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Modelling Potential Soil Erosion and Sediment Delivery Risk in Plantations of Sri Lanka

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Abstract: The current trend in agricultural practices is expected to have a detrimental impact in terms of accelerating soil erosion. Assessment of the cumulative impact of various management strategies in a major plantation is a measure of the sustainably of soil resources. Thus, the current study aimed to develop the potential soil erosion map for a selected plantation (8734 ha in size) in tropical Sri Lanka using the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) Sediment Delivery Ratio (SDR) model. The estimated mean annual soil loss rate of the selected plantation was 124.2 t ha^{-1} ranging from 0.1 to 6903.3 t ha^{-1}. Out of the total extent, ~49.5% of the area belongs to the low soil erosion hazard category (0–5 t ha^{-1} $year^{-1}$) while ~7.8% falls into very high (25–60 t ha^{-1} $year^{-1}$) and ~1.3% into extremely high (60 < t ha^{-1} $year^{-1}$) soil erosion hazard classes. The rainfall erosivity factor (R) for the entire study area is 364.5 ± 98.3 MJ mm ha^{-1} hr^{-1}. Moreover, a relatively higher correlation was recorded between total soil loss and R factor (0.3) followed by C factor (0.2), P factor (0.2), LS factor (0.1), and K factor (<0.1). It is evident that rainfall plays a significant role in soil erosion in the study area. The findings of this study would help in formulating soil conservation measures in the plantation sector in Sri Lanka, which will contribute to the country's meeting of the UN Sustainable Development Goals (SDGs).

Keywords: erosion hazard zones; Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST); potential soil erosion; Sediment Delivery Ratio (SDR) model; Universal Soil Loss Equation (USLE)

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1. Introduction

Environmental impact assessments were rarely conducted when agricultural systems were implemented in several countries. Low or no attention on the environmental impact assessments creates severe threats to the soil systems and the overall sustainability of agricultural ecosystems throughout the world [1,2]. The negative impact on the soil systems creates several environmental, biodiversity, and health issues where human-induced land degradation is prominent. Soil degradation and deterioration of soil health affect crop production, farmers' economic status, and finally food and nutritional security and sustainability [3]. Soil degradation in terms of various modes including erosion obstructs the achievement of the United Nations (UN) Sustainable Development Goals (SDGs) mainly; no poverty (SDG1), zero hunger (SDG2), good health and well-being (SDG3), clean water and sanitation (SDG6), climate action (SDG13) and life of land (SDG15) which is a serious threat to the overall sustainability. Therefore, proper assessment and prevention of soil degradation are important.

Out of several land degradation methods, soil erosion is one of the major causes that deteriorate land quality. Soil erosion is a natural process that results in the removal and transportation of topsoil into downstream areas [4–7]. It occurs due to various causative factors such as rain, wind, and gravity whereas this process is gradually induced by human activities [8]. As explained by the Food and Agriculture Organization of the UN [9], the major steps of the erosion process are soil loosening, soil transportation, and soil deposition. Therefore, as the ultimate result of this process, topsoil along with its contaminants viz. nutrients, agrochemicals, and fertilizers are transported and accumulated in downstream surface and groundwater sources [10,11]. Apart from the natural factors, human activities such as deforestation, inappropriate farming practices, and inappropriate land management practices have significantly induced the rate of soil erosion in the twentieth century [12–14]. Agricultural activities that include plantations are probably one of the most prominent anthropogenic activities that accelerate the rate of soil erosion since the topsoil is disturbed when preparing lands for cultivation [15]. Therefore, it has been revealed that this human-induced soil erosion might negatively affect soil fertility in agricultural lands [13], drinking water quality [16], and natural ecosystems [17]. Ultimately this causes long-term crop productivity losses [18], economic losses, food scarcity, and water security losses [19]. Around 85% of global land degradation is occurred due to soil erosion which reduces crop yield by 17% [20].

Soil erosion in plantations is generally higher due to the undulating to steep terrain with high intensity of rainfall, especially during the early years after planting. This soil erosion can be minimized to a greater extent by proper soil conservation measures and must be ensured in order to preserve the productivity and fertility of the estates. These measures involved minimizing soil erosion, improving the structure of the soil, to make it resistant to detachment and transportation and more absorptive for surface water, protecting the surface from rainfall impact, slowing down the runoff, and providing safe ways for the disposal of excess runoff. Some of the observed features are contour planting, cover cropping, stone terracing, drainage systems, and embankment and fences. Furthermore, as explained by Hewawasam [21], soil erosion has increased by a factor of up 100 due to intensive human-based agricultural activities. Also, the annual soil erosion-induced cost is around US$ 90–125 per hectare, whereas the annual cost of soil erosion in Sri Lanka is around 1% of the Gross Domestic Production of the country [22]. Moreover, Sri Lankan plantation lands viz. rubber, oil palm, tea, and coconut are widely varied and highly complex due to variations in the topography, soil types, elevation, climatic conditions, and diverse management practices implemented by different plantation companies. Even though the soil is considered a mass source of nutrient, in those fields, topsoil with nutrients have been depleted over time and it can be mainly due to soil erosion. Therefore, timely and accurate monitoring of soil erosion in agricultural and plantation areas is vital in order to develop soil conservation strategies and land management practices [23]. In the twentieth century, many countries are experiencing increased land degradation due to the trend of increasing human-induced soil erosion [24]. According to sustainable development goals (SDGs), in order to ensure sustainable agriculture, agricultural and plantation lands should be protected and restored. Therefore, the findings of this study will contribute to the policymakers in Sri Lanka to ensure proper land management practices in the agricultural sector on the country's way to meet the SDGs.

Soil erosion can be assessed by conventional field-based methods and soil erosion modelling [25]. With the increased availability of the finer scale global level data, agricultural automation has been increased which increased the strength of agri-environmental related modelling approaches [26]. Soil erosion modelling has many advantages over field-based soil erosion assessments since field-based methods are labor intensive, time-consuming, low degree of flexibility, and non-comparability [27,28]. Over the past years, numerous soil erosion modelling approaches were developed with different input requirements and complexity [23]. According to Smith [29], rainfall erosivity factor (R), soil erodibility factor (K), slope gradient factor (LS), crop management factor (C), and support practice factor (P) are the parameters used when developing soil erosion models. The Integrated Valuation of Ecosystem Services and Tradeoffs—Sediment Delivery Ratio (InVEST- SDR), Universal Soil Loss Equation (USLE), and Revised Universal Soil Loss Equation (RUSLE), and models are the most widely used GIS-based soil erosion models in Sri Lanka. According to the GIS-based soil erosion assessments that have been conducted in Sri Lanka up to 2021, ~50% of studies have used the RUSLE model, ~29% of studies have used the USLE model whereas ~21% of the studies have used InVEST SDR model [23]. Moreover, previous studies suggest that InVEST SDR model estimate soil losses and sediment delivery ratios accurately in different geographical scales compared with other GIS-based soil erosion models [7,15,30,31].

