Prediction of Erosion Using The USLE Method in Community Oil Palm Plantations in Kualuh Selatan District, North Labuhanbatu

Fitra Syawal Harahap[1,2], Hilwa Walida[1,2], Abdul Rauf[2,3], Rahmanta[4], Arman Harahap[5], Iman Arman[6], Sulaiman Harahap[2,6], Sudarijah[2,6], Mohamad Siarudin[2,7], Syafrudin Syafii[2], Muhammad Rizwan[8], Indra Gunawan[8]

[1]Agrotechnology Study Program, Faculty of Science and Technology, Universitas Labuhanbatu, Indonesia
[2]Indonesian Agroforestry Society (MAFI) , Indonesia
[3]Agrotechnology Study Program, Faculty of Agriculture, Universitas Sumatera Utara, Indonesia
[4]Agribusiness Study Program, Faculty of Agriculture, University of Sumatera Utara, Indonesia
[5]Biology Education Study Program, Faculty of Science and Technology, Universitas Labuhanbatu, Indonesia
[6]Precision Plantation Extension, Agricultural Development Polytechnic (Polbangtan), Medan, Indonesia
[7]Department of Agriculture of North Labuhanbatu Regency, Indonesia
[8]National Research and Innovation Agency (BRIN), Indonesia
[9]Agrotechnology Study Program, Faculty of Agriculture, Universitas Islam Sumatera Utara, Indonesia
[*] Corresponding Author:
Email: fitrasyawalharahap@ulb.ac.id

Abstract.

The process of erosion leads to the loss of fertile topsoil and a reduction in the soil's capacity to store and absorb water. At the research site, community oil palm plantations in Tanjung Pasir Village, Kualuh Selatan District, North Labuhanbatu Regency, land clearing was conducted through logging, and in some cases, burning. Subsequent plantation management was carried out without implementing soil conservation measures and while disregarding environmental factors, resulting in soil degradation and productivity decline linked to erosion. This study aims to predict the magnitude of erosion using the Universal Soil Loss Equation (USLE) method, calculate the tolerable soil loss, and analyze the erosion hazard level. The USLE method was applied by calculating the causative factors of erosion: rainfall erosivity (R), soil erodibility (K), slope length and steepness (LS), cover management (C), and conservation practices (P). The predicted erosion values were then compared to the tolerable soil loss values to determine the necessity of conservation interventions. The results indicate that the highest predicted erosion value (A) was 521.73 tons/ha/year on plot KS1, while the lowest was 111.09 tons/ha/year on plot KS5. Meanwhile, the tolerable soil loss (TSL) ranged from 43.86 to 64.38 tons/ha/year. Based on this comparison, two classes of erosion hazard were identified: very high and high. Both classes exhibited predicted erosion values far exceeding the permissible limits. Therefore, conservation measures are imperative, one of which involves planting dense Legume Cover Crops (LCC).

Keywords: *Erosion; Soil Fertility; Oil Palm; North Labuhanbatu; Topsoil and USLE.*

I. INTRODUCTION

Land degradation due to soil erosion poses a global threat to agricultural sustainability, food security, and ecosystem health [1]. As a key component of natural capital, fertile and healthy soil is the foundation of agricultural productivity, including oil palm plantations [2]. However, uncontrolled erosion systematically removes the topsoil layer, which is richest in organic matter and nutrients, ultimately leading to a permanent reduction in land production capacity [3]. Within the context of sustainable development, this soil loss represents not only an economic detriment to farmers but also a violation of intergenerational equity principles, whereby future generations inherit land of diminished quality and quantity. Consequently, a comprehensive and quantitative understanding of erosion rates is an absolute prerequisite for designing sustainable and resilient plantation management systems that minimize environmental impact. The expansion of oil palm plantations, particularly those managed by smallholders, is often associated with increased erosion risk, especially during the land clearing phase and under inadequate management [4]. Activities such as clearing natural vegetation, burning, and forming beds without sufficient soil conservation measures expose the soil surface to the impact of raindrops and surface runoff. This disruption of the natural ground cover significantly increases the runoff coefficient and accelerates the transport of soil particles [5]. Such practices, common in smallholder plantations with limited access to capital and technical knowledge, create a paradox: efforts to enhance economic welfare ultimately undermine the natural resource base upon which long-term livelihoods depend. This context frames the study of erosion in smallholder oil palm plantations not merely as a biophysical issue, but as a complex socio-ecological one. The Universal Soil Loss Equation (USLE) method and its development, the Revised USLE (RUSLE), have proven to be robust and widely accepted tools for predicting average annual soil loss rates with a relatively simple yet powerful approach [6].

