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Estimation of Soil Loss Using Rainfall Simulator and Universal Soil Loss Equation (USLE)

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ABSTRACT

Soil erosion leads to the depletion of topsoil, loss of soil fertility, and reduction in organic matter content, which consequently diminishes crop production potential, degrades surface water quality, and damages drainage systems. This study aimed to estimate soil loss using the Universal Soil Loss Equation (USLE), determine soil loss under simulated rainfall conditions, and compare the outcomes from both approaches. Field and laboratory experiments were conducted using soil samples obtained from two locations, Gwallaga and Bayara. The estimated soil loss (tons/ha/yr) from field experiments for Bayara and Gwallaga were 4.37, 4.01, 6.46 and 3.09, 2.83, 3.37, respectively. Similarly, soil loss values obtained under simulated rainfall conditions were 5.26, 3.58, 6.34 and 3.54, 2.50, 3.96 for Bayara and Gwallaga, respectively. Comparative analysis using descriptive statistics indicated a close agreement between the two methods, approaching 100% accuracy. This suggests that rainfall simulation is a reliable technique for soil erosion estimation. The soil types across both fields, ranging from clay-sandy-loam, clay-loam, to sandy-loam, exhibited relatively low soil loss rates, not exceeding 7.0 tons/ha/yr, indicating that the erosion levels are within tolerable limits..

Keywords: *erosion, soil loss, rainfall simulator,*

1. INTRODUCTION

Soil erosion is widely recognized as one of the most critical environmental challenges globally due to its significant impact on agriculture and the natural ecosystem. It is primarily caused by an increase in surface runoff, which detaches and transports soil particles from the land surface. Although soil erosion is a natural process affecting all landforms, its effects are more pronounced in agricultural settings. In this context, soil erosion refers to the removal of topsoil by natural forces such as water and wind, as well as by human-induced activities, particularly farming practices like tillage.

Tillage-induced erosion occurs when excessive soil disturbance loosens the soil structure, making it more susceptible to displacement. Regardless of the causative agent, water, wind, or tillage, soil erosion involves three fundamental processes: detachment, transportation, and deposition of soil particles. The most fertile layer, the topsoil, which is rich in organic matter and biological activity, may either accumulate at another location within the field or be transported off-site, often leading to the clogging of drainage systems.

The consequences of soil erosion include a decline in agricultural productivity and the contamination of nearby water bodies such as rivers, wetlands, and lakes. The process may occur gradually and go unnoticed over time, or it may happen rapidly, resulting in severe topsoil loss. Additionally, other forms of soil degradation such as compaction, reduced organic matter content, deterioration of soil structure, inadequate internal drainage, salinization, and increased soil acidity can further intensify the rate and impact of soil erosion.

The rate and extent of soil erosion are influenced by several key factors, including rainfall and surface runoff, soil erodibility, slope length and gradient, vegetation cover and cropping systems, as well as tillage practices (Blanco et al., 2010). Numerous studies utilizing soil loss models, rainfall simulation experiments, and field-based investigations have focused on identifying rainfall-related parameters that can effectively predict soil erosion. At both global and continental scales, parameters based on annual and seasonal rainfall totals have been widely applied.

Laboratory studies on soil splash have demonstrated that the kinetic energy and momentum of rainfall play a significant role in the detachment and transport of soil particles (Rose, 1960). This concept led to the development of the rainfall erosivity index known as EI_{30}, which was incorporated into the Universal Soil Loss Equation (USLE). When EI_{30} values for individual storm events are aggregated annually and divided by 100, the rainfall erosivity factor (R) is obtained. Furthermore, Hudson (1971) reported a strong correlation between soil erosion and the kinetic energy of rainfall occurring at intensities exceeding 25 mm/h. In the Nigerian context, Lal (1976) proposed an alternative parameter, denoted as AIm, defined as the product of the maximum rainfall intensity (cm/h) and the total rainfall amount (cm) for individual storm events.

