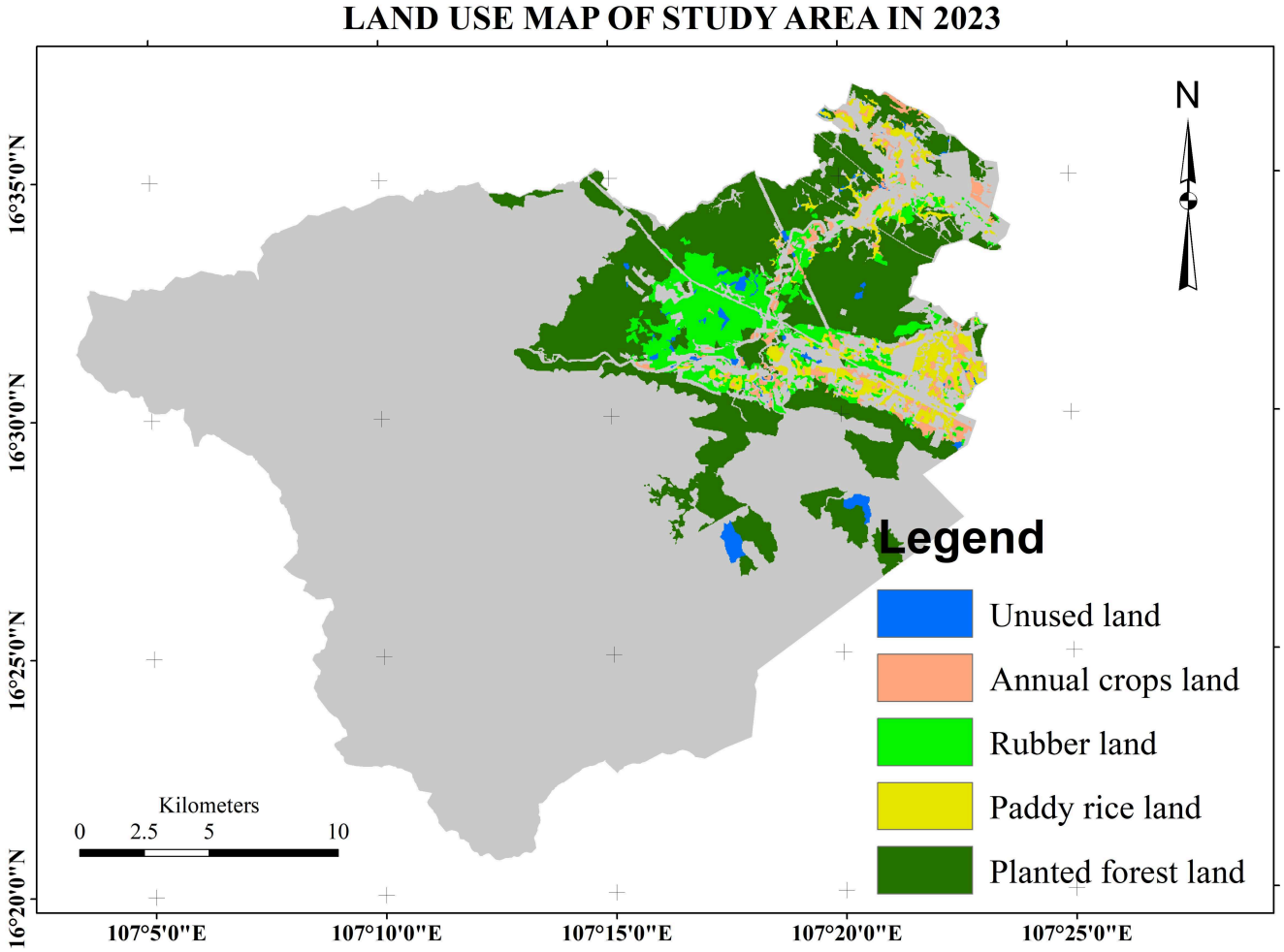


Figure 5. Land-use map of the study area in 2023.

Table 3 shows that physical suitability and current land use did not fully correspond. Therefore, the suitability map should not be used directly as an expansion map for rubber plantations. The highly suitable class covered only 38.79 ha, of which 38.16 ha, or 98.38%, was occupied by planted forest. This area is concentrated in Khanh My residential quarter, at approximately 107°21′15″ E and 16°32′37″ N, in the eastern part of Phong Dien Ward. It is characterized by natural conditions that are generally favorable for the growth and development of rubber trees. Specifically, the dominant soil type is Acrisols, with a suitability score of 90; the soil texture is loam, with a score of 100; and the effective soil depth exceeds 130 cm, also receiving a score of 100. For the other evaluated factors, elevation ranges from 12 to 32 m above sea level, with 95.82% of the total area occurring below 30 m. Slopes throughout the area are less than or equal to 2°, while annual rainfall ranges from 2410 to 2430 mm. The distributions of the biophysical factor values and suitability scores within the highly suitable area are shown in Figure 6. These areas are located relatively close to rural residential settlements and have long been used for production forest plantations. Much of the plantation forest had already been established before the implementation of the national reforestation program known as Program 327 and before rubber trees were introduced on a pilot basis in Phong Dien Ward during 1993–1994.

Table 3. Cross-tabulation of 2023 land use and physical land-suitability classes for rubber plantation.

Current Land Use Types	Suitability Classification for Rubber Plantation				Total (ha)
	High	Moderate	Marginal	Not Suitable	
Unused land	0.36	80.19	67.05	156.60	304.20
Annual crops land	-	170.91	281.34	190.35	642.60
Rubber plantation land	-	993.51	764.73	258.39	2016.63
Paddy rice land	0.27	239.04	445.50	315.27	1000.08
Planted forest land	38.16	2502.36	2177.55	3842.91	8560.98
Total (ha)	38.79	3986.01	3736.17	4763.52	12,524.49

Note: "-" indicates zero area (0.00 ha).

