Validation of universal soil loss equation for selected soil locations in Northcentral Nigeria using a rainfall simulator

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Abstract: Erosion control in Nigeria must be met with high standards to attain a sustainable agricultural practice to meet the demand of the growing population in terms of food production. The study is aimed at estimating soil loss using a locally made rainfall simulator and ascertaining the performance of the Universal Soil Loss Equation (USLE) model in predicting soil loss in the study location. For this to be investigated, experiments were conducted using rainfall simulators, which are readily unavailable in Nigeria due to their high cost. The drop velocities (DV) of the constructed rainfall simulator were 8.101 m s^{-1} and 2.443 m $s^{-1,}$ respectively, when operated at maximum and minimum intensity. The performance test revealed that the experimental coefficient of uniformity (CU) was 79.86% at 31.79 mm h^{-1}. In comparison, the rainfall intensity for the simulator equals 78.03% at 16.08 mm h^{-1}, respectively, for the maximum and minimum concentration. Two experimental plots of vegetative and bare plots to estimate soil losses. The maximum soil loss of 0.515 kg m^{-2} experienced from bare plot at maximum rainfall simulator intensity. Measurements and analysis in this experiment showed a strong correlation over a short term between erosivity index, R, and observed soil losses, which confirms the validity of Universal Soil Loss Equation (USLE) under the conditions of the experiment. Coefficient of determination (R^2) between erosivity index R and corresponding soil losses showed a weak correlation for vegetative plot due to the insufficient data of factors but a good correlation for bare land over a short term. The overall results confirmed the validity of USLE under the condition of this experiment within this study area was for a short period.

Keywords: bare, rainfall, USLE, soil, vegetative

Citation: Musa, J. J., E. A. Otuaro, P. O. Dada, J. K. Adewumi, I. A. Kuti, and J. Adams-Suberu. 2021. Validation of universal soil loss equation for selected soil locations in Northcentral Nigeria using a rainfall simulator. Agricultural Engineering International: CIGR Journal, 23(3):21 -30.

1 Introduction

The loss of valuable natural resources of a large area occurs over time which alters soil properties, thus making the land not suitable for agricultural purposes (Shaxson, 1999; Cervera et al., 2019). Therefore, soil erosion is a generally slight and gradual process as it involves the systematic elimination of the upper layer of soil, including plant nutrients through either water or wind (Bhattacharya et al., 2016; Poesen, 2018; Nwagwu et al., 2018). For years, Nigeria has faced many environmental threats (Oni, 2011; Ogwo et al., 2012; Olagunju et al., 2015), including soil degradation through surface runoff generation (Nwokoro and Chima,

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Received date: 2020-06-04 **Accepted date:** 2021-02-27

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2017; Musa et al., 2017, Kandissounon et al., 2018). Soil loss renders many agricultural lands unproductive for farmers. According to Ufoegbune et al. (2011) and Polykretis et al. (2020), soil loss estimation takes a lot of time and is capital intensive.

USLE has a high degree of versatility and data openness and relates results that adapt the model to conditions at a local, regional and global scale (Alewell et al., 2019); it is a standard procedure for setting up a rainfall simulator (Grismer, 2012; Ricks et al., 2019). Rainfall simulators are essential tools for estimating surface runoff and soil loss, whether in natural or disturbed soil conditions or under laboratory conditions (Sangüesa et al., 2010). Rainfall intensity and time under controlled conditions are helpful for soil loss quantification and predictions. This impact of rain on the different soil surface and types are possible with rainfall simulator (Yusuf et al., 2017). However, Bagarello et al. (2018) reported that erosion models were not adequate for different soil types, topography, land use and vegetation cover on a spatial scale. The factors that control soil loss vary from one place to another; therefore, it is essential to know location-specific factors for soil loss (Markose and Jayappa, 2016). The essence of this work is to validate USLE under different soil types in various locations which have not been reported in Kwara State, Northcentral, Nigeria. Rainfall simulators should validate and evaluate erosion control measures on the slope and relate the performance in reducing erosion (Ricks et al. 2019).