SOIL LOSS EQUATION

The annual quantity of soil loss from a catchment is commonly estimated using a generalized model known as the Universal Soil Loss Equation (USLE). Originally developed by Wischmeier and Smith (1978) and later expressed by Schwab et al. (1993), the USLE is a widely accepted tool in Soil and Water Conservation Engineering for predicting average annual soil loss in tons per hectare per year (ton/ha/yr).

$$A = R \times K \times L \times S \times C \times P$$

In this equation, A represents the estimated average annual soil loss per unit area (ton/ha/yr), R denotes the rainfall–runoff erosivity factor, K is the soil erodibility factor, L represents the slope length factor, S is the slope steepness factor, C refers to the crop or cover management factor, and P indicates the support or conservation practice factor.

MATERIALS AND METHODS

Description of the Study Area

Bauchi State is geographically situated between latitudes 9°30′N and 12°30′N, and longitudes 8°50′E and 11°00′E. According to the 2006 national census, the state has a population of approximately 2,178,683. It lies at an average elevation of about 600 meters above sea level and experiences a tropical climate characterized by two distinct seasons: a rainy season spanning from May to October and a dry season from November to April.

Annual rainfall in the state varies spatially, ranging from about 1300 mm in the southern region to approximately 700 mm in the northern extremes. The temperature typically fluctuates between a maximum of 30°C to 40°C and a minimum of 15°C to 30°C, while relative humidity ranges from 17% to 70% (Monde, 2017). Cloud cover is generally limited, even during the rainy season, with prolonged periods of overcast conditions being relatively uncommon.

Bauchi State is predominantly agrarian, with fertile soils that support the cultivation of major crops such as maize, rice, millet, groundnut, and guinea corn. Irrigation farming is also practiced, facilitated by water resources including dams such as the Balanga Dam. In addition to crop production, livestock rearing is a common agricultural activity. The state also hosts several manufacturing industries, including those involved in iron and steel production, water processing, ceramics, and food and beverage production (Nigeria Galleria, 2017).

Despite these advantages, farmers in the region face significant challenges, particularly soil erosion, which leads to the loss of topsoil, decline in crop yield and quality, and depletion of soil organic matter.

Figure 1. Map of Nigeria showing Bauchi State
Source: Map Monde (2017)

Methods of Data Collection

Climatic data spanning a period of 17 years (2000–2017), including rainfall, temperature, and relative humidity, were obtained from the Nigerian Meteorological Agency (NiMet). In addition, soil samples were collected for the analysis of physical properties, estimation of soil loss, and evaluation under simulated rainfall conditions.

Collection of Soil Samples

Two sites. Bayara and Gwallaga were selected for both field experimentation and laboratory analysis. These locations are situated within Bauchi State, with coordinates of 10°12′995″N, 009°43′473″E and 10°16′032″N, 009°49′847″E, respectively. The coordinates were determined using a Global Positioning System (GPS).

At each site, three soil samples were collected from a depth of 0–10 cm using a soil auger and shovel. The samples were stored in polythene bags for proper handling and transportation. To ensure adequate spatial representation, the distances between sampling points were measured using a measuring tape.

Textural Classification of Soil Samples

Soil texture was determined using the sieve analysis method. A 500 g soil sample was weighed along with the sieve and collection pan, after which the sample was manually sieved for 10 minutes. Following the sieving process, the mass of soil retained on each sieve was recorded, and the corresponding percentages retained and passing were calculated accordingly.