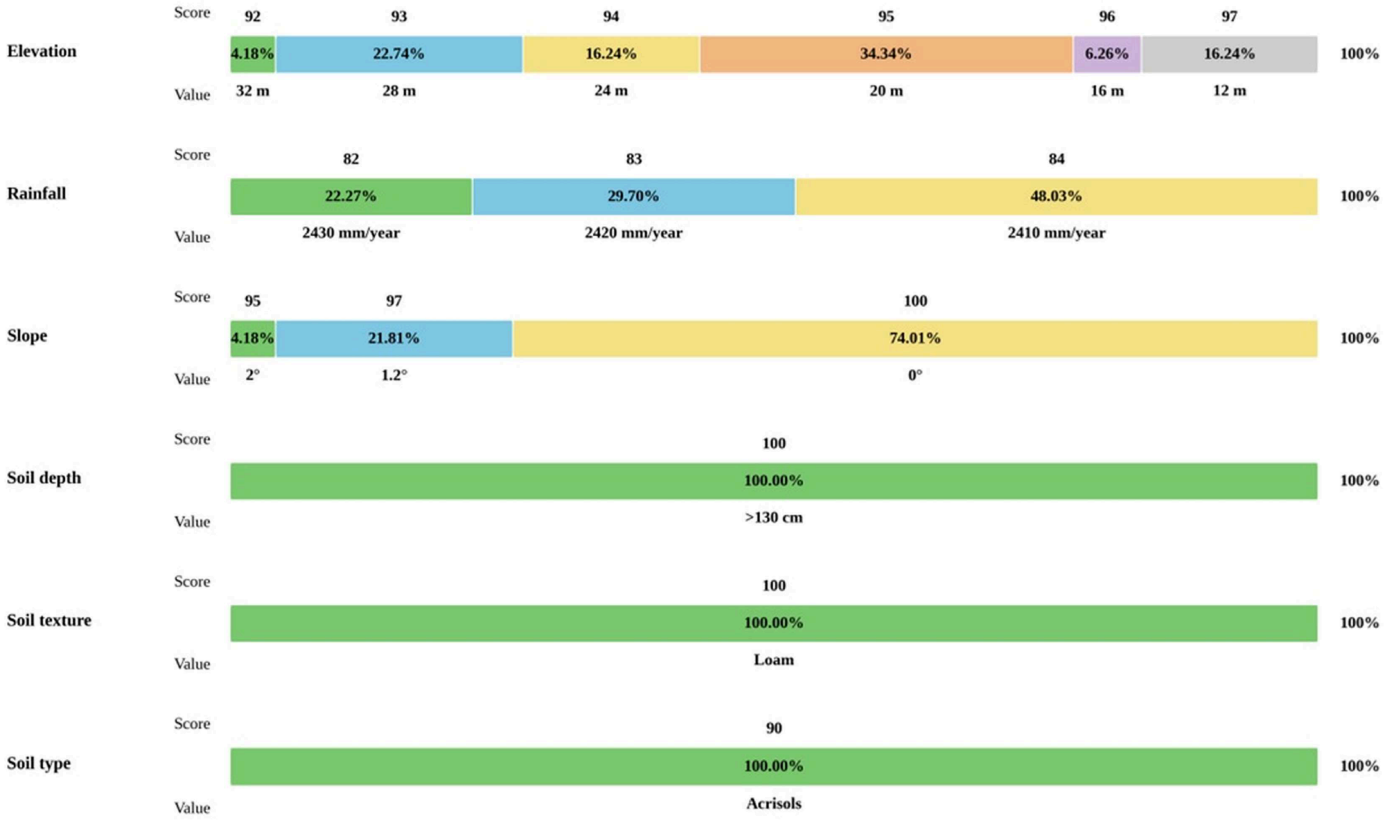


Figure 6. Distribution of biophysical factor values and suitability scores within the highly suitable (S1) area for rubber plantation.

No existing rubber plantations were located in the highly suitable class in 2023. Of the 2016.63 ha of existing rubber plantations, 993.51 ha (49.27%) occurred in the moderately suitable class, 764.73 ha (37.92%) in the marginally suitable class, and 258.39 ha (12.81%) in the not suitable class. Because no rubber plantations occurred in S1, the SbC value of 49.27% was entirely represented by the moderately suitable class, while the remaining 50.73% occurred in the marginally suitable and not suitable classes. Planted forest occupied 2502.36 ha, or 62.78%, of the moderately suitable class. After excluding planted forest, paddy rice land, and existing rubber plantations, only 251.46 ha of highly or moderately suitable land remained in unused land and annual cropland categories for further assessment.

3.3. Relationship Between LSI and Fresh Latex Yield

The locations of the survey points are shown in Figure 7, and their LSI values, production conditions, and fresh latex yields are summarized in Table 4. Tree age, tapping tree density, and annual tapping frequency showed relatively low variation, whereas household labor and total rubber plantation area per surveyed household showed greater variation. LSI values ranged from 17.72 to 55.42, with a mean of 41.59 ± 11.35 and a CV of 27.30%. This range covered not suitable, marginally suitable, and moderately suitable conditions, indicating that the sampled plantations were not restricted to a single suitability class. Fresh latex yield averaged 1147.24 ± 114.42 kg ha^{-1} year^{-1} and ranged from 930.90 to 1347.50 kg ha^{-1} year^{-1}, with a CV of 9.97%.

