EVALUATION OF SOIL LOSS ACROSS LAND USE TYPES IN NORTHERN VIETNAM, A CASE STUDY OF TAY CON LINH MOUNTAIN

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Abstract

Deforestation and farming offer two of the most serious risks to soil erosion (SER), water degradation, and desertification... Based on the Universal Soil Loss Equation (USLE) proposed by Wischmeier and Smith, the paper aims to use Geographic Information Systems (GIS) to evaluate the risk of SER in the Tay Con Linh mountain area in Vietnam. Maps of the environmental parameters and the resulting erosion risk were also proposed. The study has discovered that the kind of vegetation in the area was the primary factor in SER. It was concerned with farming methods relevant to steep topography. Studies have demonstrated that the vegetation type in this region is a key determinant of severe erosion. To validate the methodology, Google Earth images of locations identified as prone to erosion were analyzed based on strict criteria. The model demonstrated an efficiency rate of 88.5%. According to the Vietnamese standard TCVN 5299:2009, the levels of erosion in the study area are quite complex but classified as medium risk, with many regions exhibiting R-I level conditions (93.51% soil loss of 10 tons per hectare per year). The study established correlations between the degree of erosion and the amount of vegetation cover, emphasizing the impact of land use on soil erosion rates. This assessment of soil erosion not only aids land users in making informed decisions regarding land use and ecosystem conservation but also provides scientific criteria that complement traditional farmers' knowledge.

Keywords: *Deforestation; USLE; modeling; erosion; GIS.*

1. Introduction

Soil includes a multitude of organisms that make up a dynamic and complex ecosystem. Human activities gradually replaced natural forests with grasslands and agriculture [1]-[3]. The change from natural vegetation to agriculture, such as coffee, cotton, and wheat, may accelerate SER beyond the natural regeneration capacity of the land. SER causes compaction, structural loss, and deterioration [4], [5].

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DOI: 10.56651/lqdtu.jst.v8.n01.893.sce

SER has the consequences of losing productive land, especially in agriculture. It leads to deterioration of soil quality, and increased sedimentation in rivers and streams, affecting the habitat of organisms [6]. In arid areas, the soil is less able to hold water, and erosion can make flooding worse. Therefore, sustainable land use can help reduce land degradation (SER and desertification) and support sustainable agro-forestry development. Today, farmers and communities around the world care about the health of their soil because their livelihoods depend on agriculture.

The Vietnamese literature recently concentrated on quantifying land loss across huge areas. Most quantitative and geographic SER studies ignore the impacts of agricultural land use and its diversity (spatial heterogeneity). The effect of seasonal landscape elements on SER susceptibility and, as a result, landscape dynamics is studied annually [1]. Even though shifting cultivation systems implement low-level land management methods, the lack of evident soil conservation measures makes the soil more susceptible to environmental damage. Therefore, rain-dependent cropping systems, consisting mostly of soybeans and cassava, are grown on steep (hilly) lands, the areas with the highest rates of SER. Their watershed is most sensitive to the loss of land. Wischmeier and Smith [7] proposed a formula to evaluate the SER using Universal Soil Loss Erosion (USLE). From the mid-1980s to the early 1990s, different erosion models were developed based on this USLE equation in many parts of the world, such as the land loss prediction model for southern Africa - SLEMSA [8], the SOILOSS model [9] in Australia, and the ANSWERS model in the late 1970s to assess the extent of sedimentation in river basins.

Using the USLE and the techniques associated with geographic information systems, this study aims to determine the land loss level that occurred in the Tay Con Linh mountainous region of the Ha Giang province in Vietnam. The amount of land lost because of erosion has been calculated using the USLE model. The model considers the influence of rain, SER resistance, slope and slope length, layer parameters (crop growth stage, crop type, vegetation cover), and soil cultivation methods. The model also considers the length of the yearly rain periods. Because of the influence of these elements in the model, establishing and quantifying erosion factors is of the utmost significance. The model will use these factors to evaluate the potential sensitivity for erosion and its existing status. The findings of the model shift in response to adjustments made to any of its components. This is a straightforward model, and the results were widely applied primarily because of their high precision.

2. Study area, materials and methods

2.1. Study area

Tay Con Linh is a mountainous area in Ha Giang province, the central part of Northern Vietnam (Fig. 1). The map shows that trees and cropland cover most hills. The recent increase in rainfall intensity during the rainy season caused slips, landslides, pipe floods, flash floods, and erosion. The study area is a mountainous land including 2 districts: Hoang Su Phi and Vi Xuyen, Fig. 1); the terrain is mainly covered by natural and agro-forestry vegetation on sloping terrain.