This empirical model quantifies erosion as the product of six key factors: rainfall erosivity (R), soil erodibility (K), slope length and steepness (LS), cover management (C), and conservation practices (P). The strength of USLE lies in its ability to map and identify the most vulnerable areas based on specific site characteristics, thereby enabling more efficient and effective allocation of limited conservation resources. The application of USLE in the context of oil palm plantations in Indonesia, particularly in Sumatra, has revealed concerning findings. Research by Prasetyo et al. [7] in Riau demonstrated that oil palm land with bare soil can experience erosion rates of up to 400 tons/ha/year, far exceeding the typical tolerable soil loss threshold of below 15-30 tons/ha/year. A study in West Kalimantan by Tarigan et al. [8] found that the cover management factor (C-value) in young, non-productive palm plantations could reach 0.6, indicating high erosion rates during this critical phase. Meanwhile, research in Jambi by Dharmawan et al. [5] confirmed that low understory vegetation diversity and the dominance of imperata grass significantly increase the C-factor value, thereby exacerbating soil loss. Furthermore, a study by Adimugroho et al. [9] highlighted that the conversion of secondary forest to oil palm plantations in undulating topography can increase erosion rates by up to 50-fold. These empirical findings collectively build a consistent narrative: without proper management intervention, oil palm plantations, especially in non-flat topographies, are new epicenters of land degradation due to erosion.Specific studies in the North Sumatra region, particularly in North Labuhanbatu Regency, a key center for smallholder oil palm production, remain very limited. This knowledge gap is critical given the unique biophysical and socio-economic characteristics of this area.

A preliminary study by Lubis et al. [10] indicated that land clearing by burning still occurs in some smallholder plantation enclaves in Kualuh Selatan, potentially reducing soil aggregate stability and increasing susceptibility to erosion. However, quantitative, comprehensive erosion predictions based on standardized models like USLE have not been widely conducted.This research aims to fill this gap by providing accurate quantitative data on erosion magnitude, which has often only been qualitatively assumed. From a sustainable development perspective, this study holds strong relevance to several Sustainable Development Goals (SDGs), particularly SDG 15 (Life on Land), which focuses on the sustainable management of terrestrial ecosystems, combating desertification, and halting and reversing land degradation. By identifying erosion rates and hazard levels, this study provides a scientific database for formulating policies and technical recommendations that support sustainable agriculture (SDG 2) and responsible consumption and production (SDG 12). This erosion prediction data can be used by stakeholders, from farmers to local governments, for evidence-based conservation planning. Therefore, this research, entitled "Prediction of Erosion Using the USLE Method in Community Oil Palm Plantations in Kualuh Selatan District, North Labuhanbatu," is both crucial and strategic. It aims not only to map and predict erosion rates spatially and temporally but also to calculate the tolerable soil loss and determine the erosion hazard level at the study site. The expected final outcome is a scientifically-based technical recommendation for appropriate, effective, and community-adoptable soil and water conservation measures, ensuring that the economic contribution of the smallholder oil palm sector can align with the preservation of natural and environmental resources.

II. METHODS

Time and Location of Research

This research will be conducted over eight months, from June 2025 to November 2025. Activities include preparation, field surveys, soil sampling, laboratory analysis, data processing, and report compilation. The research location is in smallholder oil palm plantation areas in Tanjung Pasir Village, Kualuh Selatan District, North Labuhanbatu Regency, North Sumatra Province. The location was selected through purposive sampling, considering that the area has intensive smallholder oil palm activity, variations in slope steepness, and indications of soil degradation due to erosion.

Materials and Tools

Materials used in this study include: Undisturbed and disturbed soil samples from each sample land unit, a 1:50,000 scale Indonesian Base Map from the Geospatial Information Agency, Sentinel-2 or SPOT satellite imagery with a 10-meter spatial resolution, daily rainfall data from the last 10 years from the nearest weather station, and other relevant data such as soil type and land use maps. Tools to be used include: A handheld GPS for determining coordinates and elevation, a core sampler for taking undisturbed soil samples, a soil auger, measuring tape, and soil sample bags, a pocket penetrometer and soil pH meter, ArcGIS 10.8 or QGIS 3.28 software for spatial analysis and LS factor mapping, and Microsoft Excel and R-Stat software for calculating and statistically analyzing the R, K, C, P, and A factors.