Over the years, there have been several types of rainfall simulators, with each of them having its application and benefits and its shortcomings (Wilson et al., 2014). In Nigeria, rainfall simulators are not readily available for research purposes (Yusuf et al., 2017). Thus, there is a need to develop a local rainfall simulator using locally available materials to meet international standards for this research. Also, the uncertainties in the rainfall simulator, which is the main issue for soil loss estimation under different soils in various locations, will be removed and valuable for a similar hydrological area. The rainfall pattern makes it challenging to inquire about its eroding impacts on soils for a spatial scale (Grismer, 2012). In view of this, the study designs a rainfall simulator with available materials, and evaluates soil loss for various locations and validates the USLE model performance for predicting soil loss.

2 Materials and methods

2.1 Study site description

The study area is 324 m above sea level and lies approximately latitude 8°30'31"N and longitude 4°35'53"E and is situated within the premises of Lower Niger River Basin Development Authority, Ilorin, which is the capital of Kwara State in Nigeria. Ilorin falls within the transition zone between the savannah of the North and the deciduous forest of the South of Nigeria (Jimoh and Ajewole, 2008). Thus, with a total landmass of 100 km^2 (Ajadi et al., 2011), with a population of 777,667, constituting 296,821 males and females representing 386,886 (Ibrahim et al., 2014).

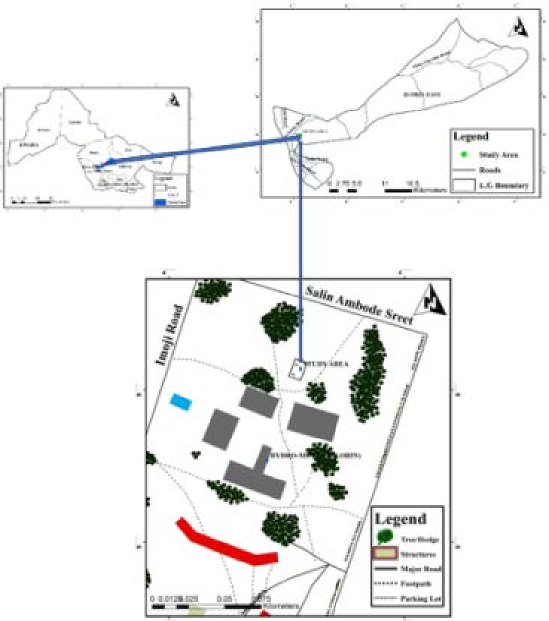

Figure 1 Maps of study location (LNRBDA Hydro-Meteorology, Headquarters)

The climate of Ilorin is both wet and dry season with annual precipitation of 1200 mm, which exhibits significant variability both spatially and temporary with temperature ranging from 33oC and 34oC between November and January and 34oC to 53oC between February and April (Ajadi et al., 2011). Sunlight hours lasts for about 6.5 to 7.7 hours daily from November to May. Figure 1 shows the location of the study area in Kwara State, Nigeria.

The experiment was conducted within the premises of the hydro-meteorology section of the Lower Niger River Basin Development Authority premises. The study area was strategically selected based on the guidelines by Lawrence (1996). The soils in these areas are generally loamy soil with a low and medium level of fertility (Ajibade and Ojelola, 2004), with significant soil types constituting lateritic soil.

2.2 Concept of Universal Soil Loss Equation (USLE)

The Universal Soil Loss Equation (USLE) of Wischmeier and Smith (1987) quantifies soil erosion as the spatial and temporal average soil loss per unit area, and this is based on the product of six factors; rainfall and run-off erosivity (R), soil erodibility (K), slope length (L), slope steepness/gradient (S), crop management (C) and conservation support practice (P). The equation is thus:

$$A = RKLSCP \tag{1}$$

Where,

A is expressed in tons per ha per year (t ha^{-1} yr^{-1})

R is the summed erosive potential of rainfall events yearly (MJ mm ha^{-1} h^{-1} yr^{-1})

K expresses the total units of soil loss per unit of rainfall erosivity (Mg ha h ha^{-1} MJ^{-1} mm^{-1}),

L, S, C and P are all dimensionless.