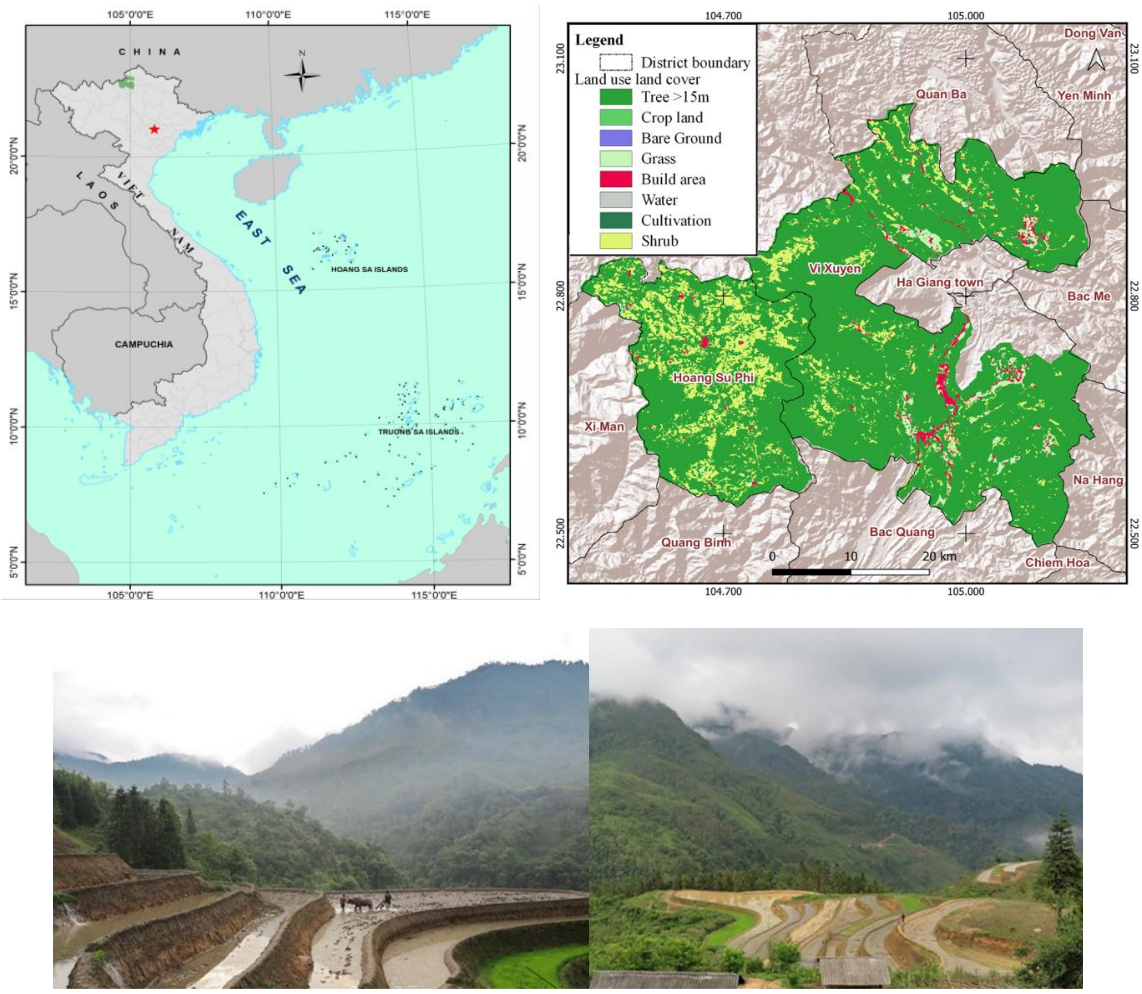

Fig. 1. Study area.

2.2. Materials and methodology

The USLE model was developed to predict SER on agricultural lands and is used to guide soil conservation efforts and land management practices. The USLE was first introduced by Wischmeier and Smith [7] and has since undergone various refinements.

The USLE model takes into account several factors that contribute to SER:

1) R - rainfall and runoff factor: This factor accounts for the erosive power of rainfall and the resulting runoff. The intensity, duration, and frequency of rainfall events are considered.

2) K - soil erodibility factor: This factor describes the susceptibility of the soil to erosion. It takes into account soil properties such as texture, organic matter content, permeability, and structure.

3) LS - slope length and steepness factor: This factor considers the combined effect of slope length and steepness on erosion. Longer slopes and steeper gradients generally lead to higher erosion rates.

4) C - cover and management factor: This factor evaluates the protective cover provided by vegetation and the impact of land management practices, such as tillage and crop rotation, on erosion.

5) P - support practice factor: This factor reflects the effect of additional erosion control practices, such as contour farming, terracing, and buffer strips.

The USLE equation is as follows:

$$A = R \times K \times LS \times C \times P \qquad (1)$$

where R, K, LS, C, and P are model factors (MFs), A is the estimated soil loss in tons (tons ha^{-1} $year^{-1}$), R is the rainfall and runoff factor, K is the soil erodibility factor, LS is the slope length and steepness factor, C is the cover and management factor, P is the support practice factor.

The USLE model provides a way to quantify the potential SER on a particular piece of land under specific conditions. However, the model has its limitations, as it simplifies complex erosion processes and may not fully account for certain site-specific factors. More advanced models and technologies have been developed over the years to address some of these limitations. According to the USLE model, maps need to be constructed for the MFs to establish a SER map. The overlay of the R, K, and LS maps allows the production of a potential erosion map using Eq. (1). Finally, overlay with the maps of the C and the P factor allows the production of the actual erosion map. The risk maps are calculated using ArcGIS 10.4.1 software which allows the integration of the R, K, and LS coefficient maps by the Rater Calculator into an erosion risk map.

Rainfall erosivity (R). R is the erosion coefficient caused by rain and the resulting runoff; it characterizes the impact of rain on SER. The calculation is based on the average annual rainfall during 10 consecutive years, Eq. (2) allows to calculate R [11]:

$$R = 0.548257 \times P - 59.9 \tag{2}$$

R is the rain-induced erosion (Joules ha^{-1} $year^{-1}$); P is the precipitation (mm $year^{-1}$), the data was raster format downloaded from worldclim.org, resolution 30 seconds (~1 km^2), file The Extract by the Mask tool to cut the study area and the Raster Calculator tool allows to calculate R with formula (2).