The main objective of this study was to develop a soil erosion hazard zone map for Sri Lankan plantations that differ in terms of crops, topography, elevation, climatic conditions, and management practices, using a novel modelling approach. In order to achieve this objective, InVEST SDR model was used in this study and the findings of the current study could be used by the government and other agencies when developing land management policies in the plantation industry in Sri Lanka.

2. Materials and Methods

2.1. Study Area

Sri Lanka is a tropical island (7.8731° N and 80.7718° E) in the Indian Ocean. The study area was located in the Kegalle district of Sri Lanka and the total land extent was 8733.76 ha. The plantation area is diversified into several crops such as Rubber, Tea, Coconut, Cinnamon, Oil palm, ancillary crops as well as timber. Also, a significant area of the plantation is covered by a natural forest (refer to Figure 1). The average annual rainfall in the study area ranges from 2900 mm to 5500 mm with an average annual temperature of 22–32 °C. Topographically, the study area consists of complex hilly areas, narrow valleys, and low flatlands. The major soil type of the study area was identified as Red Yellow Podzolic soils.

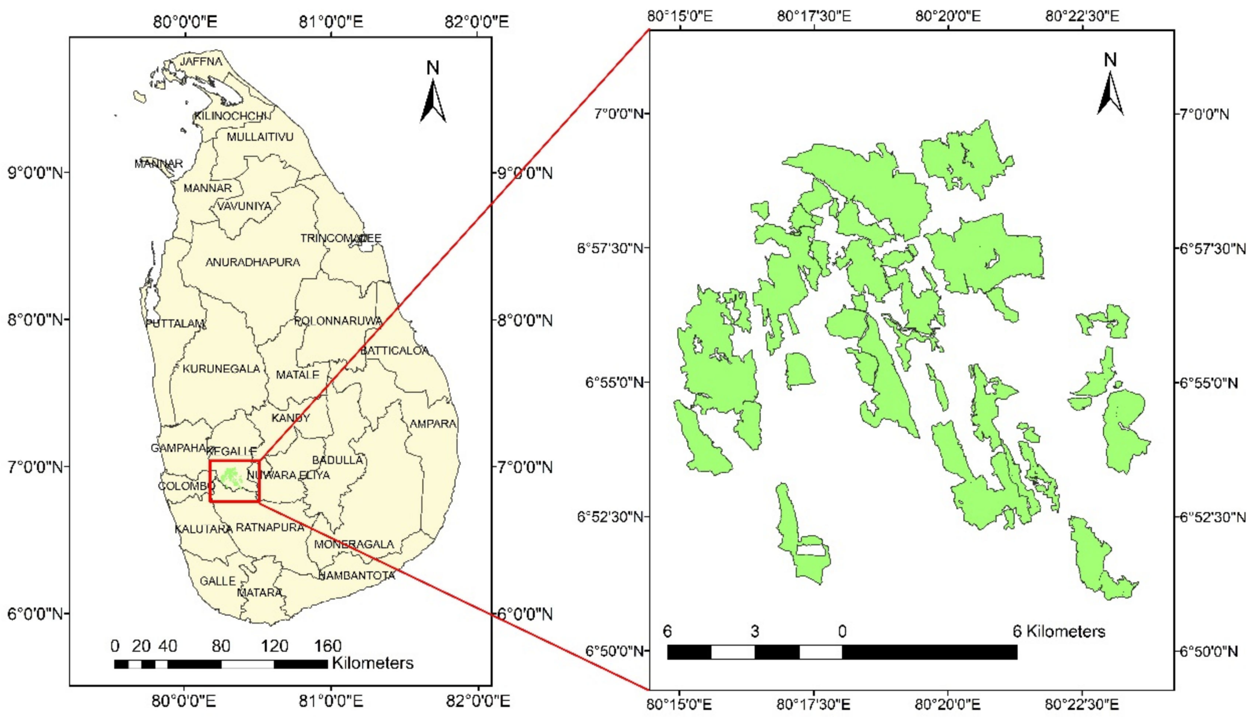

Figure 1. Map of the geographical location of the study area.

2.2. Invest SDR Model Description

The InVEST SDR model has been developed under the Natural Capital Project (www.naturalcapitalproject.org) with the contribution of Stanford University–USA, the Nature Conservancy, and the World Wildlife Fund. The InVEST SDR model is a spatially explicit model that is used to estimate the amount of annual soil loss in a specific land area based on the USLE (refer to Equation (1)) [32,33].

$$\text{USLE} = \text{R} \times \text{K} \times \text{LS} \times \text{C} \times \text{P} \quad (1)$$

where, R is rainfall erosivity factor (MJ mm (ha hr)$^{-1}$) which is the capability of rainfall to cause soil loss from slopes by rainwater [34], k is soil erodibility factor (t ha hr (MJ ha mm)$^{-1}$) that shows the vulnerability of each soil type towards soil erosion [35], LS is slope length-gradient factor that denotes the effect of the slope's length and steepness on the soil erosion by water [36], and C is a crop-management factor that reflects the effect of cultivation practices on the soil erosion process. The impacts of cropping and management options on soil conservation plans can be compared using the C factor [37]. P is a support practice factor that reflects the soil loss ratio under defined conservation measures [34].

As shown in Figure 2, the major input data of the model are digital elevation model (DEM), rainfall erosivity factor (R) map, soil erodibility factor (K) map, crop management factor (C) data, and support practice factor (P) data of each land use land cover (LULC) type. The InVEST SDR model works at a finer spatial resolution of the DEM raster, and ultimately the model estimates the amount of annual soil loss that occurs from the pixel by integrating input data according to the USLE [33]. The total soil loss map and the soil erosion potential (RKLS) map are the major outputs of the model. The soil erosion hazard zonation map can be generated using the model outputs [23].