Research Methodology

The research approach used is quantitative, employing survey and modeling methods. The empirical model applied is the Universal Soil Loss Equation (USLE) formulated by Wischmeier and Smith [11], with the following equation: $\mathbf{A = R \times K \times LS \times C \times P}$

Description: **A** = Predicted soil loss rate (tons/ha/year), **R** = Rainfall-Runoff Erosivity Factor, **K** = Soil Erodibility Factor, **LS** = Slope Length and Steepness Factor (dimensionless), **C** = Cover Management Factor (dimensionless), **P** = Support Practice Factor (dimensionless)

Experimental/Research Procedure

- **Determination of Sample Units (Plots):** The research area will be divided into several sample units (minimum 5 units) representing variations in slope, plant age, and management practices. Each sample unit will be plotted with a size of 20 m x 50 m.
- **Data Collection for R Factor (Rainfall Erosivity):** Daily rainfall data will be collected and calculated using a modified Boltzmann equation for Indonesian conditions to produce monthly and annual R values.
- **Data Collection for K Factor (Soil Erodibility):** On each sample unit, composite soil samples will be taken at a depth of 0-20 cm. Samples will be analyzed in the laboratory to determine texture, organic matter, structure, and permeability. The K value will then be calculated using the nomograph equation from Wischmeier et al. [12].
- **Determination of LS Factor (Slope Length and Steepness):** The LS factor will be determined digitally using DEM data extracted from the base map. Calculations will be performed in a GIS environment using an algorithm developed by Desmet & Govers [13].
- **Determination of C Factor (Cover Management):** The C factor value will be determined based on field observations of the percentage of oil palm canopy cover and ground cover vegetation, as well as plant growth phase. Reference values will be adapted from relevant literature for oil palm plantations.
- **Determination of P Factor (Conservation Practices):** The P factor value will be determined based on observations of the presence or absence of mechanical conservation practices such as terracing, pits, or bunds. If no conservation measures are present, a value of P = 1 will be applied.
- **Calculation of Predicted Erosion (A) and Tolerable Soil Loss (TSL):** The values of all factors will be multiplied to obtain A. TSL will be calculated based on soil solum depth and soil formation rate.
- **Erosion Hazard Level (EHL) Classification:** The EHL will be determined by comparing the A value to the TSL, then classified into applicable classes.

Measured Parameters

The parameters measured in this study are presented in Table 1.

Table 1. Measured Parameters

Parameter	Operational Definition	Measuring Tool	Unit
Predicted Soil Loss (A)	Average annual soil loss rate estimated by the USLE model.	USLE Calculation (R×K×LS×C×P)	tons/ha/year
Rainfall Erosivity (R)	An index representing the potential of rainfall to cause erosion.	Rainfall Data, Equation	MJ mm/ha/hr/year
Soil Erodibility (K)	Susceptibility of soil to detachment and transport by rainfall and runoff.	Soil Lab Analysis (Texture, Organic Matter), Nomograph	tons ha hr/ha MJ mm
Slope Factor (LS)	The ratio of soil loss from a specific slope length and steepness to that from a standard plot (9%, 22.1 m).	Topographic Map/DEM, GIS	Dimensionless (Ratio)
Cover Management Factor (C)	The ratio of soil loss from a specific cropping system to that from continuous fallow tilled land.	Field Observation (Percent Ground Cover)	Dimensionless (0-1)
Support Practice Factor (P)	The ratio of soil loss with a specific support practice to that with straight-row farming up and down the slope.	Field Observation (Presence of Terraces)	Dimensionless (0-1)
Soil Texture	The composition of sand, silt, and clay particles in the soil.	Hydrometer/Pipette	%
Organic Matter	The content of organic carbon in the soil.	Walkley and Black Method	%
Slope Steepness	The angle of the land surface relative to the horizontal plane.	GPS/Clinometer	% / Degrees
Slope Length	The horizontal distance from the origin of overland flow to the point where deposition begins.	Topographic Map/DEM, GIS	meter (m)

III. RESULT AND DISCUSSION

The calculation results show a highly significant variation in erosion rates between land units, ranging from 159.39 tons/ha/year (KS4) to 805.91 tons/ha/year (KS2), as shown in Table 2. This more than fivefold difference between the lowest and highest values indicates heterogeneity in biophysical characteristics and management among the plots. The high variation is consistent with the findings of Arekhi et al. [14], who stated that the spatiality of USLE factors, especially slope length and steepness (LS) and soil erodibility (K), are the main causes of erosion rate variability in a fragmented landscape. Plot KS2 showed the highest erosion value (805.91 tons/ha/year), heavily influenced by the combination of high K (0.22) and LS (7.29) factors.

Table 2. Predicted Erosion Values using the USLE Method in Tanjung Pasir Village.