Soil erodibility factor (K). K expresses the soil's vulnerability to erosion and is the inverse of SER resistance. The higher the K value of the soil, the more likely it will erode. K value depends on soil properties that determine the stability of the soil structure and its mechanical composition, especially in the upper soil layers and the organic components of the soil. The K value was calculated according to the formula of Wischmeier and Smith [7]:

$$100K = 2.1 \times 10^{-4} (12\text{-}a) \times M1.14 + 3.25 \times (b\text{-}2) + 2.5 \times (c\text{-}3) \tag{3}$$

in which a is % of the organic matter, b is % of the structure, and c is % of the permeability codes; M is the sum of % of silt and very fine sand and the percent of all soil fractions other than clay, the M data was raster format downloaded from https://soilgrids.org/, resolution 250 m.

The slope length and steepness factor (LS). The slope (S) and the slope length (L) influence SER: the steeper the slope, the more vulnerable it is to erosion. Therefore, the LS value can be calculated using the topographic map. The slope map was derived from the topographic map using the Digital Elevation Model (DEM) of Copernicus, with a resolution of 30 meters.

The LS map was evaluated with the formula (4) developed by Mitasova [12]:

$$\text{LS} = \left(FlowAccumulation \times \frac{\text{cellsize}}{22.13}\right)^{\text{m}} \times \left(\frac{sin(Slope) \times 0.01745)}{0.09}\right)^{1.3} \tag{4}$$

If the slope ranges from 1% to 3%, then m = 0.3; if the slope is in the range of (3.5-4.5)%, then m = 0.4; if the slope > 5% then m = 0.5. The slope is over 5% in this study area, so m = 0.5 was used.

The cover and management factor (C). It represents vegetation cover type, the thicker the vegetation, the less likely it is to erode. The C-factor map can be made using the Sentinel 2 image data. The results were similar to those of other research projects [13].

where the cover and management factor (C): water < grass < Submerged vegetation < Shrub < Built Area < Forest tree < Crops < Bare ground.

The practice support factor (P). SER is mostly determined by support practices (SPs), which and SPs are responsive to human intervention. The P-factor represents the SPs factor. Significant decreases in absolute soil loss result from the widespread use of SPs in erodible areas, such as loess zones. If SPs are disregarded, the estimated SER rate for agricultural areas is likely to be significantly higher than the true rate. Therefore, SP impacts should be factored into SER evaluations. However, it is challenging to distinguish SPs using a Land Use Land Cover (LULC) map, and their location cannot easily be determined using LULC map for global-scale research. Hence, the P-factor is seldom considered. In our analysis, we neglected to include the P value since we assumed it would be constant over the whole research region.

Validation of the model: To validate the model, satellite images were used to obtain data from 30 different sites. A focus group analyzed these locations and determined to have an appropriate soil loss volume due to erosion. To determine the accurate index of the effort, a receiver operating characteristic (ROC) curve was generated using these sites. The most recent study also showed the advantage of assessing the accuracy of land degradation when using remote sensing images [14].

Methodological challenges: The study used global data (the annual precipitation, DEM, slope…). The variables should be determined using the results of at least a few years of research to acquire reliable measurements. A short assessment time makes it difficult to determine the value of the factors [15].

3. Results and discussion

3.1. Results

Rainfall erosivity (R). The results in Fig. 2 show the extent to which the R-factor (illustrating the impact of rainfall on the process of SER) affects SER. The highest levels are usually concentrated in the eastern part of the study area. Natural rainfall was used to determine the critical values of the erosion index (indicating the runoff and soil loss in the Tay Con Linh Mountain). Table 1a shows the findings of interpolation of rain (P, mm/year) and R values in Tay Con Linh. Heavier rainfall is usually concentrated in the east due to storm surges.

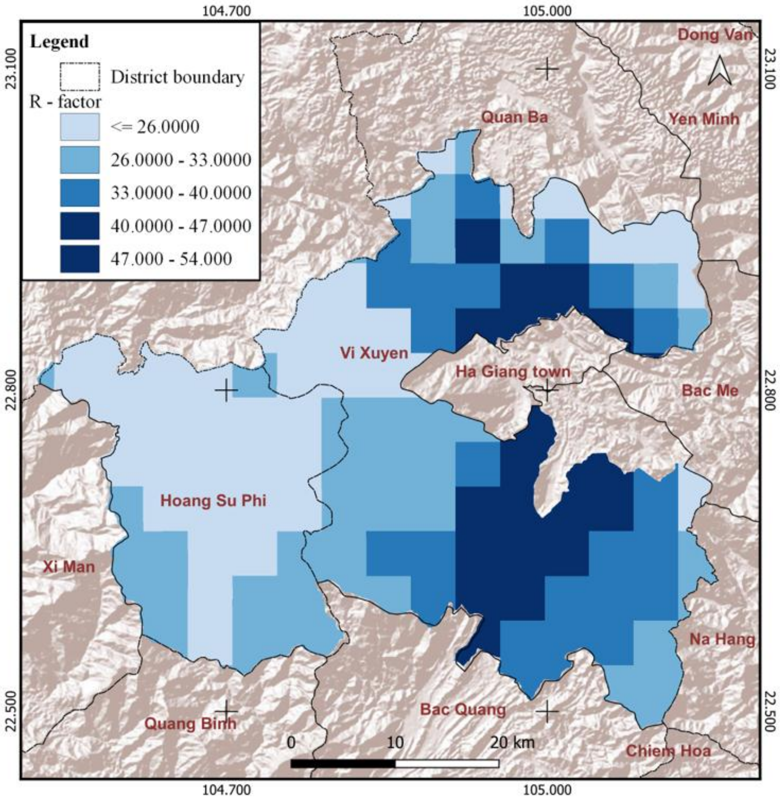

Fig. 2. R-factor map of Tay Con Linh.