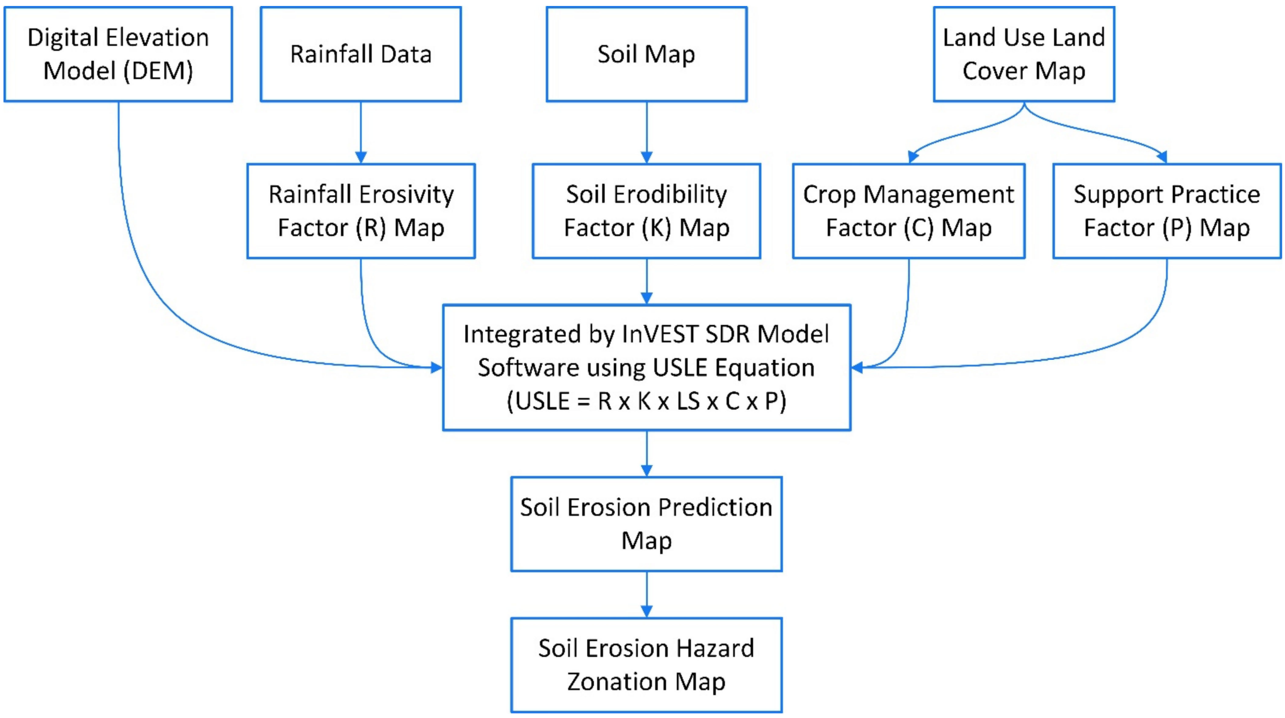

Figure 2. Graphical illustration of the theory behind running the InVEST SDR model.

2.3. Derivation Methods of Input Data for Model

2.3.1. Digital Elevation Model (DEM)

The DEM of the study area was processed using ArcGIS 10.4 software. First, the DEM grids of 30 m × 30 m resolution which covers the spatial extent of the plantation area were obtained from the United States Geological Survey (USGS) (https://earthexplorer.usgs.gov;

accessed on 28 November 2021) website. Then, DEM raster maps were filled in sinks by incorporating the ArcGIS Fill tool [33]. The final DEM raster was exported in the format of the tiff (refer to Figure 2). In order to validate the DEM, finally it was compared with the hydrographic maps of the study area.

2.3.2. Rainfall Erosivity Factor (R)

Monthly rainfall data (2015 to 2020) at fifteen rainfall gauging stations of the plantation area were collected from the respective estates of the plantations. Based on the collected rainfall data, the mean annual rainfall (MAR) interpolation map of the study site was generated using the Inverse Distance Weighted (IDW) method with power 2 under the ArcGIS environment (refer to Figure 3). Ultimately, the MAR map was converted into an R factor map with 30 m × 30 m resolution using Equation (2) developed for Sri Lanka [14]. For this purpose, the Raster Calculator tool in ArcGIS was used.

$$R = \left(\frac{972.75 + 9.95 \times MAR}{100} \right) \quad (2)$$

where MAR is mean annual rainfall (mm).

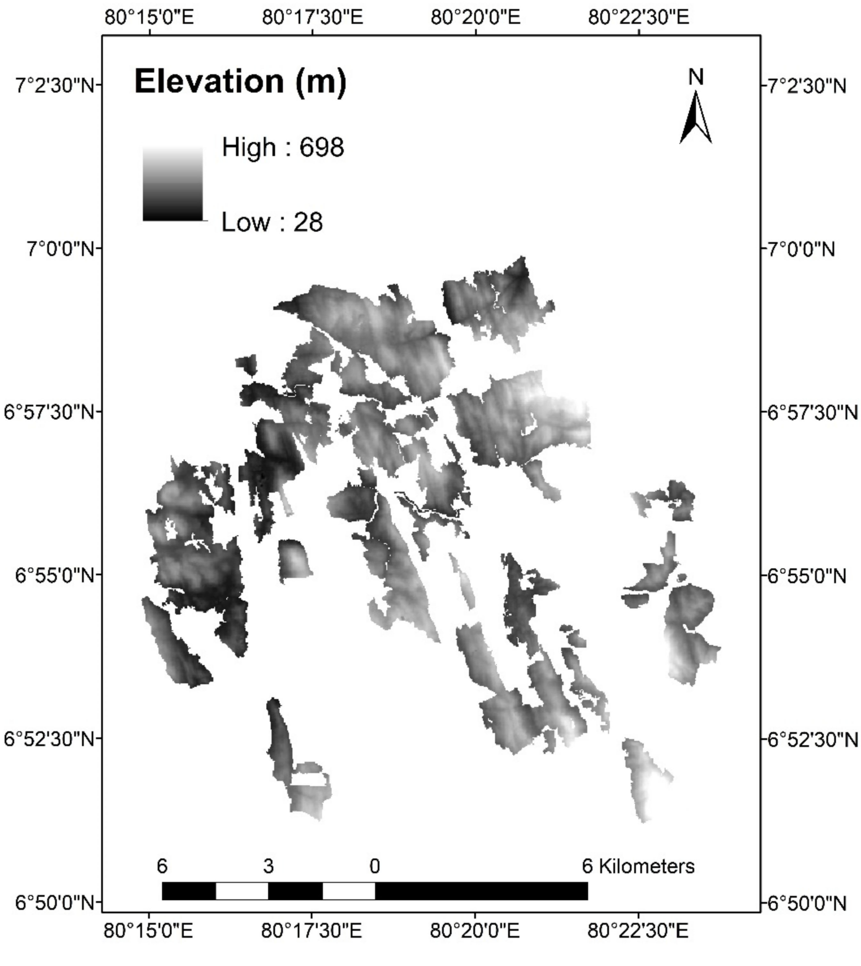

Figure 3. Generated DEM of the study area.