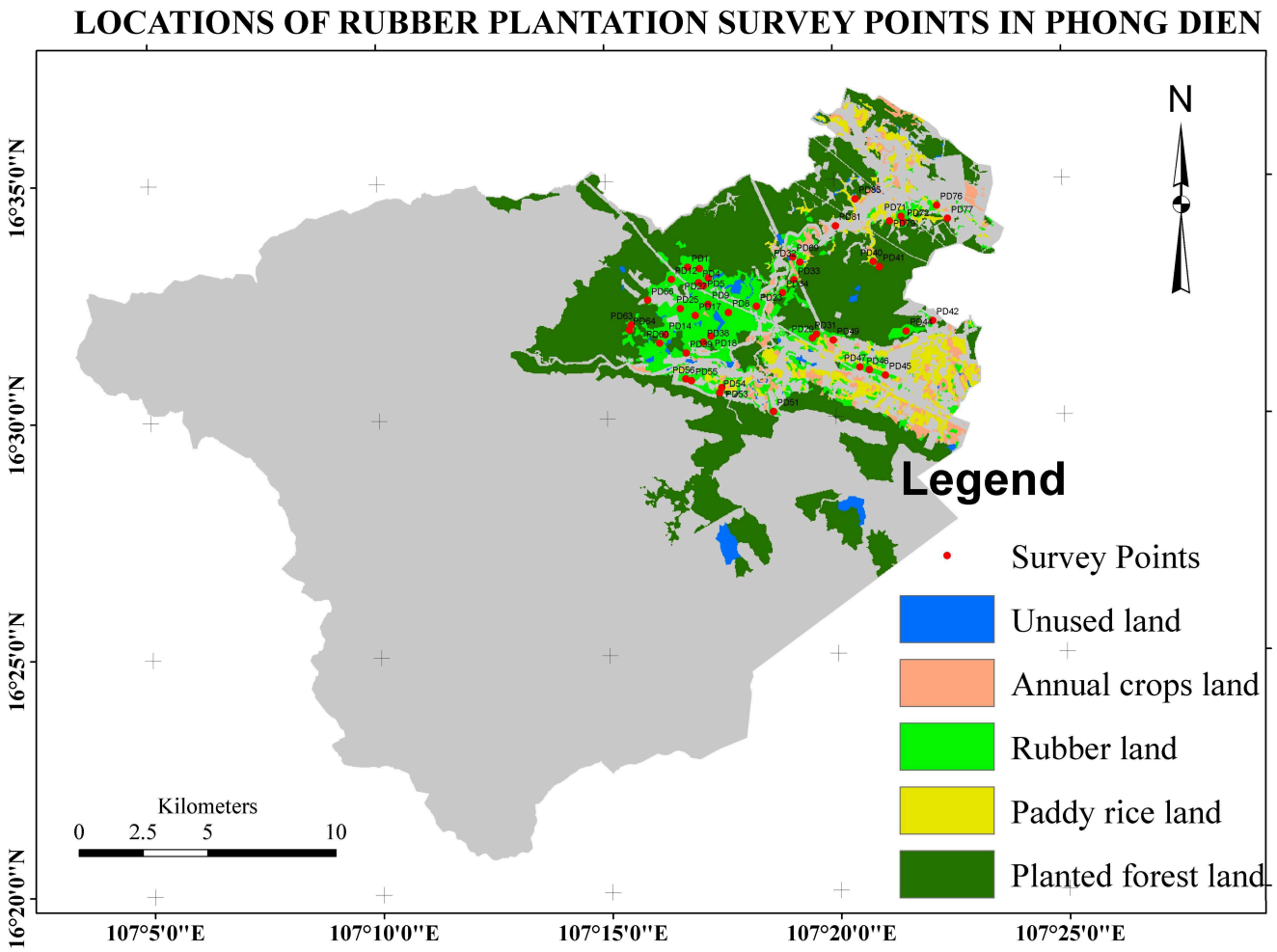


Figure 7. Locations of rubber plantation survey points in Phong Dien.

The scatter plot showed a positive relationship between LSI and fresh latex yield across the 45 sampled rubber plantations (Figure 8). In the unadjusted linear regression, a one-unit increase in LSI was associated with an increase of approximately 3.98 kg ha^{-1} year^{-1} in fresh latex yield (R^2 = 0.156, p = 0.007).

Table 4. Descriptive statistics of the sampled rubber plantations (n = 45).

Variables	Units	Mean	SD	Min	Max	CV (%)
Tree age (TA)	Years	9.04	0.77	8.00	10.00	8.48
Household labor (HL)	Persons	2.38	0.49	2.00	3.00	20.62
Total rubber plantation area of the surveyed household (RA)	Ha	2.04	0.33	1.50	2.80	16.31
Tapping tree density (TTD)	Trees/ha	330.44	15.51	300	360	4.70
Annual tapping frequency (ATF)	Times/year	108.18	3.07	102	116	2.84
Land Suitability Index (LSI)	No unit	41.59	11.35	17.72	55.42	27.30
Fresh latex yield (FLY)	Kg/ha/year	1147.24	114.42	930.90	1347.50	9.97

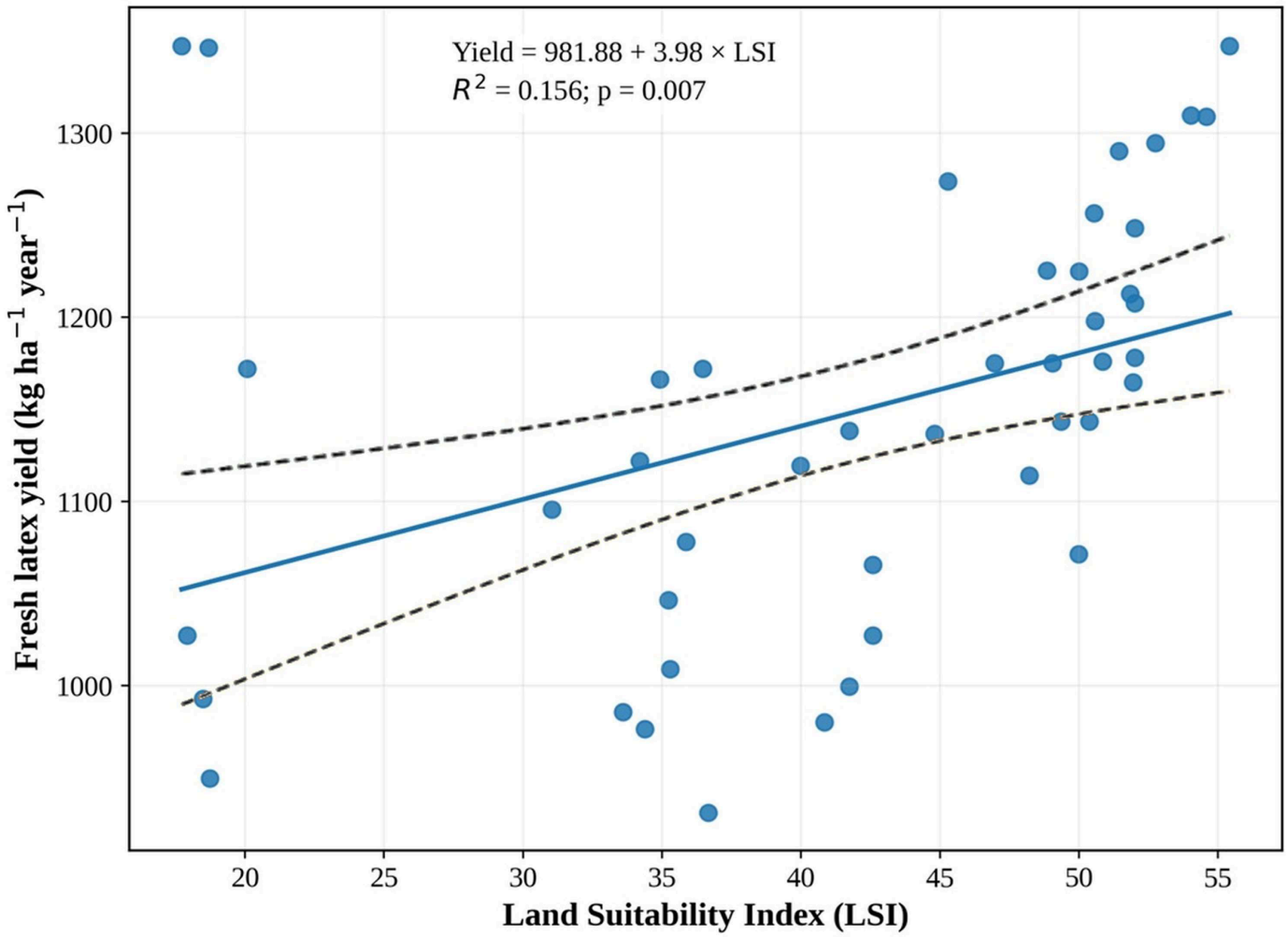


Figure 8. Relationship between Land Suitability Index (LSI) and fresh latex yield of the 45 sampled rubber plantations. The solid line represents the fitted linear regression, and the dashed lines indicate the 90% confidence interval.