Soil erodibility (K). Fig. 3 shows the K value that indicates the resistance of the soil to erosion, ranging between 0.1 and 0.44. The prevalent value of 0.22 applies to most of the area (80.43%). The difference in K value shows an important variation in how resistant the soil is to erosion (Tab. 1b).

The slope length and steepness factor (LS). Fig. 4 shows the slope categories used to calculate the LS value. Most of the slopes are homogeneously distributed over the study area. Fig. 5 shows the distribution of the LS value over the Tay Con Linh Mountain (Tab. 1d). If there is no plant cover, the higher the slope of the region, the more impact on SER. The study area shows that a steep slope covers 45% area (Tab. 1c). This study ignores slope length variation (considered L = 1 meter). The slope is the most significant factor influencing LS. LS < 3 occupies the largest area in Tay Con Linh (97.45%).

The cover and management factor (C). Vegetation may greatly reduce SER by modifying the hydrodynamic characteristics of the over-land flow. Moreover, the beginning moisture content to reduce soil loss to erosion has been determined [16], [17]. These factors are important to prevent slope instability and SER caused by climate change. Fig. 6 shows the C value for each type of vegetation. C = 0.20 (natural forest trees) occupied most of the total area (Fig. 6, Tab. 1e).

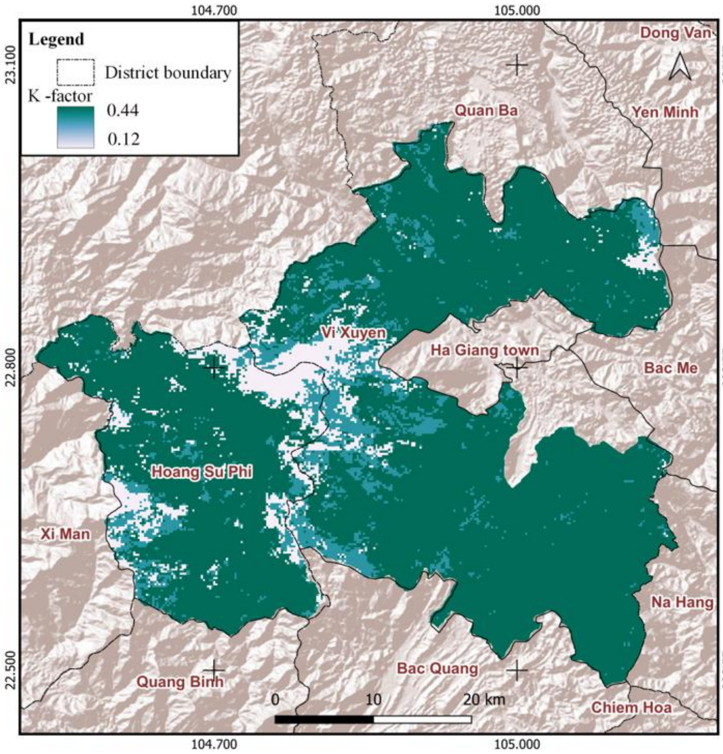

Fig. 3. K-factor map of Tay Con Linh.

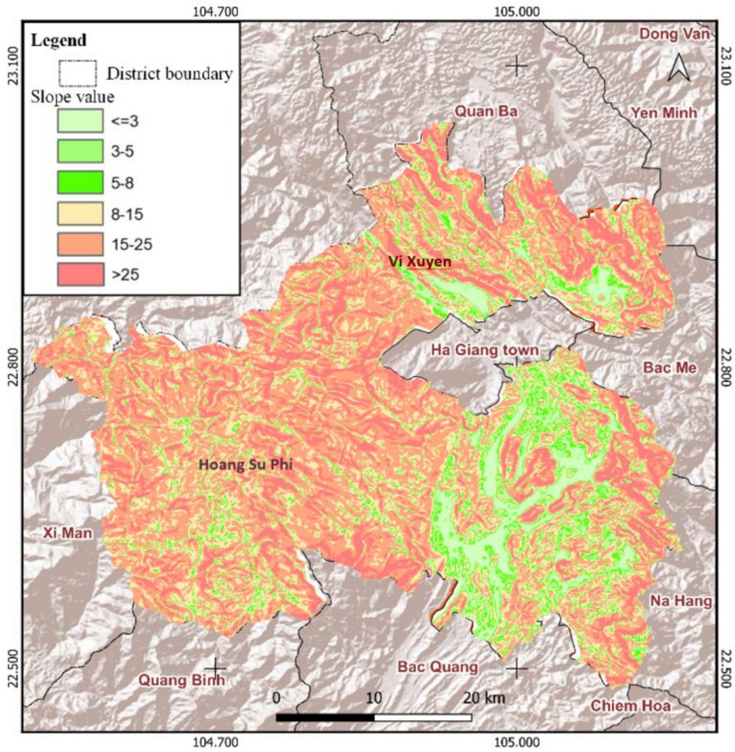

Fig. 4. The slope map of Tay Con Linh.