2.3.3. Soil Erodibility Factor (K)

The soil map of the study area was collected from the Natural Resource Management Center (NRMC), Peradeniya, Sri Lanka. The K factor is specific for each soil type and the K values for specific soil types were obtained from the previously published literature [23,38,39]. Based on the soil types of the polygon map and the obtained K factor values for each soil type, the K factor raster map was generated with 30 m × 30 m resolution using the Feature to Raster tool in ArcGIS 10.4.

2.3.4. Land Use Land Cover (LULC)

The Feature to Raster tool in ArcGIS 10.4 was used to convert the LULC polygon map of the area into a raster map (refer to Figure 4). When converting the polygon map to raster data set, a specific LULC code was assigned for each LULC type which corresponds to the biophysical table that consists of the support practice (P) and crop management (C) factors.

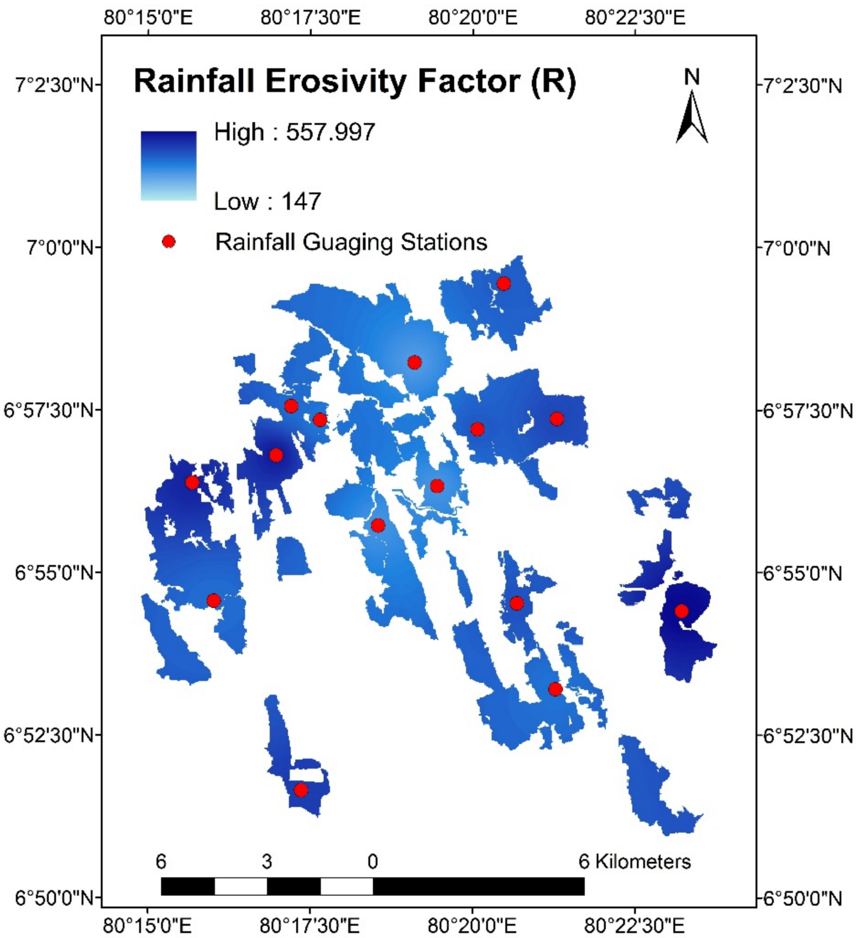

Figure 4. Map of the spatial distribution of the R factor with rainfall gauging stations of the study area.

2.3.5. Biophysical Table with Support Practice (P) and Crop Management (C) Factors

The InVEST model requires P and C factor values for each LULC type (refer to Table 1). The P factor and C factor values were collected from the literature [23,31,40,41]. Accordingly, the generated input data (refer to Figure 1) were integrated to simulate the InVEST SDR model by the InVEST 3.7 software.

Table 1. Biophysical table with C factor and P factor values used in the model [7,40–42].

Code	LULC Description	C Factor	P Factor
1	Rubber	0.2	0.35
2	Tea	0.2	0.5
3	Coconut	0.2	0.35
4	Cinnamon	0.1	0.25
5	Gliricidia	0.1	0.25

Table 1. *Cont.*

Code	LULC Description	C Factor	P Factor
6	Pepper	0.1	0.25
7	Forest	0.001	0.1
8	Scrub Land	0.001	0.1
9	Buildup area	0.001	0.001
10	Home Garden	0.05	0.25
11	Nursery	0.001	0.001
12	Barren Land	0.05	0.25
13	Village	0.05	0.25
14	Playground	0.01	0.02
15	Cemetery	0.01	0.02
16	Timber	0.01	0.02
17	Grass Land	0.01	0.2
18	Paddy Field	0.2	0.15
19	Marshy Land	0.001	0.001
20	Public Road	0.001	0.001
21	Stream	0.001	0.001

2.4. Input Components Generation in the InVEST SDR Model

As explained by Sharp et al. [33], in this model run, the LS factor is automatically calculated by the InVEST 3.7 software based on the details of input DEM. When employing USLE in soil erosion assessments, slope length factor (L) and slope steep factor (S) are considered together as slope gradient factor (LS) due to the proportionate increase in soil erosion with the increase in length and incline of slope [34]. The combined effects of slope length and slope incline gives a good estimate of the soil erosion rate [43]. The manual calculation method of the LS factor has been initially proposed by Wischmeier and Smith (1978) whereas in the twentieth century GIS/RS-based calculation methods for the LS factor has been developed based on the initial approach and become more prominent [15]. For instance, ~85% of the soil erosion assessing studies that have been conducted in Sri Lanka have used GIS/RS methods while only Jayarathne et al. [44] and Wijesekera & Samarakoon [45] have used manual methods. However, the InVEST SDR model calculates the LS factor by using Equation (3) [34,46].

$$LS = S_i \left(\frac{\left(A_{i-in} + D^2\right)^{m+1} - A_{i-in}^{m+1}}{D^{m+2} \cdot x_i^m \cdot (22.13)^m} \right) \tag{3}$$

where, S_i is the slope factor for grid cell i that is calculated as a function of slope radians θ, A_{i-in} is the contributing area (m^2) at the inlet of a grid cell that is computed from the d-infinity flow direction method, D is the linear dimension of the grid cell (m) and $x_i = |\sin \alpha_i| + |\cos \alpha_i|$ on which α_i is the aspect direction for grid cell i. m is the USLE length exponent factor.