The estimated coefficients of the multiple linear regression model are presented in Table 5 and Equation (4). The overall regression model was statistically significant. The model explained 76.5% of the variation in fresh latex yield. After adjustment for the number of explanatory variables, the adjusted R^2 was 0.728. The diagnostic results showed no serious violation of the regression assumptions. The Shapiro–Wilk test did not reject the assumption of normally distributed residuals (W = 0.991; p = 0.979 > 0.10). The Breusch–

Pagan test showed no evidence of heteroscedasticity (BP = 9.651; $p = 0.140 > 0.10$). The maximum VIF was 2.52, which was below the threshold of 5 and indicated no problematic multicollinearity among the explanatory variables. The maximum Cook's distance was 0.55, which was below the selected threshold of 1. Therefore, no observation was identified as strongly influential under this criterion. Moran's I test showed no significant positive spatial autocorrelation in the regression residuals (I = 0.074, $p = 0.146$). Therefore, there was no evidence that the residual-independence assumption was violated under the specified spatial weights matrix.

$$\hat{Yield}_i = -1029.70 + 2.09 * LSI_i + 37.19 * TA_i - 18.34 * HL_i - 0.38 * RA_i + 3.93 * TTD_i + 4.61 * ATF_i \quad (4)$$

Table 5. Multiple linear regression results.

Model Fit Measures							
R	**R^2**	**Adjusted R^2**	**F**	**df1**	**df2**	***p***	
0.875	0.765	0.728	20.664	6	38	<0.001	
Regression Coefficients							
Predictors	**Estimate**	**SE**	**t**	***p***	**90% CI lower**	**90% CI upper**	**VIF**
Intercept	−1029.70	375.80	−2.74	0.009	−1663.28	−396.11	
LSI *	2.09	0.83	2.53	0.016	0.70	3.48	1.09
TA *	37.19	18.61	2.00	0.053	5.81	68.57	2.52
HL	−18.34	24.20	−0.76	0.453	−59.15	22.46	1.74
RA	−0.38	31.49	−0.01	0.990	−53.48	52.72	1.36
TTD *	3.93	0.90	4.35	<0.001	2.41	5.46	2.43
ATF	4.61	3.88	1.19	0.241	−1.92	11.15	1.75
* Significant at p < 0.10							
Model Diagnostics							
Diagnostic test	**Statistic**	**df**	***p***	**Criterion**	**Conclusion**		
Shapiro–Wilk	W = 0.991		0.979	$p > 0.10$	No evidence of non-normal residuals		
Breusch–Pagan	BP = 9.651	6	0.140	$p > 0.10$	No evidence of heteroscedasticity		
VIF	Max = 2.52			VIF < 5	No problematic multicollinearity		
Cook's distance	Max = 0.55			D < 1	No strongly influential observation		
Moran's I	I = 0.074		0.146	$p > 0.10$	No significant positive spatial autocorrelation		

LSI, TA, and TTD were positively associated with fresh latex yield and were statistically significant at the 10% level. In contrast, no statistically significant associations were found for HL, RA, or ATF at this level. After controlling for the other production factors in the model, a one-unit higher LSI was associated with an average increase of 2.09 kg/ha/year in fresh latex yield. This result provides field-level evidence that LSI was associated with plantation performance under the surveyed production conditions. The results of the sensitivity analysis using alternative regression specifications are presented in Table 6.

Table 6. Sensitivity analysis of the LSI coefficient under alternative control-variable specifications.

Model	Additional Variables Included	LSI Coefficient	90% CI	*p*
M1	None	3.98	1.60–6.35	0.007
M2	HL, RA, ATF	3.28	1.18–5.38	0.012
M3	TA, HL, RA, ATF	2.39	0.72–4.06	0.021
M4	HL, RA, TTD, ATF	2.22	0.79–3.66	0.013
M5	TA, HL, RA, TTD, ATF	2.09	0.70–3.48	0.016

Note: TA = tree age; HL = household labor; RA = total rubber plantation area of the surveyed household; TTD = tapping tree density; ATF = annual tapping frequency.

The LSI coefficient remained positive and statistically significant at the 10% level across all model specifications. Although its magnitude decreased from 3.98 in the unadjusted model to 2.09 in the fully adjusted model, the association remained statistically significant when TA and TTD were excluded individually or jointly.

4. Discussion

4.1. Applicability of the GIS-Based Square-Root Parametric Method for Land Suitability Evaluation

The GIS-based square-root parametric method provided a transparent way to integrate multiple biophysical factors into a spatially explicit land suitability index for rubber plantation [6,36,37]. In this study, the LSI served two main purposes. It classified land into suitability classes and helped identify the main biophysical constraints on rubber plantation suitability. Therefore, the LSI should be used as a planning-support tool rather than as a direct recommendation for land conversion or rubber plantation expansion. It is particularly useful for identifying areas where further field investigation and planning feasibility assessment should be prioritized.

Several limitations should be considered when using the LSI. First, the suitability scores and thresholds were partly based on published studies and expert–farmer judgment; therefore, some subjectivity remains despite the Delphi process [35,51]. Second, the reliability of the suitability map depends strongly on the quality, scale, spatial resolution, and temporal currency of the input datasets, especially soil information. This has been emphasized by Ziadat [52], who noted that the quality of land suitability evaluation and the reliability of land-use decisions depend largely on the quality of soil information. Similarly, Dornik et al. [53] showed that different mapping units can produce different levels of accuracy in land suitability evaluation. Finally, the parametric method is most appropriate for evaluating biophysical factors that can be expressed through measurable values and crop-specific thresholds [35,54]. It is less suitable for comprehensive land evaluation when socio-economic factors such as market access, labor availability, land tenure, production costs, and farmers' decisions must also be considered [5].

Although the three soil variables were derived from the same map, the low pairwise correlations among their suitability scores indicate that they did not show strong pairwise monotonic associations and therefore do not appear to provide completely redundant spatial information. The sensitivity analysis nevertheless showed that the classification was influenced by individual soil factors, particularly soil depth, consistent with the limiting-factor behavior of the square-root method [6,8] and the importance of effective soil depth for rubber growth [19,30]. Because all three variables share the same 1:100,000 soil source, mapping uncertainty may affect several LSI components simultaneously. Therefore, the exact extent of the suitability classes should be treated with caution [40,52,53].

A key characteristic of the square-root parametric method is its strong dependence on the lowest-rated factor [6,8]. This is useful because it prevents land units with one

serious natural limitation from being classified as highly suitable merely because other factors are favorable. In hilly and high-rainfall areas such as Central Vietnam, this conservative characteristic is relevant because constraints such as shallow soil depth, steep slopes, or less favorable soil conditions may reduce the long-term suitability of perennial crop systems [3,12]. However, it may also produce conservative classifications when the lowest score is derived from coarse input data or does not fully reflect field-scale management conditions. Other approaches, such as Fuzzy AHP, can represent gradual suitability transitions and incorporate the relative importance of evaluation criteria through fuzzy membership functions and weighting procedures [55,56]. Because the square-root and Fuzzy AHP approaches were not applied to the same dataset in this study, their relative performance cannot be quantitatively assessed. Therefore, future studies should compare the square-root method with alternative approaches such as fuzzy logic or multi-criteria decision analysis and validate the suitability classes using field observations, crop growth, or yield data [5,35,40].