Amount passing = total mass – mass retained

$$\% \text{ retained} = \frac{\text{mass retained}}{\text{total mass}} \times 100$$

% passing = % remaining - % retained

$$\mathrm{Cu} = \frac{D_{60}}{D_{10}}$$

$$\mathrm{Cc} = \frac{D_{30}}{D_{60} \times D_{10}}$$

Cu = coefficient of uniformity
Cc = coefficient of curvature
D_{10}, D_{60} and D_{30} are percentage passing sieve number 10, 30 and 60

Bulk Density Determination

The bulk density of the soil was determined using the core sampling method as described by Sahlemedhin and Taye (2010). Undisturbed soil samples were collected with a core sampler, and their initial (natural) weights were recorded. The samples were subsequently oven-dried at a temperature of 105°C for 24 hours to remove moisture content. After drying, the samples were reweighed to obtain their oven-dry mass. Bulk density was then calculated as the ratio of the oven-dry mass to the original volume of the soil cores, representing the in-situ field condition of the soil.

$$\mathrm{BD} = \frac{m_d}{v_t}$$

$$v_t = \frac{\pi h d^2}{4}$$

Where,

BD = bulk density (g/cm^3)

m_d = mass of oven dry sample (g)

d = diameter of the core (cm)

h = height of the core (cm)

v_t = Volume of the core (cm^3).

Estimation of Field Soil Loss Using the Universal Soil Loss Equation (USLE)

The Universal Soil Loss Equation (USLE) was applied to estimate soil loss resulting from water erosion under slope conditions of 0.007% and 2.02%. In this analysis, the soil erodibility factor (K), crop/vegetation management factor (C), and support practice factor (P) were assumed to be constant. The slope length–steepness factor (LS) was computed using Equation (2) as described by Mafra (2015), while the rainfall–runoff erosivity factor (R) was determined using Equation (4) following the method proposed by Bollinne et al. (1990).

Estimation of Soil Loss Using a Rainfall Simulator

Sample Preparation

Disturbed soil samples were collected from the field at a depth of 0–10 cm and transported to the laboratory for analysis. The physical properties of the soil, including texture and bulk density, were determined using sieve analysis and the core sampling method, respectively, in accordance with procedures outlined by the United States Department of Agriculture (USDA). The prepared samples were placed in wash-off trays (Appendix C), after which water was added and allowed to infiltrate for 24 hours to achieve field capacity (FC).

Experimental Setup

The experimental procedure followed a method similar to that described by Arthur et al. (2014). The rainfall simulator was configured for laboratory use, with a test table positioned directly beneath the spray nozzle. Wash-off trays containing the soil samples were placed on the table at an elevation suitable for runoff collection. The trays were adjusted to slopes of 2.2% and 0.7%, respectively. A cylindrical container was used as a rain gauge, while a collection bucket was positioned beneath the trays to collect runoff.

The simulator, equipped with a shower-head spray nozzle connected to a pump via a plastic pipe, was operated at a pressure of 0.4 bar, a rotational speed of 40 revolutions per minute, and a duration of 30 minutes. As the simulated rainfall was applied, the soil gradually became saturated, leading to the initiation of runoff and the detachment and transport of topsoil into the collection bucket.

At the end of the 30-minute period, the system was shut down, and the runoff—comprising water and eroded sediment—was collected. The mixture was allowed to settle for 10 minutes, after which the supernatant water was decanted into a measuring cylinder. The remaining sediment was oven-dried for 24 hours and subsequently weighed. This procedure was repeated for all six soil samples.

Calculation of Soil Loss

Soil loss from the laboratory experiment was initially measured in kilograms (kg) for each sample. The values were then converted to tonnes and normalized by the corresponding surface area in hectares (ha) to obtain soil loss in tons/ha.

RESULTS AND DISCUSSION

Table 4.1 presents the estimated soil loss (tons/ha/yr) for the Bayara site using the USLE model. The estimation accounts for variations in land slope and soil type across the plots. The slope at the site was determined to be approximately 0.007%, while the soil textural classes identified include clay loam, sandy loam, and coarse sandy loam. The corresponding annual soil loss estimates for each plot are summarized in the table.