2.5. Data Analysis

The correlation between total soil loss and model parameters (R, K, LS, C, and P) were assessed using the Pearson correlation. The model parameters (R, K, LS, C, and P) data of 30 known points were extracted using the Multivalues to Points Tool of ArcGIS 10.4 software and tested for their correlation using Minitab 17 statistical software.

3. Results and Discussion

3.1. Generated Input Components of the InVEST SDR Model

Figure 3 presents the generated DEM for the study area. The DEM illustrates that the elevation varies from 28 m to 698 m with a mean of 198.6 ± 92.2 m.

The spatial distribution map of the R factor with rainfall gauging stations of the plantation area is shown in Figure 4. The R factor map illustrates that the estimated mean R-value for the entire study area is 364.5 ± 98.3 MJ mm ha^{-1} hr^{-1} whereas the R values varied from 147.0 to 557.9 MJ mm ha^{-1} hr^{-1}. As explained by [47], when calculating the R factor, various methods have been employed worldwide corresponding to the geographical area. However, in ~76% of GIS/SR-based soil erosion modeling studies in Sri Lanka, the correlation developed by Wickramasinghe & Premalal [14] (refer to Equation (2)) has been used to calculate the R factor [15]. Approximately, ~15% and ~8% of studies used the Roose equation [48] and the original K.E. > 25 Index method, respectively.

The soil map of the study area revealed that the entire plantation area was covered by Red Yellow Podzolic soil (refer to Figure 5). According to the previously published literature, the soil erodibility factor for Red-Yellow Podzolic soils was determined as 0.22 t ha hr (MJ ha $mm)^{-1}$ [23,38,39]. Therefore, the K factor for the entire area was determined as 0.22 t ha hr (MJ ha $mm)^{-1}$. The K factor values directly depend on the soil type and they generally vary from 0.05 to 0.45 t ha hr (MJ ha $mm)^{-1}$ [48]. Soil types that are low susceptible to detachments have low K factor values whereas high erosion susceptible soil types viz. sandy soils have high K factor values near 0.45 [49]. Thus, it can be inferred that the Red Yellow Podzolic soils ranged in the medium in terms of erodibility. Moreover, in order to estimate exact K factor values for a specific area, some data of soil parameters viz. organic matter (OM) percentage, sand, and silt percentage, and permeability are required [36], and it can be derived based on the method employed by Yitayew et al. [50]. However, due to the fact that this manual method is highly time-consuming and labour-intensive, approximately ~85% of the previous GIS/RS-based soil erosion modeling studies that have been conducted in Sri Lanka have obtained K factor values from the previously published sources whereas, only [51,52] have used field-based manual calculation methods of K factor [23].

Based on the generated LULC map, the plantation field consists of 22 LULC types including crop types of namely rubber, coconut tea, cinnamon, pepper, and paddy (refer to Figure 5). The percentage area of each crop type was calculated using the Tabulate Area Tool of the ArcGIS software. According to the calculations, rubber occupied the largest area covering ~64.6% of the total land area. It was followed by natural forests comprising ~9.8% and scrublands comprising ~5.6%. The area also consisted of other crops viz. coconut (~4.7%), tea (~1.4%), paddy (~0.2%), cinnamon (~0.1%), and pepper (<0.1%), and other LULC types (~13.6%).

The biophysical table is one of the most significant inputs of the model which is shown in Table 1. According to the formulated biophysical table, the C factor values for each LULC type ranged from 0.001 to 0.2 (refer to Table 1). Generally, C factor values ranged from 0 to 1.5 whereas finely covered land areas with proper crop systems are assigned nearly 0 values and higher values are assigned for highly vulnerable LULC types for soil erosion [53]. However, there are two derivation methods of the C factor available as a derivation of C factor using Normalized difference vegetation index (NDVI) techniques and derivation of C factor values based on previous studies for similar LULC types in similar geographical regions [53]. It was reported that ~93% of the soil erosion modeling studies that were conducted in Sri Lanka have used previous literature to determine the C factor since the NDVI method is time-consuming, labour intensive, and requires advanced technology viz. satellite imagery, aerial photography, and image processing [23]. The P factor value for the selected plantation varied from 0.001 and 0.35 (refer to Table 1). According to Bagherzadeh [54], the P factor ranges from 0 to 1 whereas near 0 values are assigned to LULC types with good land management practices and nearly 1 assigned to LULC types with poor land management practices which allow the soil to erode easily.

P factor can also be utilized as a direct recognition of how soil conservation practices are effective in land management practices.

Similar to the C factor, generally, the P factor also can be obtained from the previously published literature related to the interested area or region where the study has been conducted. Moreover, ~86% of Sri Lanka soil erosion modeling studies have used previously published data for obtaining P factor values for each land use and land cover class [23]. Other ~14% of studies have omitted using the P factor when developing soil erosion models. Furthermore, in order to develop soil erosion models more precisely and accurately, the employment of geographical-specific data is vital [23]. Since the development of such methods is labor-intensive and time-consuming, already published data were used in the previous studies. In the current study, we also have used previously published data although area-specific data are recommended by the authors.