4.2. Spatial Correspondence and Planning Implications for Rubber Plantation Expansion

The comparison between current land use and the land suitability classification shows that physical suitability should not be considered equivalent to land available for rubber plantation expansion. Although most existing rubber plantations occurred within the moderately or marginally suitable classes, those located in the not suitable class indicate important biophysical limitations. This pattern suggests that rubber plantation distribution is not determined solely by biophysical suitability. Previous studies have emphasized that current land use and farmers' knowledge should be considered in land suitability evaluation because land-use decisions may reflect local management practices, land availability, and farmers' responses to natural constraints [14]. This is particularly relevant for rubber, whose expansion in Southeast Asia and Vietnam has also been driven by economic incentives, policy mechanisms, market demand, and livelihood strategies [11,12,15,16]. Consequently, rubber may be planted in areas with suboptimal physical conditions because of existing land access, previous land-use decisions, or limited livelihood alternatives.

Another important finding is that much of the land classified as highly or moderately suitable is currently occupied by planted forest. This pattern may reflect historical land designation and the role of plantation forests in rural livelihood strategies in upland Vietnam [57]. Under Vietnam's current legal framework, the conversion of forest land to perennial crop land, including rubber plantations, is strictly regulated and subject to approval through prescribed legal and administrative procedures [58,59]. More specifically, forest land conversion must be consistent with approved forestry and land-use plans, authorized by the competent state agencies, and accompanied by replacement forest planting or the fulfilment of equivalent financial obligations. These requirements make land conversion based only on suitability results difficult and, in many cases, impractical. Moreover, although the natural conditions in these areas may be suitable for rubber plantation, their practical suitability may still be constrained by production-related factors, including road accessibility, market access, input availability, labor supply, and local land-use arrangements [5,14]. Therefore, suitability results should be considered together with forest protection requirements, land-use planning, and relevant socio-economic conditions.

Although 4024.80 ha were classified as highly or moderately suitable, this physical potential was greatly reduced after current land use was considered. After excluding planted forest, paddy rice land, and existing rubber plantations, only 251.46 ha remained in unused land and annual cropland categories for further assessment. Existing rubber plantations located in marginally suitable and not suitable areas should also be reviewed carefully, because unfavorable land conditions may constrain productivity, increase management

requirements, and increase the risk of runoff, soil erosion, and soil degradation, particularly in steep areas with high rainfall and insufficient ground cover [60,61].

These findings may also be relevant to other hilly rubber-growing regions in Southeast Asia, where rubber expansion often occurs within mixed land-use landscapes, including forest land, smallholder rubber plantations, paddy rice land, annual cropland, and unused land [11,12]. Therefore, planning based solely on biophysical suitability may lead to overly optimistic estimates of the potential for rubber plantation expansion. The assessment framework used in this study can help distinguish areas suitable for expansion from those that require protection, reassessment, or improved management.

4.3. Production Conditions, Land Suitability, and Fresh Latex Yield in Phong Dien

Fresh latex yield in Phong Dien was generally comparable to that reported in Hue City. However, yield may differ among plantations and regions because of differences in tree age, clone, ecological conditions, pests and diseases, and management practices [62,63]. In this study, tree age and tapping tree density were positively associated with yield, which is consistent with the role of stand maturity and the number of tapped trees in determining latex production per unit area [64,65]. The lack of statistical significance of household labor, rubber plantation area, and annual tapping frequency at the 90% confidence level does not mean that these variables are unimportant. In practice, household labor and plantation area mainly reflect the scale of household resources, but they do not directly represent technical skills, labor quality, expenditure on hired labor, or investment per hectare, all of which may substantially affect rubber yield and latex quality [66]. In addition, annual tapping frequency showed only limited variation among the surveyed plantations, which may explain why it did not show a significant independent association with yield.

A limitation of the regression analysis is that TA and TTD were treated as control variables, although these variables may themselves be influenced by LSI. To examine this issue, the full model was compared with alternative model specifications in which TA and TTD were excluded individually and jointly. The consistency of the LSI association across these specifications suggests that the main result was not driven solely by the inclusion of TA and TTD as control variables. However, the present study cannot determine whether TA and TTD are themselves influenced by LSI.

The yield analysis provides an additional field-level check on the practical meaning of the LSI. The positive relationship between LSI and latex yield suggests that the index reflects differences in natural conditions among rubber plantations and has practical relevance for plantation planning under the surveyed conditions. This finding is consistent with previous studies showing that natural factors are important determinants of land suitability for rubber plantation [19,67]. However, in this study, the LSI was derived mainly from relatively stable biophysical characteristics, including elevation, slope, rainfall, soil depth, soil texture, and soil type. These factors cannot be easily changed through farm management. Therefore, management improvements may increase yield without necessarily changing the assigned suitability class. This is consistent with the FAO land-evaluation framework, which states that land can be upgraded from its current suitability level to a higher potential level only when the main limitations can be corrected through technically feasible measures at a reasonable cost [68]. For new planting or replanting, S1 and S2 areas may therefore be prioritized for further assessment, because severe biophysical limitations are absent or less pronounced in these areas. In contrast, marginally suitable and not suitable areas are often constrained by relatively fixed factors, such as steep slopes, shallow soil depth, unfavorable soil types, or unsuitable soil texture. In these areas, further investment should be considered only after field verification and assessment of technical, economic, and

environmental feasibility. Soil fertility management may improve productivity in existing plantations [69], but it cannot fully compensate for severe site limitations.

5. Conclusions and Limitations

This study shows that planning-relevant land evaluation for rubber plantations requires the integration of biophysical suitability with current land use, practical land availability, and field evidence of plantation productivity. The main contribution of this study is to show how GIS-based suitability information can be translated into practical guidance for rubber plantation planning.

Although 4024.80 ha were classified as highly or moderately suitable, most of this area was occupied by planted forest, paddy rice land, or existing rubber plantations. After excluding these land-use categories, only 251.46 ha remained within unused land and annual cropland for further assessment, comprising 80.55 ha of unused land and 170.91 ha of annual cropland. The SbC value of 49.27% should not be interpreted as indicating a defined level of planning consistency. These findings indicate that a land suitability map should not be used directly as a map for plantation expansion. Therefore, future rubber development should focus only on suitable areas outside forest and paddy rice land that meet legal requirements and are socio-economically feasible. In addition, the 1023.12 ha of existing rubber plantations located in marginally suitable and not suitable areas should be prioritized for field reassessment before replanting or further investment.

The positive association between LSI and fresh latex yield further supports the practical relevance of the index, indicating that it reflects differences in plantation productivity under the surveyed production conditions. However, the LSI should not be used as the sole basis for rubber plantation planning because yield is also influenced by tree age, tapping tree density, management practices, labor quality, investment level, and other farm-level conditions.