Plot	**R**	**K**	**LS**	**C**	**P**	**A (Ton/Ha/Year)**
KS 1	2512.49	0.14	3.68	0.4	1.0	517.77
KS 2	2512.49	0.22	7.29	0.2	1.0	805.91

Plot	R	K	LS	C	P	A (Ton/Ha/Year)
KS 3	2512.49	0.18	4.44	0.2	1.0	401.60
KS 4	2512.49	0.13	1.22	0.4	1.0	159.39
KS 5	2512.49	0.17	2.33	0.2	1.0	199.04
KS 6	2512.49	0.19	2.33	0.2	1.0	222.46

*Source: Data Analysis Results (2025). Note: *A = R x K x LS x C x P*

An LS value of 7.29 indicates very steep and long topographic conditions, which accelerates the accumulation of surface runoff energy. This finding aligns with research by Gharibreza et al. [15], which proved that the LS factor is a dominant driver in the USLE equation in sloping areas, where an exponential increase in LS value will increase the erosion rate even if other factors remain relatively constant. A comparison between KS1 (C=0.4; A=517.77 tons/ha/year) and KS3 (C=0.2; A=401.60 tons/ha/year) with relatively similar K and LS characteristics shows that reducing the C factor through improved vegetation cover can reduce erosion by up to 22.4%. This reinforces the findings of Mawardi et al. [16] that effective cover crop management can suppress the C factor value to 0.1-0.3 in oil palm plantations, thus serving as one of the most efficient conservation strategies. All land units have a P factor value of 1, indicating the absence of significant soil conservation practices such as terracing, pits, or bunds. This value explains why the erosion rates across all study locations are exceptionally high and far exceed the general tolerance threshold of <15 tons/ha/year [3]. This condition reflects the reality revealed by Dharmawan et al. [5] that limited technical knowledge and access to capital among smallholder oil palm farmers often hinder the implementation of soil conservation structures. All predicted erosion values (159.39 - 805.91 tons/ha/year) consistently exceed the tolerable soil loss for tropical regions, which generally ranges from 10-12 tons/ha/year [1].

Such high erosion rates not only threaten land productivity through the loss of fertile topsoil but also potentially cause sedimentation in nearby water bodies. A study by Khasanah et al. [17] warned that without conservation intervention, land degradation due to erosion in smallholder oil palm plantations could reduce productivity by up to 30% over 10 years.Based on the calculations, the Tolerable Soil Loss (TSL) values varied between land units, from 56.44 tons/ha/year (KS1) to 75.33 tons/ha/year (KS6), as shown in Table 3. This variation reflects differences in soil characteristics and biophysical conditions of each plot. The higher TSL values for KS5 and KS6 were primarily influenced by a combination of higher soil productivity and greater bulk density values. This finding is consistent with research by Panagos et al. [6], which emphasizes that TSL determination must consider the spatial variability of soil properties, as each land unit has different regenerative capacities. Analysis of soil parameters showed that land with a deeper solum (KS3-KS6: 1500 mm) tended to have higher TSL values compared to land with a shallow solum (KS1: 980 mm, KS2: 1100 mm). This aligns with the principle articulated by Lal [3], that soils with a deeper solum have a larger soil reserve to support natural regeneration processes. The varying Bulk Density values between 0.93-1.19 gm/cm³ also contributed to the TSL variation, where higher bulk density generally results in a larger TSL due to a greater mass of soil per unit volume.

Table 3. Tolerable Soil Loss (TSL) Values in Tanjung Pasir Village.

Plot	Solum (mm)	Depth Factor	Dmin (mm)	MPT (yr)	PT	TSL (mm/yr)	Bulk Density (gm/cm³)	TSL (Ton/Ha/yr)
KS 1	980	0.95	300	300	2.5	4.6	1.17	56.44
KS 2	1100	0.95	300	300	2.5	5.11	1.15	57.23

Plot	Solum (mm)	Depth Factor	Dmin (mm)	MPT (yr)	PT	TSL (mm/yr)	Bulk Density (gm/cm³)	TSL (Ton/Ha/yr)
KS 3	1500	0.95	300	300	2.5	6.25	0.93	58.16
KS 4	1500	0.95	300	300	2.5	6.25	0.94	58.77
KS 5	1500	0.95	300	300	2.5	6.25	1.05	65.67
KS 6	1500	0.95	300	300	2.5	6.25	1.19	75.33

*Source: Data Analysis Results (2025). Note: * EDP = [(DE-Dmin)/ MPT] + PT ** EDP = EDP x BI x 10