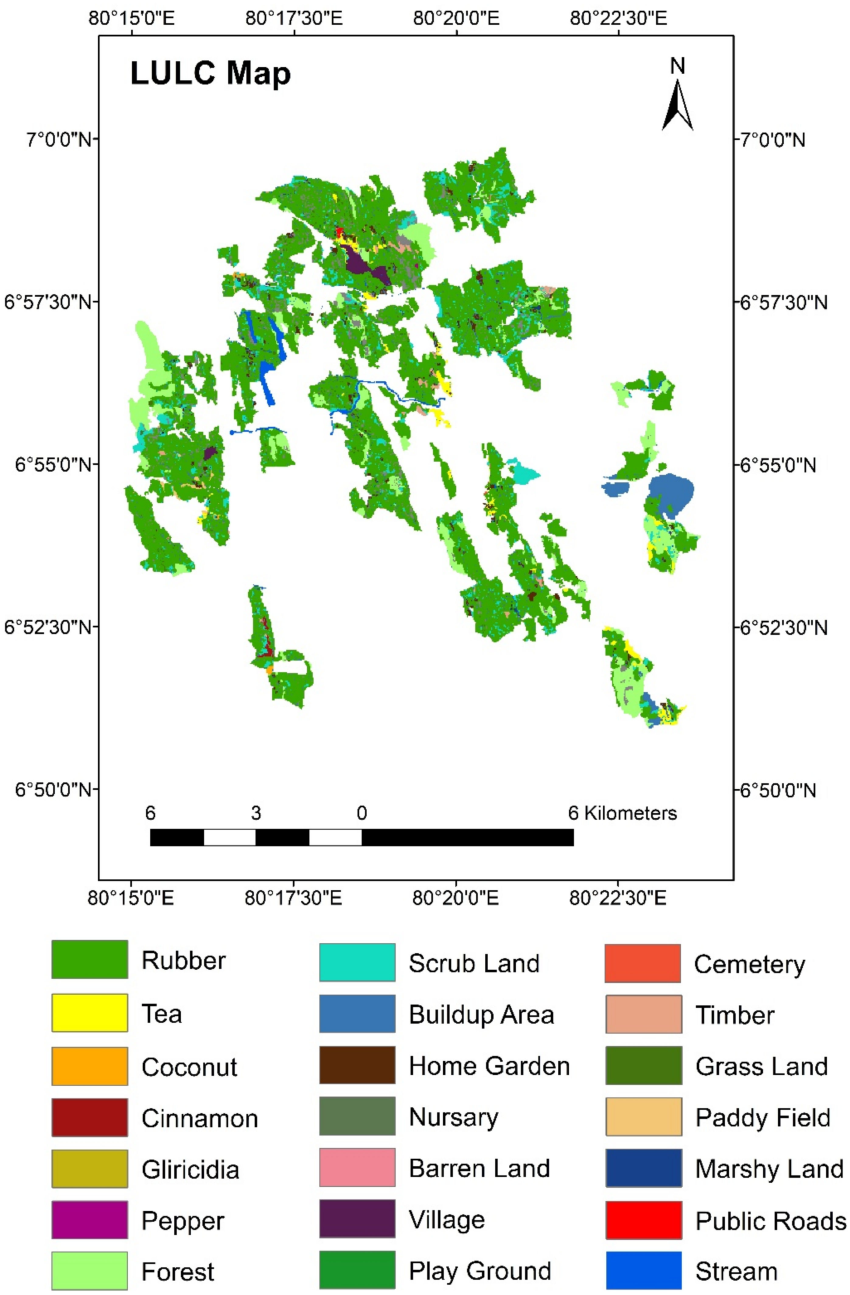

Figure 5. Map of the spatial distribution of LULC types of the study area.

3.2. Outputs of InVEST SDR Model

3.2.1. Soil Erosion Potential Map (RKLS)

The RKLS is one of the outputs obtained after the simulations (Figure 6). Soil erosion potential is described as soil loss values in bare soil [15]. Therefore, RKLS was calculated based on only R, K, and LS factors while excluding C and P factors which describe the effect of LULC types and land management practices.

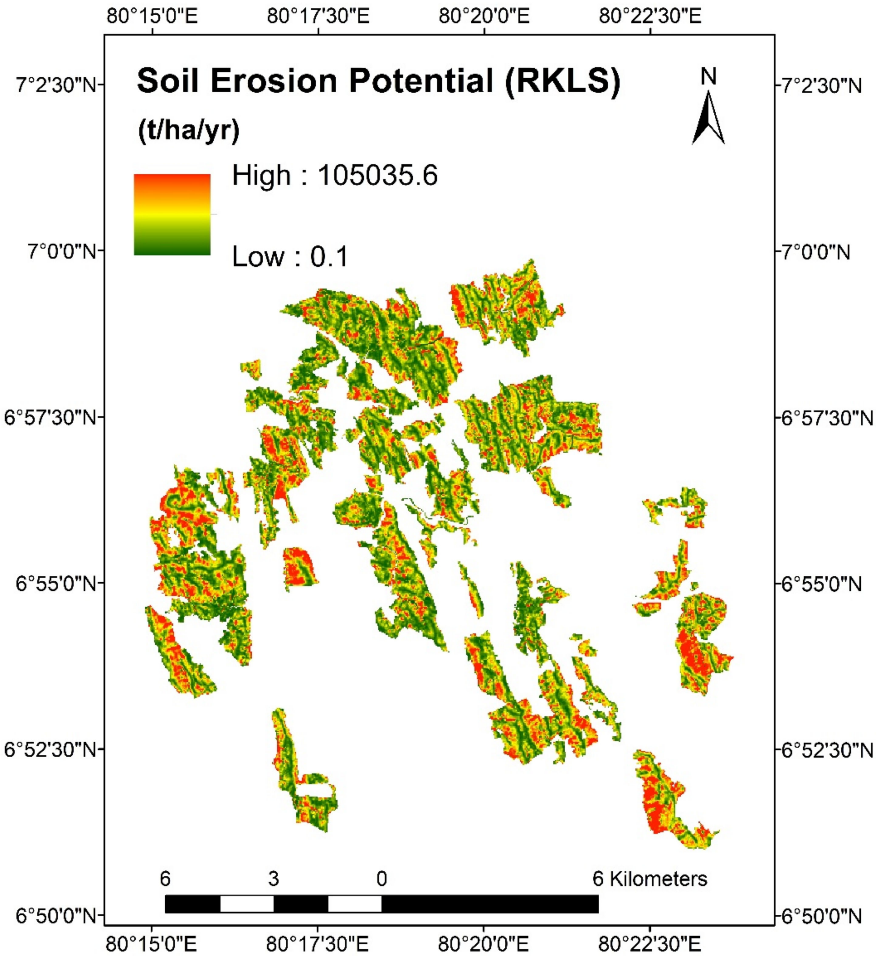

Figure 6. Soil erosion potential map (RKLS) of the study area.

The mean annual soil erosion potential of the study areas is 2458.6 t ha^{-1} $year^{-1}$ whereas RKLS values varied from 0.1 to 105,035.6 t ha^{-1} $year^{-1}$ (refer to Figure 6). As illustrated in Figure 7, a nearly equal fraction of areas falls under high, middle, and low RKLS values. Furthermore, the K factor of the entire area is high and remains approximately unchanged. Also, the R factor of the study areas does not vary compared to the RKLS map (refer to Figure 4). Moreover, when compared to the RKLS map (refer to Figure 6) with the DEM (refer to Figure 3), it is apparent that the areas with high RKLS values are overlaid with the highly elevated areas. It is evident that the RKLS of the study area is directly related to the LS factor which is derived based on the DEM (refer to Figure 3).