Several limitations of this study should be considered. First, the suitability assessment focused mainly on biophysical conditions and did not fully integrate factors such as market access, road accessibility, land tenure, production costs, household decisions, and other socio-economic factors. Second, the spatial results depend on the quality and spatial resolution of the input datasets, particularly the 1:100,000 soil map and the 30-arc-second rainfall data resampled to the 30 m analysis grid. The 2023 land-use data originated from parcel-level cadastral vector data but were rasterized to 30 m for spatial integration, which may introduce some generalization along parcel boundaries. Third, although the Delphi process improved the transparency of the scoring procedure, factor scores still depended partly on published thresholds and participant judgment. Fourth, the yield analysis was conducted on only 45 PB260 rubber plantations with trees aged 8–10 years, which may not fully represent all sources of yield variation. In addition, the sampled LSI values ranged from 17.72 to 55.42 and did not include the highly suitable class (S1). Therefore, the observed LSI–yield relationship was evaluated within this range, while its applicability to S1 conditions remains to be verified with additional field observations.

Future research and planning in the study area should focus on three aspects. First, the 251.46 ha of unused land and annual cropland classified as highly or moderately suitable should be verified through field surveys, including direct measurements of soil depth and soil properties, together with assessments of land tenure, road accessibility, production costs, and other socio-economic constraints. Second, rubber plantations currently located in marginally suitable and unsuitable areas should be monitored using repeated yield observations to determine how the identified biophysical limitations influence plantation performance over time. Third, the robustness of the LSI should be examined using higher-

quality spatial datasets and alternative land-evaluation methods, such as Fuzzy AHP, applied to the same study area and validated against field-measured yield data.

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References

1. Öztan, Ö.; Bozdağ, A.; Karkınlı, A.E.; Hüsrevoğlu, M.; Eren, F.; Yomralıoğlu, T.; Kuçak, R.A.; Ünal, Z. Variable Screening and Rank-Stability Diagnostics for GIS-Based Pre-Transformation Valuation Support in an Istanbul Urban Renewal Area. *Land* **2026**, *15*, 1445. [CrossRef]
2. Bagherzadeh, A.; Gholizadeh, A. Modeling Land Suitability Evaluation for Wheat Production by Parametric and TOPSIS Approaches Using GIS, Northeast of Iran. *Model. Earth Syst. Environ.* **2016**, *2*, 126. [CrossRef]
3. Herzberg, R.; Pham, T.G.; Kappas, M.; Wyss, D.; Tran, C.T.M. Multi-Criteria Decision Analysis for the Land Evaluation of Potential Agricultural Land Use Types in a Hilly Area of Central Vietnam. *Land* **2019**, *8*, 90. [CrossRef]
4. Al-Taani, A.; Al-Husban, Y.; Farhan, I. Land Suitability Evaluation for Agricultural Use Using GIS and Remote Sensing Techniques: The Case Study of Ma'an Governorate, Jordan. *Egypt J. Remote Sens. Space Sci.* **2021**, *24*, 109–117. [CrossRef]
5. Akpoti, K.; Kabo-Bah, A.T.; Zwart, S.J. Agricultural Land Suitability Analysis: State-of-the-Art and Outlooks for Integration of Climate Change Analysis. *Agric. Syst.* **2019**, *173*, 172–208. [CrossRef]
6. Mousavi, S.; Sarmadian, F.; Alijani, Z.; Taati, A. Land Suitability Evaluation for Irrigating Wheat by Geopedological Approach and Geographic Information System: A Case Study of Qazvin Plain, Iran. *Eurasian J. Soil Sci.* **2017**, *6*, 275–284. [CrossRef]
7. Jafarzadeh, A.A.; Abbasi, G. Qualitative Land Suitability Evaluation for the Growth of Onion, Potato, Maize, and Alfalfa on Soils of the Khalat Pushan Research Station. *Biologia* **2006**, *61*, S349–S352. [CrossRef]
8. Elaalem, M. A Comparison of Parametric and Fuzzy Multi-Criteria Methods for Evaluating Land Suitability for Olive in Jeffara Plain of Libya. *APCBEE Procedia* **2013**, *5*, 405–409. [CrossRef]
9. Azadi, A.; Jalali, S.A.S.; Navidi, M.N. Assessment of Land Suitability for Sugarcane Cultivation Using TOPSIS and Parametric Methods in Southwestern Iran. *Eurasian Soil Sci.* **2023**, *56*, 818–829. [CrossRef]
10. Kohani, F.; Matinfar, H.R.; Rostaminia, M.; Amirian-Chakan, A. Comparison of Determination of Suitability of Lands by Storie and Square Root Methods and Geographic Information Systems with Methods of Soil Quality Indices. *Agric. Eng.* **2024**, *47*, 161–183.
11. Fox, J.; Castella, J.-C. Expansion of Rubber (Hevea Brasiliensis) in Mainland Southeast Asia: What Are the Prospects for Smallholders? *J. Peasant. Stud.* **2013**, *40*, 155–170. [CrossRef]
12. Ahrends, A.; Hollingsworth, P.M.; Ziegler, A.D.; Fox, J.M.; Chen, H.; Su, Y.; Xu, J. Current Trends of Rubber Plantation Expansion May Threaten Biodiversity and Livelihoods. *Glob. Environ. Change* **2015**, *34*, 48–58. [CrossRef]
13. Singh, A.K.; Liu, W.; Zakari, S.; Wu, J.; Yang, B.; Jiang, X.J.; Zhu, X.; Zou, X.; Zhang, W.; Chen, C.; et al. A Global Review of Rubber Plantations: Impacts on Ecosystem Functions, Mitigations, Future Directions, and Policies for Sustainable Cultivation. *Sci. Total Environ.* **2021**, *796*, 148948. [CrossRef] [PubMed]