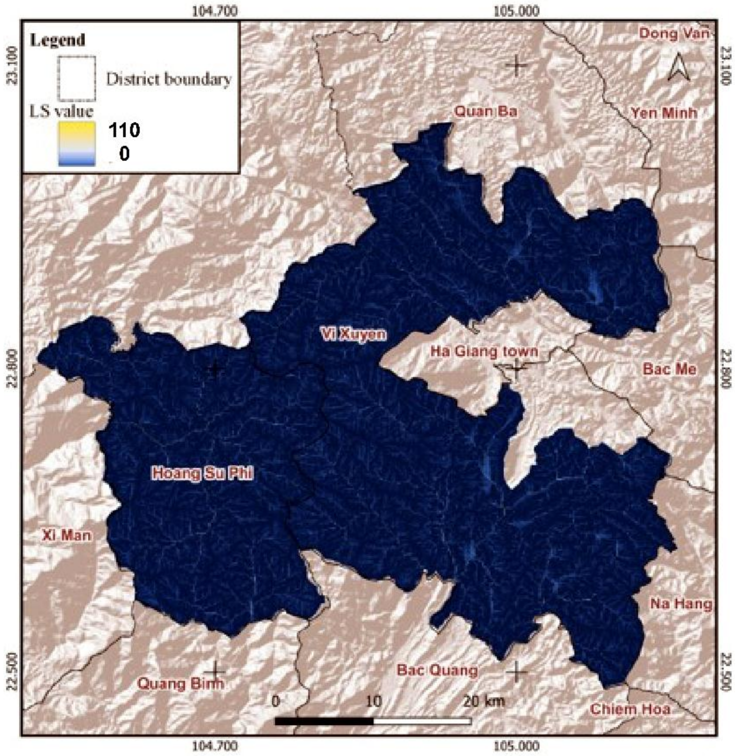

Fig. 5. LS-factor map in Tay Con Linh.

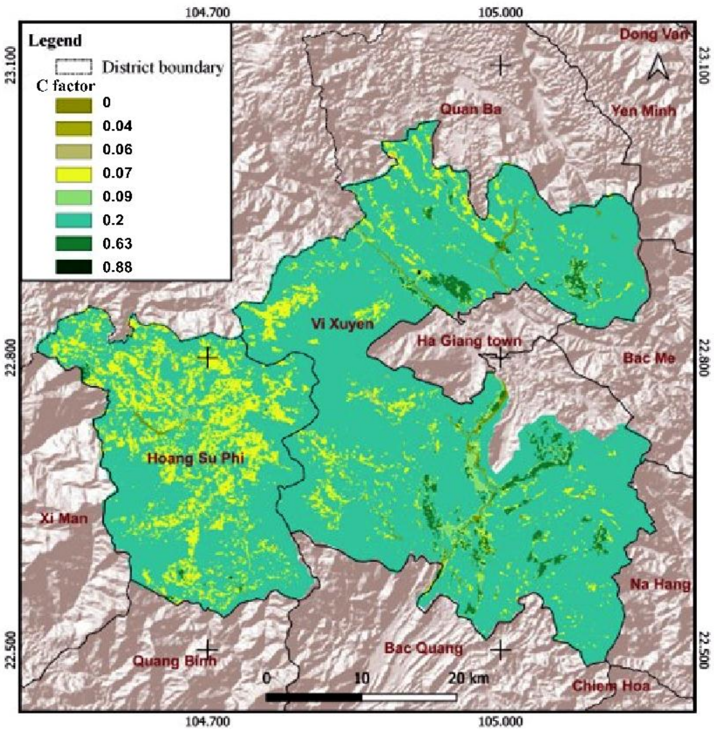

Fig. 6. C-factor map of Tay Con Linh.

Tab. 1. The value of MFs used in the USLE model

Tab. 1a. R-factor

No.	P (mm/year)	**R-value**	Area (ha)
1	144 - 156	19 - 26	68151
2	156 - 168	26 - 33	59132.28
3	168 - 180	33 - 40	43528.36
4	180 - 192	40 - 47	30278.48
5	192 - 204	47 - 54	2000.76

Tab. 1b. K-factor

No.	Soil type	**K-value**	Area (ha)
1	Humus gray soil on the mountain	0.19	21525.84
2	Silver gray soil	0.22	7285.68
3	Gley alpine humus	0.12	17668.08
4	Ferric gray soil	0.22	156020.4
5	Dark brown soil on basalt	0.12	467.48
6	Sour alluvial soil	0.44	4.4
7	Red-brown soil	0.22	43.44
8	Red-brown soil on limestone	0.28	42.48
9	Low acidity neutral gley soil	0.1	33.04

Tab. 1c. The Slope factor

No.	**Slope (º)**	Area (ha)	%
1	0º - 3º	68261.88	33.61
2	3º - 5º	4113.92	2.03
3	5º - 8º	3845	1.89
4	8º - 15º	10060.16	4.95
5	15º - 25º	25011.68	12.32
6	> 25º	91798.24	45.2

Tab. 1d. LS-factor

No.	**LS-value**	Area (ha)	%
1	0 - 3	197915.8	97.45
2	3 - 20	4496.6	0.21
3	20 - 40	354.2	0.17
4	40 - 70	179.6	0.09
5	70 - 110	86.92	0.04
6	> 110	57.76	0.03

Tab. 1e. C-factor

No.	LULC	**C-value**	Area (ha)
1	Water	0	1147.8
2	Grass	0.04	0.36
3	Submerged vegetation	0.06	241.56
4	Shrub	0.07	26507.2
5	Built area	0.09	3799.56
6	Forest tree	0.2	166673.2
7	Crops	0.63	4689.6
8	Bare ground	0.88	31.6

Erosion risk map. The erosion risk depends on the precipitation, topography, soil type, and LULC. The individual addresses these parameters; appropriate approaches are described above. The maps represent values for each component of MFs. This study produced maps of each factor (MFs). Finally, the SER risk map of Tay Con Linh mountain at a resolution of 30 m was established (Fig. 7). Table 1 presents the statistical characteristics of each component factor. This model confirms that the discrete distribution of vegetation affects the degree of erosion.