Not many models can be feasible for use, especially in remote locations with no data or poor accessibility. Thus, many authors consider USLE (Onori et al., 2006; Tamene and Vlek, 2007; Bakker et al., 2008; Tallis and Polasky, 2009; Grafius et al., 2016) to provide an excellent model for predicting soil loss because of its applicability (in terms of required input data) and the reliability of the obtained soil loss estimates (Oliveira et al., 2013). Geographic Information Systems (GIS) has helped to facilitate the application of USLE on a river basin scale, making their combination to be considered a valuable tool for soil and water conservation planning. Salehi et al. (1991) validated the Universal Soil Loss Equation for the region of Quebec, Canada, based on the hypothesis that when all factors other than the rainfall are held constant, storm soil losses from cultivated fields are directly proportional to the erosivity of the storm events identified as the R which proved to be useful for local testing.

Kinnell (2011) did further state that USLE was designed to predict sheet and rill erosion from a field-sized area with only rainfall erosivity E and soil erodibility K. He further stated that the value of the L, S, C and P factors should not exceed the value of 1.0 for the bare fallow area of 22.1 m length field with a slope of not more than 9%. Thus, soil loss for the unit plot was given by Equations 2 and 3.

$$A_1 = RK \tag{2}$$

While for different sizes of slope length, crop management and conservation practice

$$A = A_1 LSCP \tag{3}$$

Where A_1 is the product of R and K (L= S = C = P = 1.0)

To reduce long term experiments in determining K values for soils where K is unknown, a nomograph was developed by Wischmeier (1971) for determining K from soil properties that have 70% silt in the USA (Equation 4).

$$K = \frac{\left(2.1\, X_1^{1.14}\, 10^{-4}(12 - X_2) + 3.25\,(X_3 - 2) + 2.5\,(X_4 - 3)\right)}{100} \tag{4}$$

Where X_1 is the $\%\, silt\, X\, (100 - \%\, clay)$, X_2 is the % organic matter, X_3 is the soil structure code used in the US soil classification as presented in Table 1, and X_4 is the profile permeability code as shown in Table 2.

Table 1 USLE k-factor soil structural code for the determination of parameter X_3

Harmonized World Soil Database code	Value	Structure class	Structure code
1	Very poor	Solid	4
2	Poor	Slightly Structured	3
3	Imperfectly	Slightly Structured	3
4	Moderately well	Fairly Structured	2
5	Well	Fairly Structured	2
6	Somewhat excessive	Very Structured or particulate	1
7	Excessive	Very Structured or particulate	1

Source: Turpie et al. (2015)

Table 2 USLE k-factor soil permeability code for the determination of parameter X_4

Harmonized World	Texture class	Typical infiltration rate	Grouping	Infiltration rate	Infiltration class

Soil Database code		(mm h^{-1})			
1	Clay (heavy)	0.508	0.038 to 1.52	Very slow	6
2	Silty clay	1.016	0.038 to 1.53	Very slow	6
3	Clay (light)	1.27	0.0381 to 1.53	Very slow	6
4	Silty clay loam	1.524	1.524 to 5.08	Slow	5
5	Clay loam	2.286	1.524 to 5.08	Slow	5
6	Silt		1.524 to 5.08	Slow	5
7	Silt loam	4.318	1.524 to 5.08	Slow	5
8	Sandy clay		5.08 to 50.8	Moderately slow	4
9	Loam	6.858	5.08 to 50.8	Moderately slow	4
10	Sandy clay loam	13.208	5.08 to 50.8	Moderately slow	4
11	Sandy loam	25.908	5.08 to 50.8	Moderate	3
12	Loamy Sand	61.214	50.8 to 152.4	Moderately rapid	2
13	Sand	210.058	50.8 to 152.4	Moderately rapid	2

Source: Turpie et al. (2015)

Slope length factor L of the catchment area and the slope gradient factor S both form the topography factor LS, and it varies from 0.1 to 5 in the most frequently farmed regions of West Africa (Roose, 1996). Zhang et al. (2017) provided an improved way of estimating topography factors in Equations 5a, 5b, 5c and 6.

$$S = 10.8\sin\theta + 0.03\ (\theta < 9\%) \qquad (5a)$$

$$S = 16.8\sin\theta - 0.05\ (9\% \leq \theta < 17.6\%) \qquad (5b)$$

$$S = 21.9\sin\theta - 0.96\ (\theta \geq 17.6\%) \qquad (5c)$$

$$L = \left(\frac{\lambda}{22.1}\right)^{m} \qquad (6)$$

$m = 0.2,\ \theta \leq 1.7\%$

$m = 0.3,\ 1.7\% < \theta \leq 5.2\%$

$m = 0.4,\ 5.2\% < \theta \leq 9\%$

$m = 0.5,\ \theta < 9\%$

Where L is the Slope length factor, S is the Slope gradient factor, λ is the slope length (m), m is the variable slope-length exponent, and θ is the slope angle (°).