The significant variation in TSL values between land units indicates the need for differentiated conservation approaches tailored to each land condition. Plots with low TSL, such as KS1 (56.44 tons/ha/year), require more intensive conservation measures compared to those with higher TSL. Borrelli et al. [1] affirm that site-specific conservation planning based on local characteristics is key to effective erosion control. On land with low TSL, a combination of vegetative and mechanical methods is necessary, while on land with higher TSL, efforts can focus on improving vegetation cover. The TSL calculation, which considers solum depth, soil formation rate, and plant production life, reflects a sustainability approach to land management. The use of a 2.5-year Plant Production Life in the calculation indicates a medium-term consideration in conservation planning. Khasanah et al. [17] emphasize that such a TSL-based approach ensures that the erosion rate does not exceed the soil's regenerative capacity, thereby maintaining land productivity for future generations. Detailed TSL data for each land unit provides a scientific basis for developing conservation priority maps.

Plots with the highest A:TSL ratio should be the primary focus for conservation implementation [18]. The results in Table 4 show that all land units (KS1-KS6) have predicted erosion values (A) that far exceed the tolerable soil loss (TSL). The A:TSL ratio ranges from 2.95 (KS6) to 14.08 (KS2), indicating very serious ecological pressure across the entire study area. This finding is consistent with research by Borrelli et al. [1], which states that over 90% of agricultural land in the tropics experiences erosion rates above sustainable thresholds, with oil palm plantations recording among the highest values. There is significant spatial variation in the extent of TSL exceedance. Plot KS2 shows the most critical condition, with an A value of 805.91 tons/ha/year, which is 14 times higher than its TSL (57.23 tons/ha/year). In contrast, KS6, despite having the third-highest A value (222.46 tons/ha/year), is only 2.95 times its TSL (75.33 tons/ha/year) due to its higher TSL value. This variability, as revealed by Syahrin et al. [18], reflects differences in soil and topographic characteristics that influence both parameters differently. The consistent exceedance of actual erosion over TSL indicates progressive land degradation. Lal [3] emphasizes that when the erosion rate exceeds the soil formation rate, an irreversible thinning of the soil solum occurs within a human timescale.

Table 4. Comparison of Predicted Erosion (A) and Tolerable Soil Loss (TSL)

Plot	Value A (tons/ha/yr)	Value TSL (tons/ha/yr)	Comparison
KS 1	517.77	56.44	A > TSL
KS 2	805.91	57.23	A > TSL
KS 3	401.60	58.16	A > TSL
KS 4	159.39	58.77	A > TSL
KS 5	199.04	65.67	A > TSL

Plot	Value A (tons/ha/yr)	Value TSL (tons/ha/yr)	Comparison
KS 6	222.46	75.33	A > TSL

Source: Data Analysis Results (2025)

On plot KS2, with an erosion excess of 748.68 tons/ha/year, it is estimated to lose 1 cm of topsoil in just 2-3 years, far faster than the natural regeneration capacity, which requires 100-400 years to form 1 cm of soil. The high discrepancy between A and TSL has direct implications for plantation productivity decline. A study by Khasanah et al. [17] proved that every 10 tons/ha/year of erosion in excess of TSL can reduce Fresh Fruit Bunch (FFB) productivity by 1.2-1.8% per year. Based on this finding, plot KS2 has the potential to experience a productivity decline of up to 90% over the next 10 years without immediate conservation intervention. This comparative data between A and TSL provides a scientific basis for determining conservation implementation priorities. Plots KS2 and KS1 should be the top priority given their very high A:TSL ratios. Mawardi et al. [16] recommend an integrative conservation approach combining vegetative and mechanical methods for land with an A:TSL ratio >5, while for land with a ratio of 2-5, improvement of vegetation cover may suffice.

IV. CONCLUSION

1. All land units in the community oil palm plantations in Kualuh Selatan District experience erosion rates (A) that far exceed the tolerable soil loss (TSL), with A:TSL ratios ranging from 2.95 to 14.08. This condition indicates progressive land degradation that threatens the long-term sustainability of land productivity.
2. There is significant spatial variation in predicted erosion values, with plot KS2 showing the most critical condition (805.91 tons/ha/year), followed by KS1 (517.77 tons/ha/year). This variability is primarily influenced by differing topographic (LS) and soil erodibility (K) factors among the land units.
3. The slope length and steepness factor (LS) and the support practice factor (P) are the most influential determinants of the high erosion rates. A P value of 1 across all units confirms the absence of effective conservation practices to control erosion.
4. The calculation of tolerable soil loss (TSL) shows variation between land units (56.44-75.33 tons/ha/year), reflecting differences in soil characteristics and biophysical conditions, thus necessitating specific conservation approaches for each.

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