Based on the classification of the erosion risk according to the Vietnamese standard [10], the erosion risks in Tay Con Linh were classified. The results of such classification are shown in Fig. 7 and Tab. 2. Erosion rank 1 (R-I: 0-10 tons ha^{-1} $year^{-1}$) covers a large part (93.51%) of the study area. R-II (10-60 tons $ha^{-1}year^{-1}$) occupied 11650.32 ha (5.74% of the total area). Their distribution was interspersed with risk areas classified as R-I. Other parts (R-III: 60-160 tons ha^{-1} $year^{-1}$; R-IV: 160-300 tons ha^{-1} $year^{-1}$; R-V: 300-400 tons ha^{-1} $year^{-1}$; R-VI: 400-600 tons ha^{-1} $year^{-1}$; R-VII: > 600 tons ha^{-1} $year^{-1}$) occupied an insignificant part of the entire area.

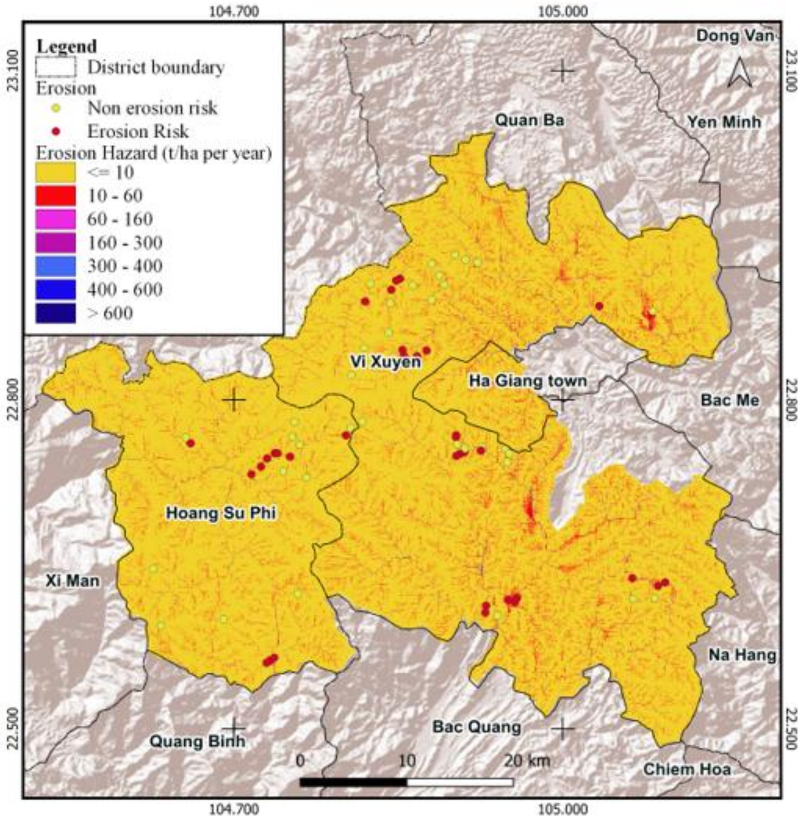

Fig. 7. Tay Con Linh erosion risk map.

They all have the same erosion coefficient considering the topography, soil type, and rainfall. Overall, mapping the potential erosion status of the Tay Con Linh mountain showed that vegetation coverage is the most important to protect the soil. Usually, agro-forestry vegetation is planted in places with steep slopes and a high erosion risk. It is necessary to have solutions to mitigate the strong erosion once the cover is lost.

In general, the USLE model coupled with GIS allowed the simulation of SER patterns and generated a spatial distribution map of the SER. Furthermore, due to the temporal and spatial variability of the C-factor, more field experiments will be necessary to validate this parameter to forecast its evolution using vegetation indices. The predicted average annual soil loss was classified into categories according to the intensity of the soil loss. Higher SER rates were found in densely forested and intensively planted areas, similar to the literature of Pham *et al.* [18], Pham [19], and Nguyen [20].

Tab. 2. The classification of SER in Tay Con Linh

Level		SER	ha	%
1	R-I	A < 10	189903.96	93.51
2	R-II	A: 10 - 60	11650.32	5.74
3	R-III	A: 60 - 160	949.48	0.47
4	R-IV	A: 160 - 300	283.36	0.14
5	R-V	A: 300 - 400	86.00	0.04
6	R.VI	A: 400 - 600	106.60	0.052
7	R-VII	A > 600	111.16	0.055
Sum			**203090.88**	**100**

Unit: tons ha^{-1} $year^{-1}$

The results in Fig. 8 showed that most soil loss happens on land with tree cover and shrub (soil loss < 10 tons ha^{-1} $year^{-1}$) and crops (10-60 tons ha^{-1} $year^{-1}$). More detailed estimates for distinct parts of such LULC reveal the relationships between the intensity of SER and vegetation cover and allow to assess the impact of vegetation type on the rates of the erosion processes.

Validation of the results

Consistent with prior research, the present study leveraged high-resolution imagery from Google Earth to delineate regions susceptible to SER. To substantiate the methodology, a compilation of 30 images corresponding to 30 distinct locations, identified as susceptible to erosion based on a rigorous criterion, was acquired from Google Earth for validation purposes. This validation approach is similar to the methodology articulated by Tolche *et al.* [14]. The Area Under the Curve (AUC) metric, demonstrates a robust performance, yielding a notable accuracy rate of 88.5%. The results are shown in Fig. 9. Additionally, USLE model affirms the soundness of the research findings, underscoring their proficiency in prognosticating regions prone to SER within the study locale. This proficiency is corroborated by applying the model to training and test data extracted from Google Earth.