Crop management C is also stated to combine plant cover, its production level and the associated cropping techniques (Roose, 1996) thus, it is said to vary from 1 on bare soil to 0.001 for forest conditions, 0.01 for grasslands and cover plants and 0.9 – 0.1 for root and tuber crops. It was further stated that conservation factor P took account of specific erosion control practices such as contour tilling or mounding, or contour ridging. It also varied from 1 on bare soil with no erosion control to 0.1 with tied ridging on a gentle slope, contouring, contour strip-cropping and terracing all had P values of 0.6, 0.35 and 0.15, respectively (Kuok et al., 2013).

2.3 Rainfall simulator characteristics

A 2.2 m × 2 m sized rainfall simulator was designed, fabricated, calibrated for this study. The rainfall simulator rested on a wooden frame 2 m × 2 m by size, made using a 0.0508 m × 0.0508 m sized wood, 1.65 m high and 2 m length and breadth, with 0.3 m of each leg buried into the ground to stand firmly. The rainfall simulator had a primary pipe connection that received water from the pump and supplied the laterals. These laterals, in turn, distribute water to the sub-lateral, where the water was sprayed through the shower roses. Each of the shower roses was 90 mm in diameter, made up of 105 holes, and each of the holes had an approximate diameter of 2 mm, as presented in Figure 2. The drop velocity (DV) was calculated to be 8.101 m s^{-1} and 2.443 m s^{-1} when operated at the maximum and minimum intensity, respectively. The performance test revealed the experimental coefficient of uniformity (CU) and rainfall intensity from the simulator to be 79.86 % at 31.79 mm h^{-1} and 78.03 % at 16.08 mm h^{-1} when running at maximum and minimum intensity, respectively. Table 3 presents the characteristics of the rainfall simulator at both minimum and maximum velocity.

Table 3 Characteristics of the rain simulator at both maximum and minimum intensity

Flow rate	At Max. Intensity	At Min. Intensity
Coefficient of Uniformity CU (%)	79.86	78.03
Standard Deviation	0.82	0.44
Area (m^2)	4.00	4.00
Average Intensity (mm h^{-1})	31.79	16.08
Kinetic Energy (J mm^{-2} h^{-1})	26.07	22.23
Erosivity Index R (MJ mm ha^{-1} h^{-1})	1278.63	543.46

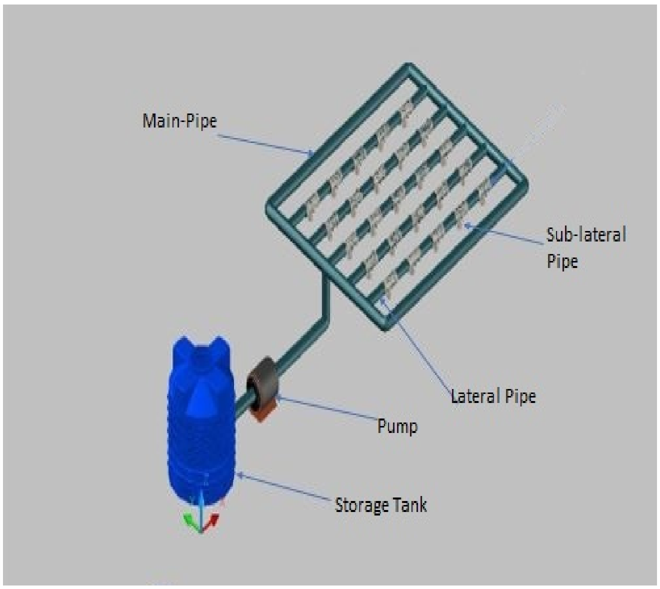

Figure 2 3D view of the rainfall simulator

2.4 Experimental design

A complete block design (CBD) was adopted to design the soil estimation experiment with no replication in each block. Two treatments, a disturbed soil surface evenly done by using the hoe and undisturbed soil surface (vegetative plot), which has been left fallow for a year. Factors considered for this experiment were runoff, rainfall and rainfall intensity with soil loss as the primary response. Data were analysed using Microsoft Excel and Minitab Statistics tool, Design of Experiment (DOE) was used to analyse soil loss estimation, and general linear model (GLM). Analysis of variance (ANOVA) was determined between runoff and soil physio-chemical properties (Soka and Rolf, 1981).