Table 4.1 Estimated soil loss of Bayara sample using USLE

Land unit	**Particle size distribution(%)**			**Soil textural class**	**Bulk density (g/m^3)**	**A(ton/ha/yr)**
	Sand	**Silt**	**clay**			
	Bayara					
P1	49.6	11.9	38.5	CSL	1.39	4.37
P2	14.9	31.7	53.4	CL	1.28	4.01
P3	51.6	31.6	16.8	SL	1.24	6.46

CSL- coarse sandy loam
CL- clay loam
SL- sandy loam
A-amount of soil loss
P-Plot

Table 4.2 shows the estimated quantity of soil loss in tons/h/yr using the USLE in Gwallaga, which is based on the land slope and soil type of each plot. The area has a slope of 2.02%, and the soil is classified as clay-loam, sandy-loam, and coarse-sandy-loam, with a total yearly anticipated soil loss shown in the table below.

Table 4.2. Estimated Soil loss Gwallaga Sample Using USLE

Land unit	**Particle size distribution(%)**			**Soil textural class**	**Bulk density (g/m^3)**	**A(ton/ha/yr)**
	Sand	**Silt**	**clay**			
	Gwallaga					
P1	57.8	11.6	30.6	CSL	1.33	3.09
P2	18.5	32.3	49.2	CL	1.37	2.84
P3	54.6	28.5	16.9	SL	1.29	3.37

CSL- coarse sandy loam
CL- clay loam
SL- sandy loam
A-amount of soil loss
P-Plot

Table 4.3 presents the estimated soil loss (tons/ha/yr) obtained from laboratory analysis using the rainfall simulator. The estimation is based on calibrated rainfall conditions applied for a duration of 30 minutes at a rotational speed of 40 rev/min. The soil samples analyzed were classified as clay loam, sandy loam, and coarse sandy loam, with the corresponding total annual soil loss values summarized in the table.

Soil loss was calculated by dividing the measured mass of eroded soil by the corresponding surface area expressed in hectares. The results are consistent with findings from similar studies; for instance, Nolan et al. reported a soil loss value of 7.50 tons/ha/yr for a slope of 1.07%, which aligns reasonably with the observations obtained in this study.

Table 4.3 Laboratory Estimated Soil Loss Using Rainfall Simulator (Bayara samples)

Land unit	**Particle size distribution(%)**			**Soil textural class**	**Bulk density (g/m^3)**	**A(ton/ha/yr)**
	Sand	**Silt**	**Clay**			
	Bayara					
P1	49.6	11.9	38.5	CSL	1.28	5.26
P2	14.9	31.7	53.4	CL	1.39	3.58
P3	51.6	31.6	16.8	SL	1.24	6.34

CSL- coarse sandy loam
CL- clay loam
SL- sandy loam
A-amount of soil loss
P-Plot.

Table 4.4 laboratory Estimated result of soil loss (Gwallaga samples)

Land unit	**Particle size distribution(%)**			**Soil textural class**	**Bulk density (g/m^3)**	**A(ton/ha/yr)**
	Sand	**Silt**	**clay**			
	Gwallaga					
P1	57.8	11.6	30.6	CSL	1.33	3.54
P2	18.5	32.3	49.2	CL	1.37	2.50
P3	54.6	28.5	16.9	SL	1.29	3.96

CSL- coarse sandy loam
CL- clay loam
SL- sandy loam
A-amount of soil loss
P-Plot

Table 4.4 present the mean values obtained from the comparative analysis of soil loss across samples from the two study locations using both experimental approaches. These results highlight the relative effectiveness of each method employed in the study. The comparison indicates that the rainfall simulator provides more reliable and practical estimates of soil loss under controlled conditions. In contrast, the Universal Soil Loss Equation (USLE) method is comparatively more time-consuming, labor-intensive, and costly to implement. Consequently, the findings suggest that the rainfall simulation technique is a more efficient and preferable method for estimating soil erosion in field conditions.