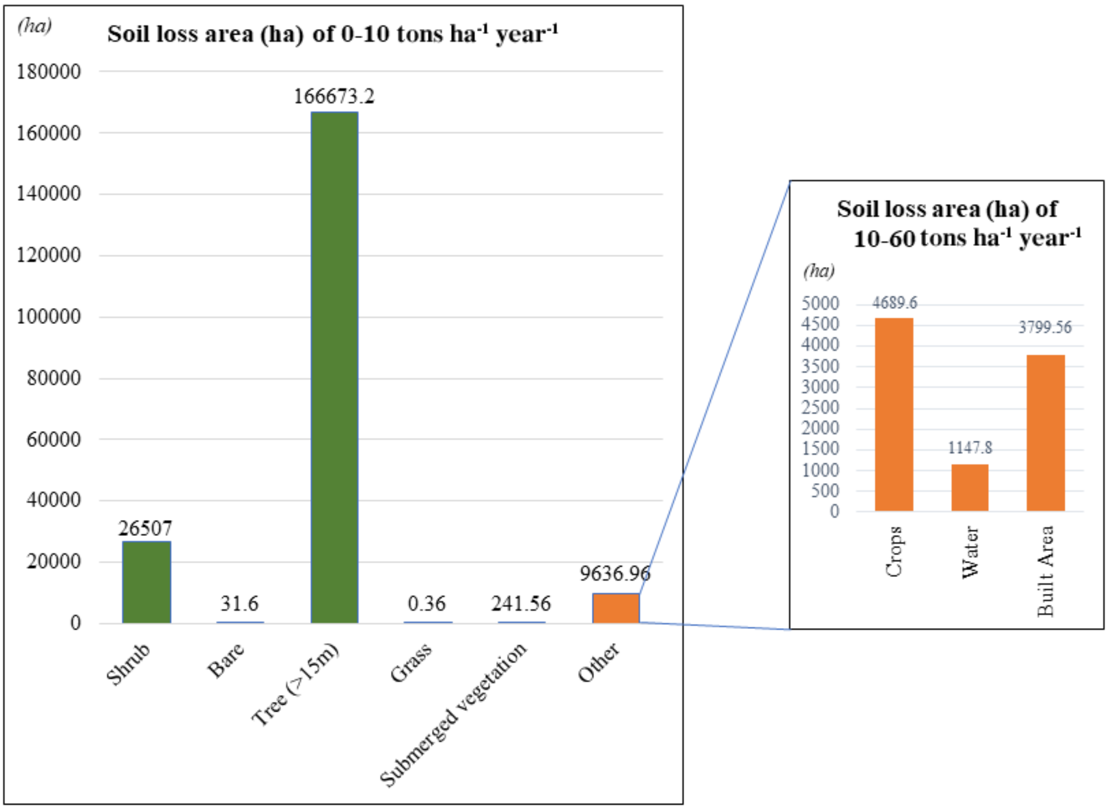

Fig. 8. Area of LULC significantly affected by erosion (tons ha^{-1} year^{-1}) in the Tay Con Linh mountain.

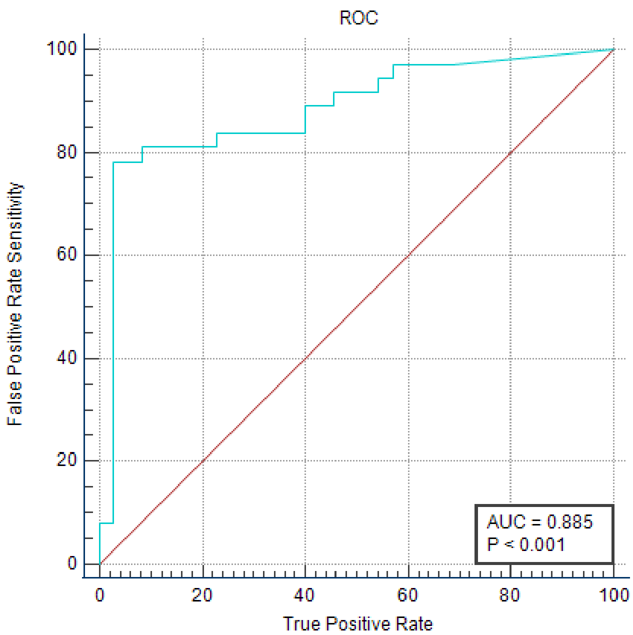

Fig. 9. ROC curve of the SER using the USLE model.

3.2. Discussion

The findings indicated that the mean extent of SER in the area of interest is estimated to be between 0-10 tons per hectare per year. These results agree with previous research conducted on SER in the mountainous regions of Northern Vietnam, as reported by Nguyen [20]. Hence, it is suggested that the predominant factor contributing to SER in this area is the specific composition of vegetation. Furthermore, our research findings indicate that planted forests are faced with significant risks of erosion, which corresponds to the findings of Pham *et al.* [18]. In contrast to previous research conducted in southern Vietnam, there is variation in the extent of soil loss caused by erosion. According to Pham *et al.*, a study was conducted to assess the average soil loss in the central districts of Vietnam resulting from the depletion of natural forest land, which was found to be approximately 19 tons per hectare per year. In the present investigation, the influence of the P coefficient was ignored and a fixed value of 1. Therefore, the increased soil erosion rates observed in forested areas may be attributed to specific geographical factors. Natural forests often exhibit a distribution pattern that is predominantly observed in sloping terrains, whereas planted forests tend to be concentrated within areas characterized by a slope gradient ranging from 8° to 15°.