2.5 Establishment of runoff plots

Galvanised iron sheets with approximately 30 cm in height were driven 10 cm into the soil to guide runoff into the collection system, to handle the complexity of the interactions and minimise disturbance. For optimal lengths for estimation of sediment and runoff parameters based on the adequate coverage of the rainfall simulator, the size 2 m by 1 m was adopted for each plot. The runoff collection systems consisted of a fabricated iron ground frame, buried into the ground and a 60-Litre sized container, installed at the lower part of each plot (Sadeghi et al., 2011).

2.6 Measurement of soil detachment

The splash-traps, each with dimension, 16.7 cm × 10.8 cm with hollow rectangular plastic containers buried in the ground. The containers were arranged per plot to capture loose soil particles as a result of a splash at about a minimum radius of at least approximately 0.5 m of the width of the plot and a maximum radius of at least 0.7 m of the length of the runoff plot. Considering the total area of each plot, the average adequate space of the splash was evaluated to be approximately 0.798 m, contributing simultaneously to each of the splash traps. The measured weight and the soil collected from the splash traps are expressed per unit area (g m^{-2}) (Adewumi, 2019). To overcome the error that may be occurred during the field measurement, an equation for correcting the effect of soil detachment was proposed by Nearing et al. (2017);

$$A = B.\exp(0.054D) \tag{7}$$

A is the actual mass of splashed soil (g cm^{-3}), B is the measured mass of splashed soil (g cm^{-3}), and D is the diameter of splashed traps.

3 Results and discussion

The level of soil detachment against the experimental runs, at a minimum and maximum intensity, are presented in Figures 3 and 4, respectively. Soil detachment from the bare plot at both passions exceeded soil detachment from vegetative plots, with soil detachment at a maximum intensity from bare and vegetative plots having higher yields than soil detachment at a minimum level from bare and vegetative plots. This result confirms the importance of crop cover in reducing the effects of the direct impact of water drops leading to water erosion. It was also observed that the graphical pattern of both Figures 3 and 4 were not of specific concern during the experimental runs, which indicate considerations of other factors such as the interacting effect of raindrop and surface crusting (Adewumi, 2019). It was observed that there was a weak correlation between soil detachment from both plots (vegetative and bare) and kinetic energy at minimum and maximum intensities except for the soil detachment from bare soil at the minimum concentration, ($p>0.05$, R^2= 0.6354) and regression between soil detachment from vegetative and bare soil at maximum intensity ($p<0.05$, $R^2=0.92$) as presented in Table 4.