3.2.2. Total Soil Loss Map (USLE)

The most vital output of the model is the total soil loss map (refer to Figure 7) since it gives the spatial distribution of total soil loss in the selected plantation based on the USLE equation (refer to Equation (1). The mean annual soil loss of the study area was estimated as 124.2 t ha^{-1} $year^{-1}$ while the USLE value varied from 0.1 to 6903.3 t ha^{-1} $year^{-1}$. Therefore, it is evident that there is a significant reduction in the averaged USLE value

(124.2 t ha^{-1} $year^{-1}$) compared to the RKLS value (2458.6 t ha^{-1} $year^{-1}$) and it can be hypothesized that this occurs due to the effects of crops and land management practices in Sri Lankan plantations. Out of the several factors affecting soil erosion in agricultural fields, the type of vegetation plays a major role [55]. Generally, soil erosion from plantations is relatively lower compared to annual crops, but since crops require a few years to close the canopies, the erosion from plantation crops is relatively higher during the early stage [56]. Natural vegetation is disturbed in the expansion of plantations; therefore, comparatively higher soil erosion was reported among various types of plantations that include tea and rubber [55–57]. The undulating terrain and the steep lands in high rainfall areas trigger erosion.

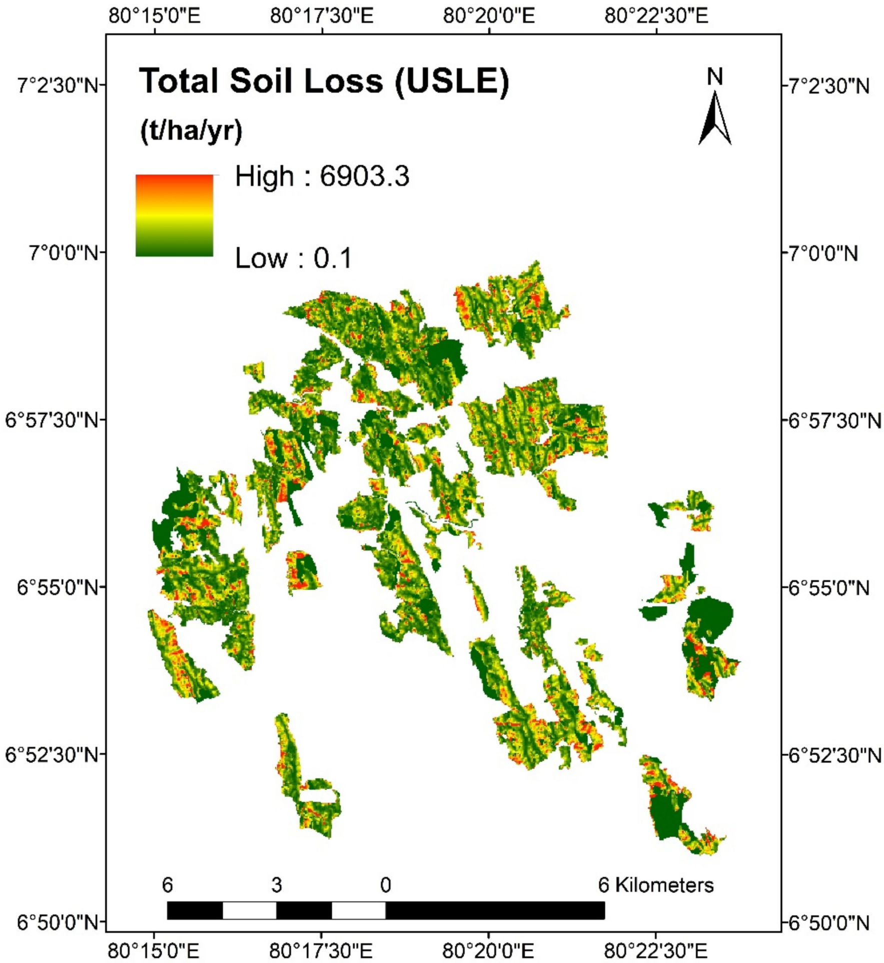

Figure 7. Total soil loss (USLE) map of the study area.

The USLE map (Figure 8) was classified into five soil erosion hazard levels (refer to Table 2) and the area percentages of each hazard level were calculated using Zonal Geometry Tool in ArcGIS 10.4 software [18,37]. The results revealed that ~49.5% of the plantation belongs to the low soil erosion hazard category. Out of the total land, ~23.4% belong to moderate ~18.0% is high, ~7.8% very high, and ~1.3% extremely high soil erosion hazard classes.

According to the Pearson correlation analysis, the relatively highest correlation was recorded between total soil loss and R factor (0.3) followed by C factor (0.2), P factor (0.2), LS factor (0.1), and K factor (<0.1). Therefore, it can be inferred that the effects of rainfall play the most significant role in soil erosion in the study area, and it was observed that comparatively high rainfalls are normally experienced in this plantation area since the area belongs to the wet zone of the country. This might increase the soil erosion vulnerability of the plantation area. Furthermore, since the same soil type (Red Yellow Podzolic) was laid in the entire study area, it can be inferred that the effect of the K factor is approximately equal in the entire area. However, Red-Yellow Podzolic is a prominent soil type in extremely high soil erodible areas in Sri Lanka viz. Badulla district [15]. Furthermore, the mountainous, steeply dissected, and rolling topography, nature was identified in the study area, and those fall under high, very, and extremely highly vulnerable areas. Also, low mountainous and flat terrains were identified in areas where soil erosion vulnerability is recorded as low to moderate. Most importantly, the most prominent LULC type in these areas is rubber (refer to Figure 5). Since rubber is a perennial crop, it suits mountainous and steep lands to reduce soil erosion vulnerability [18]. However, the study area consists of several crop types and the descriptive statistics of soil erosion in each crop type are shown in Table 3. According to the results, the rubber and tea land areas fall under the extremely high soil erosion hazard category, coconut, cinnamon, and paddy fall under the very high soil erosion hazard category, and pepper falls under the high soil erosion hazard category. Therefore, when crop types are individually evaluated, the soil erosion vulnerability is relatively higher. However, contour staggered trenches [58], implementation of various types of cover crops [58,59], advanced weed management strategies [60], and intercropping with other cash crops [61] were reported as some of the effective methods to control soil erosion on plantations. Other than that, existing soil conservation methods in plantations in Sri Lanka include contour planting and growing soil conservation grasses along the lower side of the slope, maintenance of ground cover during the early stages of planting, leader drain and lateral drain system with reverse slope steps in leader drain and stone terracing along the contour of the sloppy land can be practiced to minimize the soil erosion.