Table 4.5 mean for laboratory estimate (Bayara Sample)

(Bayara lab)

Lab	Mean	N	Std. Deviation	% of Total N	% of Total Sum
3.58	4.0100	1	.	33.3%	27.0%
5.26	4.3700	1	.	33.3%	29.4%
6.34	6.4600	1	.	33.3%	43.5%
Total	4.9467	3	1.32289	100.0%	100.0%

Table 4.5 presents the average soil loss estimated from the laboratory experiment using the rainfall simulator for the three samples obtained from Bayara. The results indicate that the mean soil loss values for plots P1, P2, and P3 are 5.26, 3.58, and 6.34 tons/ha/yr, respectively, with an overall mean of 4.95 tons/ha/yr. Among the plots, Plot 3 recorded the highest soil loss value (6.34 tons/ha/yr), accounting for 43.5% of the total, whereas Plot 2 exhibited the lowest value (3.58 tons/ha/yr), contributing 27.0%.

The computed standard deviation of 1.32 suggests a moderate level of variability across the plots. This observed variation is primarily attributed to differences in soil texture. Specifically, Plot 3, characterized by sandy loam with a higher sand fraction, exhibited greater susceptibility to erosion, while Plot 2, classified as clay loam, demonstrated increased resistance due to its higher clay content and stronger particle cohesion.

Overall, the findings from the rainfall simulation experiment indicate that the method is effective in differentiating soil types based on their erodibility under controlled laboratory conditions

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Table 4.6 Mean Average for Field Estimate (Bayara Sample)

(Bayara field)

field	Mean	N	Std. Deviation	% of Total N	% of Total Sum
4.01	3.5800	1	.	33.3%	23.6%
4.37	5.2600	1	.	33.3%	34.7%
6.46	6.3400	1	.	33.3%	41.8%
Total	5.0600	3	1.39083	100.0%	100.0%

Table 4.6 presents the mean soil loss estimated from field experiments using the Universal Soil Loss Equation (USLE) for the three Bayara samples. The results show that the mean soil loss values for plots P1, P2, and P3 are 4.37, 4.01, and 6.46 tons/ha/yr, respectively, with an overall mean of 5.06 tons/ha/yr. Consistent with the laboratory findings, Plot 3 recorded the highest soil loss (6.46 tons/ha/yr), representing 41.8% of the total, while Plot 2 exhibited the lowest value (4.01 tons/ha/yr), contributing 23.6%.

The calculated standard deviation of 1.39 indicates a moderate level of variability among the plots. When compared with the laboratory results presented in Table 4.5, the USLE-based field estimates are slightly higher, with a marginal difference of 0.11 tons/ha/yr in the overall mean values. This slight variation may be attributed to inherent field conditions such as surface crusting, micro-topographic differences, and antecedent soil moisture content, which are difficult to replicate under controlled laboratory conditions.

Despite these minor differences, the relative ranking of the plots in terms of erosion severity remains consistent across both methods, reinforcing the reliability and comparability of the two approaches.

Table 4.7 Mean Average for Laboratory Estimate (Gwallaga Sample)

(Gwallaga lab)					
Lab	Mean	N	Std. Deviation	% of Total N	% of Total Sum
2.50	2.8400	1	.	33.3%	30.5%
3.54	3.0900	1	.	33.3%	33.2%
3.96	3.3700	1	.	33.3%	36.2%
Total	3.1000	3	.26514	100.0%	100.0%

Table 4.7 presents the average soil loss estimated from the laboratory experiment using the rainfall simulator for the three samples collected from Gwallaga. The results indicate mean soil loss values of 3.54, 2.50, and 3.96 tons/ha/yr for plots P1, P2, and P3, respectively, with an overall mean of 3.10 tons/ha/yr. Among the plots, Plot 3 recorded the highest soil loss (3.96 tons/ha/yr), accounting for 36.2% of the total, whereas Plot 2 exhibited the lowest value (2.50 tons/ha/yr), contributing 30.5%.

The standard deviation of 0.27 reflects low variability among the plots, suggesting relatively uniform erosion characteristics across the Gwallaga site when compared to the Bayara samples. This consistency may be attributed to more homogeneous soil physical properties within the study area.