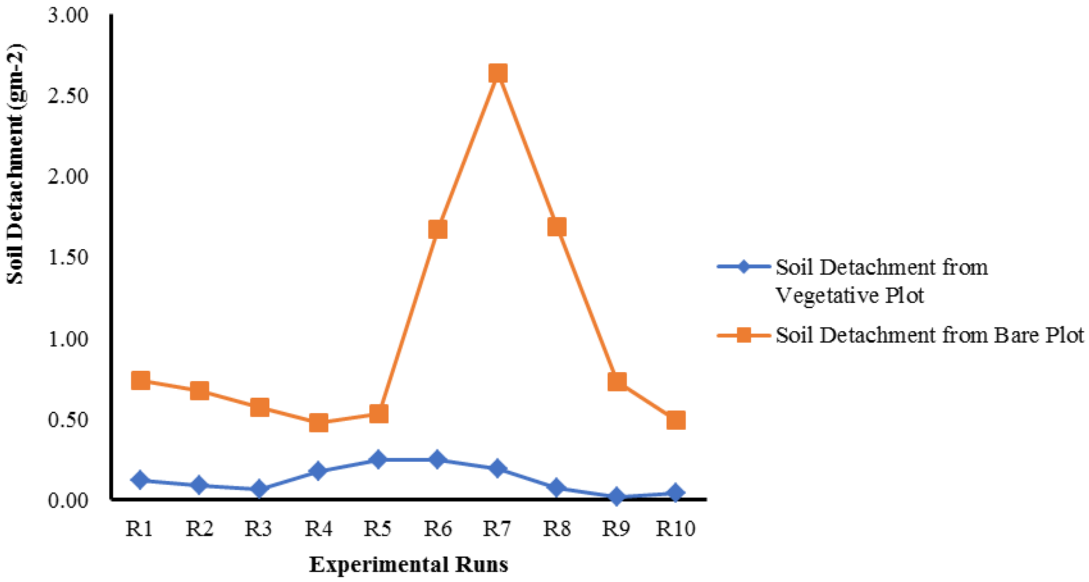

Figure 3 Soil detachment at minimum intensity

Note: Where R1 to R10 is the total experimental runs carried out in the study area.

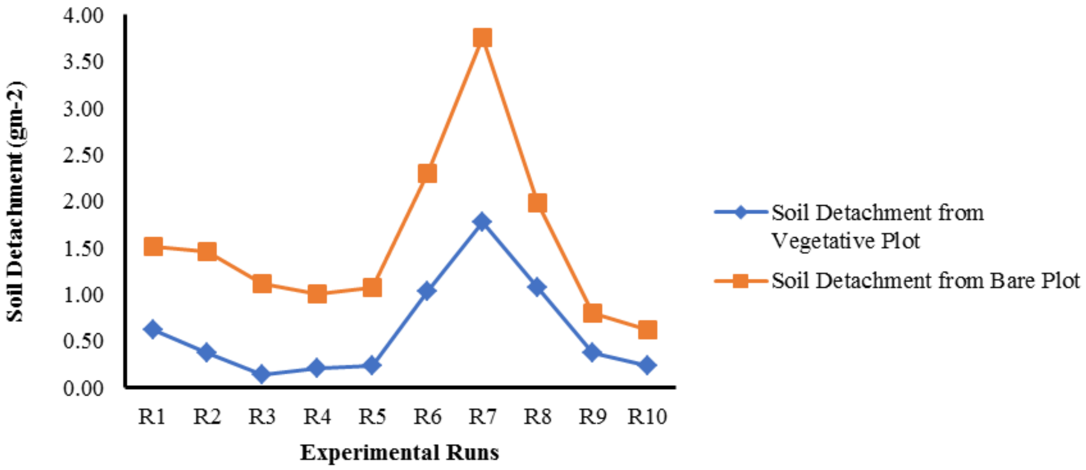

Figure 4 Soil detachment at maximum intensity

Note: Where R1 to R10 is the total experimental runs carried out in the study area.

Table 4 Results of linear regression analysis (soil detachment)

Equations	R^2	Significant Level
$SDV_{min} = -0.3368KE^3 + 23.298KE^2 - 537.08KE + 4126.2$	0.21	$p>0.05$
$SDB_{min} = 3.8999KE^2 - 177.47KE + 2019.4$	0.64	$p>0.05$
$SDV_{max} = 9.4209KE^2 - 492.37KE + 6433.4$	0.38	$p>0.05$
$SDB_{max} = 15.601KE^2 - 815.73KE + 10664$	0.32	$p>0.05$
$SDV_{min} = -0.1792SDBmin^3 + 0.8611SDBmin^2 - 1.1405SDBmin + 0.5012$	0.49	$p>0.05$
$SDV_{max} = -0.5473SDBmax^3 + 0.3915SDBmax^2 - 1.5088SDBmax + 2.0527$	0.92	$p<0.05$

Where;

KE = Kinetic energy of raindrop

SDVmin = Soil detachment from the vegetative plot at minimum intensity

SDVmax = Soil detachment from the vegetative plot at maximum intensity

SDBmin = Soil detachment from the bare plot at minimum intensity

SDBmax = Soil detachment from the bare plot at maximum intensity

Comparison of soil detachment from vegetative and bare plots showed a reduced level of significance $p>0.05$ and R^2 of 0.493 for the minimum simulated rainfall intensity as presented in Table 4. The level of soil detachment from the vegetative plot compared with the bare plot at maximum rainfall intensity showed a significant degree of correlation at $p<0.05$ and R^2 of 0.9164. It was stated by Adewumi (2019) that it was challenging to isolate the effects of various controlling factors adequately and therefore, no satisfactory system of field measurement of splash erosion has been obtained.