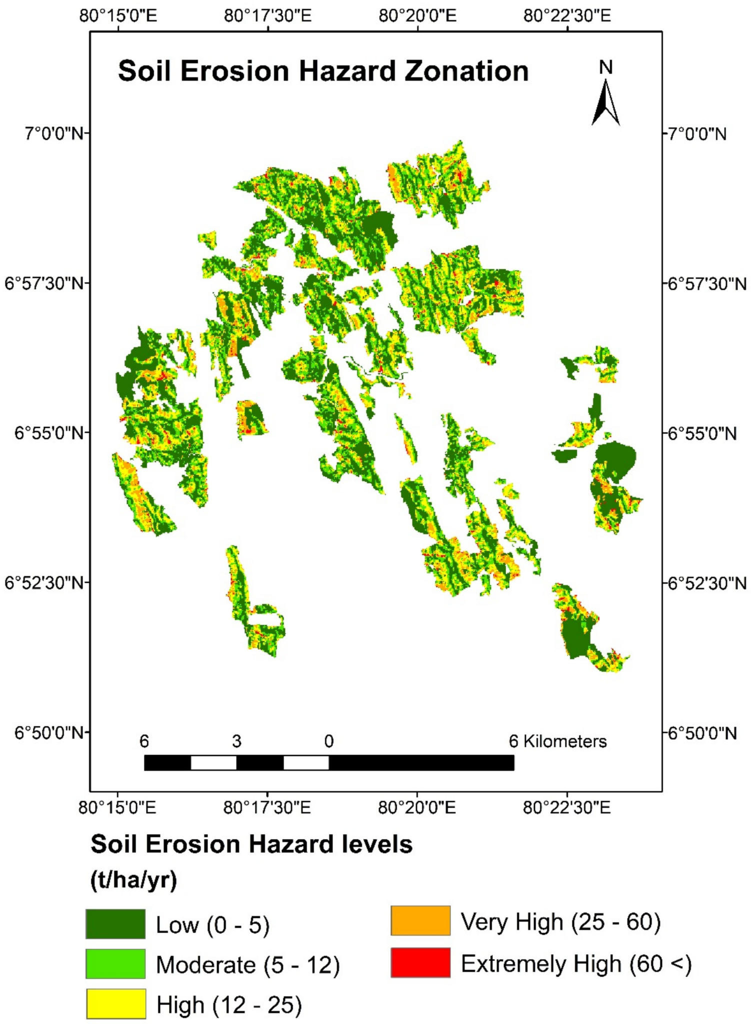

Figure 8. Soil erosion hazard zonation map of the study area.

Table 2. Soil erosion hazard classes in the study area.

Erosion Hazard Level	Average Annual Soil Loss (t ha^{-1} $Year^{-1}$)	Area Percentage (%)
Low	0–5	49.5
Moderate	5–12	23.4
High	12–25	18.0
Very High	25–60	7.8
Extremely High	60<	1.3

Table 3. Descriptive statistics of soil erosion in each crop type.

LULC	Max (t ha^{-1} yr^{-1})	Min (t ha^{-1} yr^{-1})	Mean (t ha^{-1} yr^{-1})	SD (t ha^{-1} yr^{-1})
Rubber	5231.1	12.2	131.1	167.8
Tea	1064.4	38.9	138.9	157.8
Coconut	627.8	21.1	37.8	47.8
Cinnamon	192.2	54.4	34.4	37.8
Pepper	62.2	2.2	17.8	17.8
Paddy	578.9	108.9	48.9	87.8

3.3. Limitations of the Model

The InVEST SDR model is completely dependent on the USLE while USLE only represents the rill and inter-rill soil erosion process excluding mass erosion and gully erosion processes [53]. However, mountainous and steeply sloped land areas might be significantly undergone mass erosion and gully erosion. Furthermore, in this model, the C and P factor values are incorporated respectively into the given LULC data whereas the effects of certain LULC changes viz. road development, construction, and crop changes are not represented in the model. Further, the impact of current soil conservation measures viz contour planting, stone terracing, and drainage systems are not accounted for in the model to reduce soil erosion. Other than that, as an empirical equation initially developed in the USA, the USLE equation may show limited performance when incorporating previously published methods of obtaining the R factor, K factor, C, factor, and P factor. However, this limitation might be overcome by employing geographical-specific local derivation methods [62]. Moreover, the outputs of the model are very sensitive to the input parameters since this model uses a low number of parameters to predict soil erosion. Therefore, the errors in deriving input parameters may have a large effect on soil erosion prediction. However, it was observed that the soil erosion hazards in forests and scrublands are very low and this might be due to the fact that not exposing the topsoil to erosion. The methodology used in this study can be effectively used by the Sri Lankan plantation sector to model the soil erosion hazards easily whereas the results of the current study can be used in prioritization of high-risk plantation areas for conservation.

4. Conclusions

This study provides important information on the soil erosion risk in plantations of Sri Lanka and the effects of rainfall, soil types, crop types, land management practices, and slope gradient on soil erosion. The estimated mean R-value for the entire study area was 364.5 ± 98.3 MJ mm (ha hr)$^{-1}$ whereas the R values vary from 147.0 to 557.9 MJ mm (ha hr)$^{-1}$. The generated DEM of the study area illustrates that the elevation ranged from 28 m to 698 m whereas the mean elevation was recorded as 198.6 ± 92.2 m. Based on the RKLS map, the mean RKLS of the study areas was estimated as 2458.6 t ha^{-1} $year^{-1}$ while the RKLS values varied from 0.1 to 105,035.6 t ha^{-1} $year^{-1}$. The USLE of the study area was estimated as 124.2 t ha^{-1} $year^{-1}$ whereas the USLE value ranged from 0.1 to 6903.3 t ha^{-1} $year^{-1}$. Out of the total extent, ~49.5% of the area belongs to the low soil erosion hazard category (0–5 t ha^{-1} $year^{-1}$) while ~7.8% falls into very high (25–60 t ha^{-1} $year^{-1}$) and ~1.3% into extremely high (60< t ha^{-1} $year^{-1}$) soil erosion hazard classes. The outcomes of this study can be used in formulating agricultural making and soil conservation measures planning in the plantation sector in Sri Lanka and to prioritize the vulnerable lands to ensure proper land management practices in the agricultural sector on the country's way to meet the SDGs.

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