14. Ziadat, F.M.; Sultan, K.A. Combining Current Land Use and Farmers' Knowledge to Design Land-Use Requirements and Improve Land Suitability Evaluation. *Renew. Agric. Food Syst.* **2011**, *26*, 287–296. [CrossRef]
15. Dao, N. Rubber Plantations in the Northwest: Rethinking the Concept of Land Grabs in Vietnam. *J. Peasant Stud.* **2015**, *42*, 347–369. [CrossRef]
16. To, P. Powers of Exclusion: A Case Study of State-Led Large Scale Rubber Development in Vietnam's North-Western Region. *J. Land Use Sci.* **2023**, *18*, 249–262. [CrossRef]
17. Nguyen, B.T. Large-Scale Altitudinal Gradient of Natural Rubber Production in Vietnam. *Ind. Crops Prod.* **2013**, *41*, 31–40. [CrossRef]
18. Van Binh, N.; Linh, H.N.; Tien, N.D.; Tuyet, T.T.A.; Hoa, H.T.T. Assessment of Land Suitability in Perennial Crops Using FAHP and GIS in Central Vietnam. *Indian J. Agric. Res.* **2024**, *59*, 227–233. [CrossRef]
19. Tran, T.M.C.; Le, D.H.; Le, N.P.Q.; Nguyen, T.H.; Tran, T.T.; Trinh, N.H. Assessment of Physical Land Suitability by GIS-Based Fuzzy AHP for Rubber Plantation at the Nam Dong District, Thua Thien Hue Province. *J. Vietnam. Environ.* **2020**, *12*, 108–113. [CrossRef]
20. Van Ranst, E.; Tang, H.; Groenemam, R.; Sinthurahat, S. Application of Fuzzy Logic to Land Suitability for Rubber Production in Peninsular Thailand. *Geoderma* **1996**, *70*, 1–19. [CrossRef]
21. Ali, S.; Techato, K.; Taweenkun, J.; Gyawali, S. Assessment of Land Use Suitability for Natural Rubber Using GIS in the U-Tapao River Basin, Thailand. *Kasetsart J. Soc. Sci.* **2020**, *41*, 110–117. [CrossRef]
22. Samarappuli, L.; Wijesuriya, W.; Dissanayake, D.M.A.P.; Karunaratne, S.B.; Herath, H.M.L.K. Land Suitability for Sustainable Rubber Cultivation in Moneragala District. *J. Environ. Prof. Sri Lanka* **2014**, *3*, 48. [CrossRef]
23. Hazir, M.H.M.; Kadir, R.A.; Gloor, E.; Galbraith, D. Effect of Agroclimatic Variability on Land Suitability for Cultivating Rubber (Hevea Brasiliensis) and Growth Performance Assessment in the Tropical Rainforest Climate of Peninsular Malaysia. *Clim. Risk Manag.* **2020**, *27*, 100203. [CrossRef]
24. Purnamasari, R.A.; Noguchi, R.; Ahamed, T. Land Suitability Assessments for Yield Prediction of Cassava Using Geospatial Fuzzy Expert Systems and Remote Sensing. *Comput. Electron. Agric.* **2019**, *166*, 105018. [CrossRef]
25. Duong, T.N. Study on the Sustainable Use of Agricultural Land in the Hilly Region of Thai Nguyen Province (Nghiên Cứu Sử Dụng Bền Vững Đất Nông Nghiệp Vùng Gò Đồi Tỉnh Thái Nguyên). Ph.D. Thesis, Hanoi University of Agriculture, Hanoi, Vietnam, 2011.
26. Thừa Thiên Huế CPC. *Thua Thien Hue Gazetteer (Dư Địa Chí Thừa Thiên Huế)*; Natural Resources; Social Sciences Publishing House: Hanoi, Vietnam, 2005; Volume 1.
27. Thua Thien Hue Hydro-Meteorological Center. *Summary of Climatic and Hydrological Conditions in Thua Thien Hue Province, 2020–2024*; Thua Thien Hue Hydro-Meteorological Center: Hue City, Vietnam, 2025.
28. Phong Dien Ward People's Committee. *Report on the 2025 Socio-Economic Development Situation*; Phong Dien Ward People's Committee: Hue City, Vietnam, 2025.
29. Carr, M.K.V. The Water Relations of Rubber (Hevea Brasiliensis): A Review. *Exp. Agric.* **2012**, *48*, 176–193. [CrossRef]
30. Rao, D.V.K.N.; Jessy, M.D. Impact of Effective Soil Volume on Growth and Yield of Rubber (Hevea Brasiliensis). *Geoderma* **2007**, *141*, 332–340. [CrossRef]
31. Fick, S.E.; Hijmans, R.J. WorldClim 2: New 1-km Spatial Resolution Climate Surfaces for Global Land Areas. *Int. J. Climatol.* **2017**, *37*, 4302–4315. [CrossRef]
32. U.S. Geological Survey. *Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global*; U.S. Geological Survey: Reston, VA, USA, 2018.
33. Vietnam National Institute of Agricultural Planning and Projection. *Soil Type Map of Thua Thien Hue Province (Scale 1:100.000)*; Vietnam National Institute of Agricultural Planning and Projection: Hanoi, Vietnam, 2005.
34. Department of Natural Resources and Environment of Thua Thien Hue Province. *Land Use Map of Thua Thien Hue Province*; Department of Natural Resources and Environment of Thua Thien Hue Province: Hue, Vietnam, 2023.
35. Mugiyo, H.; Chimonyo, V.G.P.; Sibanda, M.; Kunz, R.; Masemola, C.R.; Modi, A.T.; Mabhaudhi, T. Evaluation of Land Suitability Methods with Reference to Neglected and Underutilised Crop Species: A Scoping Review. *Land* **2021**, *10*, 125. [CrossRef] [PubMed]
36. Elsheikh, R.; Shariff, A.R.B.M.; Amiri, F.; Ahmad, N.B.; Balasundram, S.K.; Soom, M.A.M. Agriculture Land Suitability Evaluator (ALSE): A Decision and Planning Support Tool for Tropical and Subtropical Crops. *Comput. Electron. Agric.* **2013**, *93*, 98–110. [CrossRef]
37. Mazahreh, S.; Bsoul, M.; Hamoor, D.A. GIS Approach for Assessment of Land Suitability for Different Land Use Alternatives in Semi Arid Environment in Jordan: Case Study (Al Gadeer Alabyad-Mafraq). *Inf. Process. Agric.* **2019**, *6*, 91–108. [CrossRef]
38. Yang, X.; Blagodatsky, S.; Marohn, C.; Liu, H.; Golbon, R.; Xu, J.; Cadisch, G. Climbing the Mountain Fast but Smart: Modelling Rubber Tree Growth and Latex Yield under Climate Change. *For. Ecol. Manag.* **2019**, *439*, 55–69. [CrossRef]