3.1 Model validation

A greatly reduced coefficient of determination for vegetative plot (R^2= 0.190) was observed in Figure 5, indicating that rainfall erosivity was not a good estimator for short term rainfall events for vegetative plot with the rainfall simulator but on the other hand, the rainfall erosivity did characterize the erosive action of the rainfall simulator and supported the validity of the USLE for the study area on a short term given the high coefficient of determination for bare plot (R^2 = 0.723). There was a spike in the observed soil loss data reading when erosivity index value attained 446 MJ mm^{-1} ha^{-1} h^{-1} especially for the vegetative plot which suggests that this could be the threshold value of erosivity index in this location.

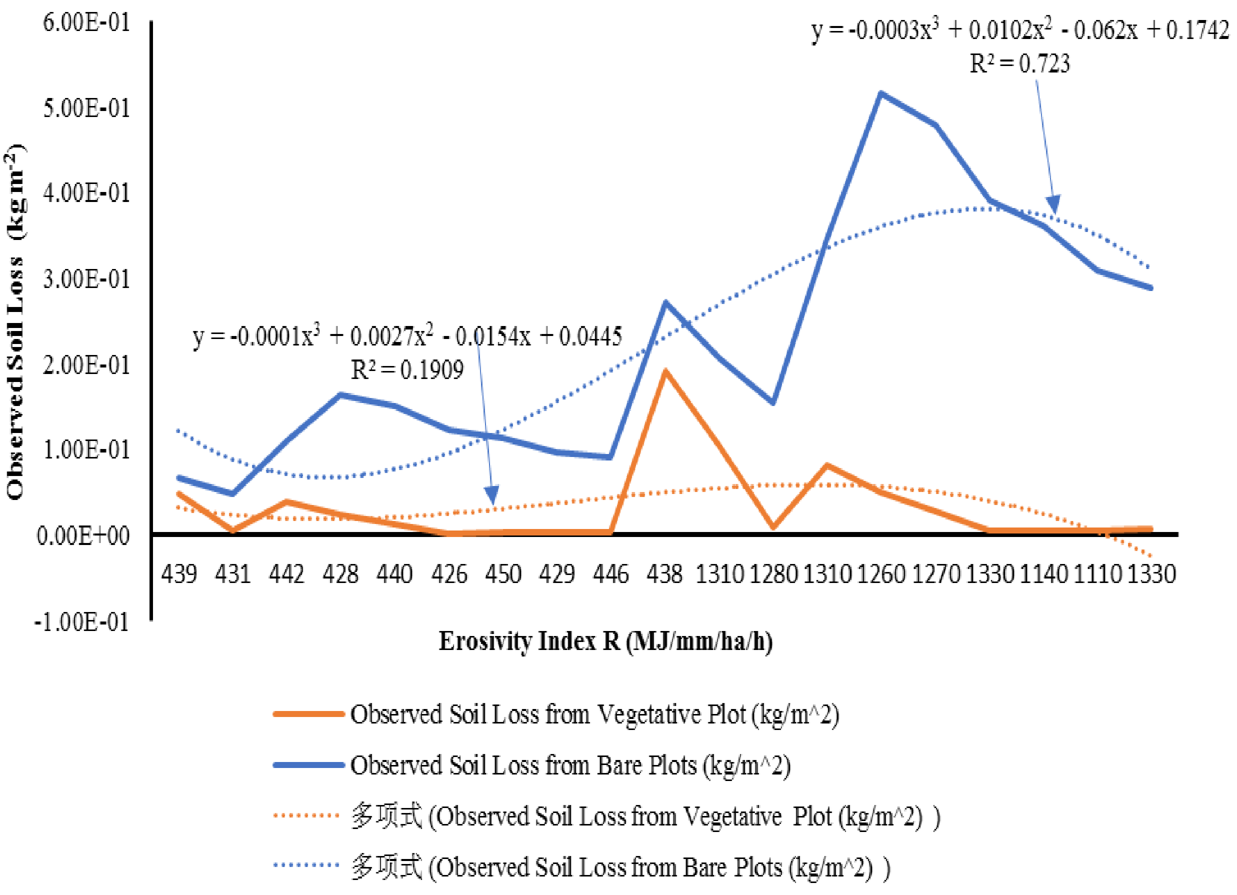

Figure 5 Graph of observed soil loss against the erosivity index