The USLE model employed a P-factor derived from the 2020 land use map, which was constructed using the Normalized Difference Vegetation Index (NDVI). Certain regions depicted on the land use map are designated as areas with vegetation exceeding a height of 15 meters. It is important to note that these areas may encompass a variety of land types, including natural forests, plantations, or agricultural land. Consequently, this categorization can rise to inaccuracies in computations while acquiring outcomes. Furthermore, this study reveals a limitation in this respect. Additional research should be conducted on large-scale LULC maps.

The K-factor is significantly influenced by various factors, including the dimensions (length and slope) of the ridge, the crop management coefficient, the permeability of the soil, as well as the moisture content and bulk density of the soil. The research findings indicate that the moisture and bulk density of soil regularly depart from the predictions made by the USLE model. The utilization of soil moisture and bulk density as predictors gives more accurate and comprehensive estimations of SER coefficients in cases when there is a noticeable alteration in land cover over a period of time.

To calculate the extent of erosion more accurately, a modern model should be developed that incorporates additional parameters, such as topographical features, rock fragment concentration, and vegetation characteristics. A study suggests that the model's accuracy can be further improved by adjusting the coefficient C for high-altitude regions based on soil characteristics and components derived from remote sensing imagery. An analysis indicates the need to develop strategies for reducing fieldwork and establishing effective land resource monitoring procedures [21]. Although the research demonstrated that the model is suitable for estimating soil loss in mountainous regions, its accuracy can be improved through detailed field observations. Future investigations should include detailed information on the K and C factors. The recognized vulnerability of SER rates at various levels must be monitored and integrated into recovery efforts, along with appropriate soil management and conservation policies. This is essential to minimize the rising soil SER.

4. Conclusion

A precondition to prioritize areas and implement suitable management strategies, both of which are fundamental components of sustainable development, is the availability of measured, recent and reliable information on watershed SER. Tay Con Linh Mountain is predominantly an agricultural region characterized by dense forest cover. The average annual SER is shown to be less than 10 tons ha^{-1} $year^{-1}$. This proved to be an effective tool to manage the massive amounts of data required for soil loss investigations, especially on forest land, which are subject to significant erosion. Soil loss is widespread across various land use types, the most cause of the higher soil loss is that forests are concerned with steep slope area. A collection of photos representing various sites that were determined to be prone to erosion using a strict criterion was obtained from Google Earth in order to validate the methodology. The efficiency of the model is 88.5%. The results on the SER evaluation may assist farmers and managers in developing appropriate soil improvement techniques in the varied areas. However, to confirm and validate the findings of the USLE prediction for soil loss, direct field measurement data of soil loss in the mountain region and the sub-areas are required.

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ĐÁNH GIÁ TÌNH TRẠNG MẤT ĐẤT GIỮA CÁC LOẠI HÌNH SỬ DỤNG ĐẤT Ở MIỀN BẮC VIỆT NAM, NGHIÊN CỨU TẠI NÚI TÂY CÔN LĨNH

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Tóm tắt: Phá rừng và canh tác nông nghiệp là hai trong số những rủi ro nghiêm trọng nhất đối với xói mòn đất (SER), suy thoái chất lượng nước và sa mạc hóa... Dựa trên phương trình mất đất phổ quát (USLE) do Wischmeier và Smith đề xuất, bài báo này hướng đến mục tiêu ứng dụng hệ thống thông tin địa lý (GIS) để đánh giá rủi ro xói mòn đất tại khu vực núi Tây Côn Lĩnh, Việt Nam. Bản đồ các thông số môi trường và bản đồ nguy cơ xói mòn đã được xây dựng. Kết quả nghiên cứu cho thấy loại thảm thực vật trong khu vực là yếu tố chính tác động đến hiện tượng xói mòn đất. Nó liên quan đến các phương thức canh tác phù hợp với địa hình đồi núi dốc. Các phân tích đã chứng minh rằng kiểu loại thảm thực vật là yếu tố then chốt quyết định mức độ xói mòn nghiêm trọng trong khu vực này. Để xác thực phương pháp luận, hình ảnh Google Earth của các địa điểm được xác định là dễ bị xói mòn đã được phân tích dựa trên các tiêu chí nghiêm ngặt. Mô hình đánh giá cho thấy tỉ lệ hiệu quả đạt 88,5%. Theo tiêu chuẩn Việt Nam TCVN 5299:2009, mức độ xói mòn ở khu vực nghiên cứu tương đối phức tạp, song phần lớn được phân loại vào mức rủi ro trung bình, với nhiều khu vực thể hiện điều kiện cấp độ R-I (chiếm 93,51% diện tích tương đương với lượng mất đất khoảng 10 tấn/ha/năm). Nghiên cứu đã thiết lập mối tương quan giữa mức độ xói mòn và độ che phủ của thảm thực vật, đồng thời nhấn mạnh tác động của việc sử dụng đất đến tốc độ xói mòn đất. Đánh giá này không chỉ giúp người sử dụng đất đưa ra quyết định hợp lý về việc sử dụng đất và bảo tồn hệ sinh thái, mà còn cung cấp các tiêu chí khoa học bổ sung cho kiến thức truyền thống của người nông dân.

Từ khóa: *Phá rừng; USLE; mô hình hóa; xói mòn; GIS.*

Received: 06/03/2024; Revised: 27/05/2025; Accepted for publication: 25/06/2025

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