39. Schober, P.; Boer, C.; Schwarte, L.A. Correlation Coefficients: Appropriate Use and Interpretation. *Anesth. Analg.* **2018**, *126*, 1763–1768. [CrossRef] [PubMed]
40. Chen, Y.; Yu, J.; Khan, S. Spatial Sensitivity Analysis of Multi-Criteria Weights in GIS-Based Land Suitability Evaluation. *Environ. Model. Softw.* **2010**, *25*, 1582–1591. [CrossRef]
41. Yin, S.; Li, J.; Liang, J.; Jia, K.; Yang, Z.; Wang, Y. Optimization of the Weighted Linear Combination Method for Agricultural Land Suitability Evaluation Considering Current Land Use and Regional Differences. *Sustainability* **2020**, *12*, 10134. [CrossRef]
42. Khoi, D.D.; Murayama, Y. Delineation of Suitable Cropland Areas Using a GIS Based Multi-Criteria Evaluation Approach in the Tam Dao National Park Region, Vietnam. *Sustainability* **2010**, *2*, 2024–2043. [CrossRef]
43. Montgomery, D.C.; Peck, E.A.; Vining, G.G. *Introduction to Linear Regression Analysis*, 6th ed.; John Wiley & Sons: Hoboken, NJ, USA, 2021.
44. Shapiro, S.S.; Wilk, M.B. An Analysis of Variance Test for Normality (Complete Samples). *Biometrika* **1965**, *52*, 591–611. [CrossRef]
45. Breusch, T.S.; Pagan, A.R. A Simple Test for Heteroscedasticity and Random Coefficient Variation. *Econometrica* **1979**, *47*, 1287. [CrossRef]
46. O'Brien, R.M. A Caution Regarding Rules of Thumb for Variance Inflation Factors. *Qual. Quant.* **2007**, *41*, 673–690. [CrossRef]
47. Ngabire, M.; Wang, T.; Xue, X.; Liao, J.; Sahbeni, G.; Huang, C.; Duan, H.; Song, X. Soil Salinization Mapping across Different Sandy Land-Cover Types in the Shiyang River Basin: A Remote Sensing and Multiple Linear Regression Approach. *Remote Sens. Appl.* **2022**, *28*, 100847. [CrossRef]
48. Cook, R.D. Detection of Influential Observation in Linear Regression. *Technometrics* **1977**, *19*, 15–18. [CrossRef]
49. Dhakal, C.P. Dealing with Outliers and Influential Points While Fitting Regression. *J. Inst. Sci. Technol.* **2017**, *22*, 61–65. [CrossRef]
50. Bivand, R.S.; Wong, D.W.S. Comparing Implementations of Global and Local Indicators of Spatial Association. *TEST* **2018**, *27*, 716–748. [CrossRef]
51. Belton, I.; MacDonald, A.; Wright, G.; Hamlin, I. Improving the Practical Application of the Delphi Method in Group-Based Judgment: A Six-Step Prescription for a Well-Founded and Defensible Process. *Technol. Forecast. Soc. Change* **2019**, *147*, 72–82. [CrossRef]
52. Ziadat, F.M. Land Suitability Classification Using Different Sources of Information: Soil Maps and Predicted Soil Attributes in Jordan. *Geoderma* **2007**, *140*, 73–80. [CrossRef]
53. Dornik, A.; Cheţan, M.A.; Drăguţ, L.; Iliuţă, A.; Dicu, D.D. Importance of the Mapping Unit on the Land Suitability Assessment for Agriculture. *Comput. Electron. Agric.* **2022**, *201*, 107305. [CrossRef]
54. Zhang, J.; Su, Y.; Wu, J.; Liang, H. GIS Based Land Suitability Assessment for Tobacco Production Using AHP and Fuzzy Set in Shandong Province of China. *Comput. Electron. Agric.* **2015**, *114*, 202–211. [CrossRef]
55. Mahabadi, N.Y.; Soltani, S.M. Applicability of Fuzzy and Fuzzy Analytic Hierarchy Process (Fuzzy AHP) Methods to Determine the Optimum Soil Depth in Land Suitability Evaluation for Irrigated Rice. *Pol. J. Soil Sci.* **2021**, *54*, 103. [CrossRef]
56. Xue, L.; Cao, P.; Xu, D.; Guo, Y.; Wang, Q.; Zheng, X.; Han, R.; You, A. Agricultural Land Suitability Analysis for an Integrated Rice–Crayfish Culture Using a Fuzzy AHP and GIS in Central China. *Ecol. Indic.* **2023**, *148*, 109837. [CrossRef]
57. Van Khuc, Q.; Le, T.-A.T.; Nguyen, T.H.; Nong, D.; Bao, T.Q.; Meyfroidt, P.; Tran, T.; Duong, P.B.; Nguyen, T.T.; Tran, T.; et al. Forest Cover Change, Households' Livelihoods, Trade-Offs, and Constraints Associated with Plantation Forests in Poor Upland-Rural Landscapes: Evidence from North Central Vietnam. *Forests* **2020**, *11*, 548. [CrossRef]
58. The National Assembly of the Socialist Republic of Vietnam. *The Vietnam Forestry Law 2017*; The National Assembly of the Socialist Republic of Vietnam: Hanoi, Vietnam, 2017.
59. The National Assembly of the Socialist Republic of Vietnam. *The Vietnam Land Law 2024*; The National Assembly of the Socialist Republic of Vietnam: Hanoi, Vietnam, 2024.
60. Fox, J.M.; Castella, J.C.; Ziegler, A.D.; Westley, S.B. *Rubber Plantations Expand in Mountainous Southeast Asia: What Are the Consequences for the Environment?* East-West Center: Honolulu, HI, USA, 2014.
61. Neyret, M.; Robain, A.; Janeau, J.-L.; Durand, T.; Kaewthip, J.; Trisophon, K.; Valentin, C. Higher Runoff and Soil Detachment in Rubber Tree Plantations Compared to Annual Cultivation Is Mitigated by Ground Cover in Steep Mountainous Thailand. *Catena* **2020**, *189*, 104472. [CrossRef]
62. Đông, T.P.; Hòa, T.Đ.; Lam, N.H.; Toản, H.K. Đánh Giá Hiện Trạng Sản Xuất Cao Su Tiểu Điền Tại Tỉnh Thừa Thiên Huế (Evaluation of Smallholder Rubber Production in Thua Thien Hue). *Hue Univ. J. Sci. Agric. Rural Dev.* **2018**, *127*, 45–58. [CrossRef]
63. Thanh, T.; Tuy, L.M.; Lam, L. Van Genotype × Environment Interaction of Hevea Clones in Traditional and Non-Traditional Rubber Growing Regions of Vietnam. *J. Plant Interact.* **2016**, *11*, 20–29. [CrossRef]
64. Binang, W.; Ittah, M.; Ntia, J.; Edem, E. Latex Yield of Para Rubber (Hevea Brasilliensis Muell. Arg) as a Function of Clonal Variation and Age at Tapping in Three Locations in the Niger Delta Region of Nigeria. *J. Appl. Life Sci. Int.* **2017**, *10*, 1–7. [CrossRef]
65. Thanh, T.; Nhan, N.T.; Van Truong, V.; Minh, T.D. Effects of Planting Density on Growth and Yield Attributes of Rubber Trees (*Hevea brasiliensis*). *Trop. Agric. Sci.* **2022**, *45*, 245–256. [CrossRef]

66. Poungchompu, S.; Chantanop, S. Factor Affecting Technical Efficiency of Smallholder Rubber Farming in Northeast Thailand. *Am. J. Agric. Biol. Sci.* **2015**, *10*, 83–90. [CrossRef]
67. Kharche, V.K.; Sehgal, J.L.; Challa, O. Evaluation of Soil-Site Conditions for Suitability of Rubber. *Agropedology* **1995**, *5*, 69–78.
68. Food and Agriculture Organization of the United Nations. *A Framework for Land Evaluation*, 1st ed.; Food and Agriculture Organization of The United Nations: Rome, Italy, 1976.
69. Akpan, A.U.; Edem, S.O.; Ndaeyo, N.U. Latex Yield of Rubber (Hevea Brasiliensis Muell Argo) as Influenced by Clone Planted and Locations with Varying Fertility Status. *J. Agric. Soc. Sci.* **2007**, *3*, 28–30.

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