Furthermore, the overall mean soil loss recorded at Gwallaga (3.10 tons/ha/yr) is significantly lower than that observed at Bayara (4.95 tons/ha/yr) as presented in Table 4.5. This difference may be explained by variations in slope gradient and soil texture between the two locations, with Gwallaga characterized by a slope of 2.02% and Bayara by a much gentler slope of 0.007%, alongside differences in soil composition.

Table 4.8 Mean Average for Field Estimate (Gwallaga Sample)

Gwallaga field					
field	Mean	N	Std. Deviation	% of Total N	% of Total Sum
2.84	2.5000	1	.	33.3%	25.0%
3.09	3.5400	1	.	33.3%	35.4%
3.37	3.9600	1	.	33.3%	39.6%
Total	3.3333	3	.75162	100.0%	100.0%

Table 4.8 presents the mean soil loss estimated from field experiments using the Universal Soil Loss Equation (USLE) for the three Gwallaga samples. The results indicate mean soil loss values of 3.09, 2.84, and 3.37 tons/ha/yr for plots P1, P2, and P3, respectively, with an overall mean of 3.33 tons/ha/yr. As observed in previous analyses, Plot 3 recorded the highest soil loss (3.37 tons/ha/yr), contributing 39.6% of the total, while Plot 2 exhibited the lowest value (2.84 tons/ha/yr), accounting for 25.0%.

The standard deviation of 0.75 reflects moderate variability among the plots and is notably higher than the laboratory-based standard deviation of 0.27 reported in Table 4.7. This indicates that field conditions introduce additional sources of variability that are not fully captured under controlled laboratory settings.

A comparison between Tables 4.8 and 4.7 reveals that the USLE field estimates (mean of 3.33

tons/ha/yr) are slightly higher than those obtained from the rainfall simulator (mean of 3.10 tons/ha/yr), with a marginal difference of 0.23 tons/ha/yr. This close agreement further supports the validity of the rainfall simulator as a reliable tool for soil erosion estimation. Moreover, both methods consistently identified Plot 3 as having the highest erosion potential and Plot 2 as the least susceptible, reinforcing the effectiveness of the laboratory approach in ranking soil erosion risk.

Conclusion

The findings of this study indicate that soil loss is influenced by several key factors, including soil texture, bulk density, slope length, and slope steepness. Soils with a higher proportion of sand particles are generally more vulnerable to erosion due to their lower cohesion, whereas soils with higher clay content exhibit greater resistance to detachment and transport by erosive forces. The processes of detachment, transportation, and deposition contribute to the loss of topsoil and may lead to significant nutrient depletion over time.

Based on the soil characteristics of the two study sites—ranging from clay sandy loam to clay loam and sandy loam—the estimated soil loss values (in tons/ha/yr) were relatively low, not exceeding 7.0 tons/ha/yr. These values fall within tolerable limits in the short term. However, sustained exposure to both anthropogenic activities and natural erosion processes may result in progressive increases in soil loss over time, posing long-term risks to soil productivity and environmental sustainability.

Recommendations

Soil erosion contributes to the depletion of topsoil, reduction in soil fertility, and loss of organic matter, ultimately leading to decreased agricultural productivity, deterioration of surface water quality, and damage to drainage systems (FAO, 1992). To mitigate these impacts and promote sustainable land management within the study area, the following measures are recommended:

1. **Strip Cropping:** The adoption of strip cropping, which involves dividing farmland into alternating strips of different crops, can help reduce erosion by minimizing runoff velocity, particularly on sloped terrain.
2. **Contour Farming:** Cultivating along contour lines across slopes can significantly reduce surface runoff and decrease the erosive force of rainfall.
3. **Terracing:** The construction of terraces, ridges, and diversion channels across slopes can effectively control runoff, while the establishment of vegetative waterways further enhances erosion control.
4. **Farmer Education and Awareness:** Government agencies, in collaboration with Agricultural Development Programmes (ADPs), should intensify efforts to educate farmers on the causes, types, and control measures of soil erosion to encourage the adoption of sustainable agricultural practices.

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