Figure 6 shows the observed soil loss against the erosivity index. The coefficient of determination for vegetative plot (R^2= 0.10) and bare plot (R^2= 0.61) for erosivity index is lesser than the estimated threshold of 446 MJ mm-1 ha-1 h-1, but the values are reduced in Figure 7. The coefficient of determination for vegetative plot (R^2= 0.46) having a greater reduction as compared to bare plot (R^2= 0.78) for erosivity index greater than 446 MJ mm-1 ha-1 h-1. This is because as more raindrops fall more soil particles are detached and eroded until the point where the soil moisture must have reached saturation level with ponding on the surface. The kinetic energy to detach soil particles tend to be constant as the ponding would absorb any energy upon impact.

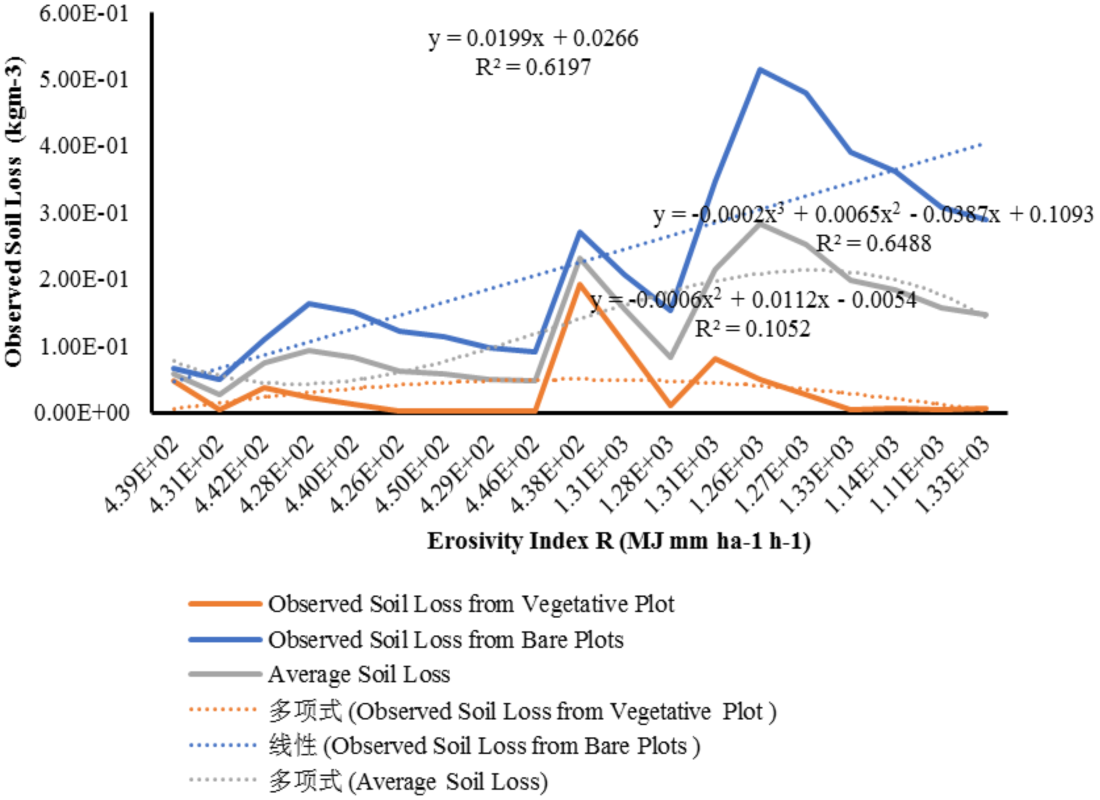

Figure 6 Graph of observed soil loss against the erosivity index

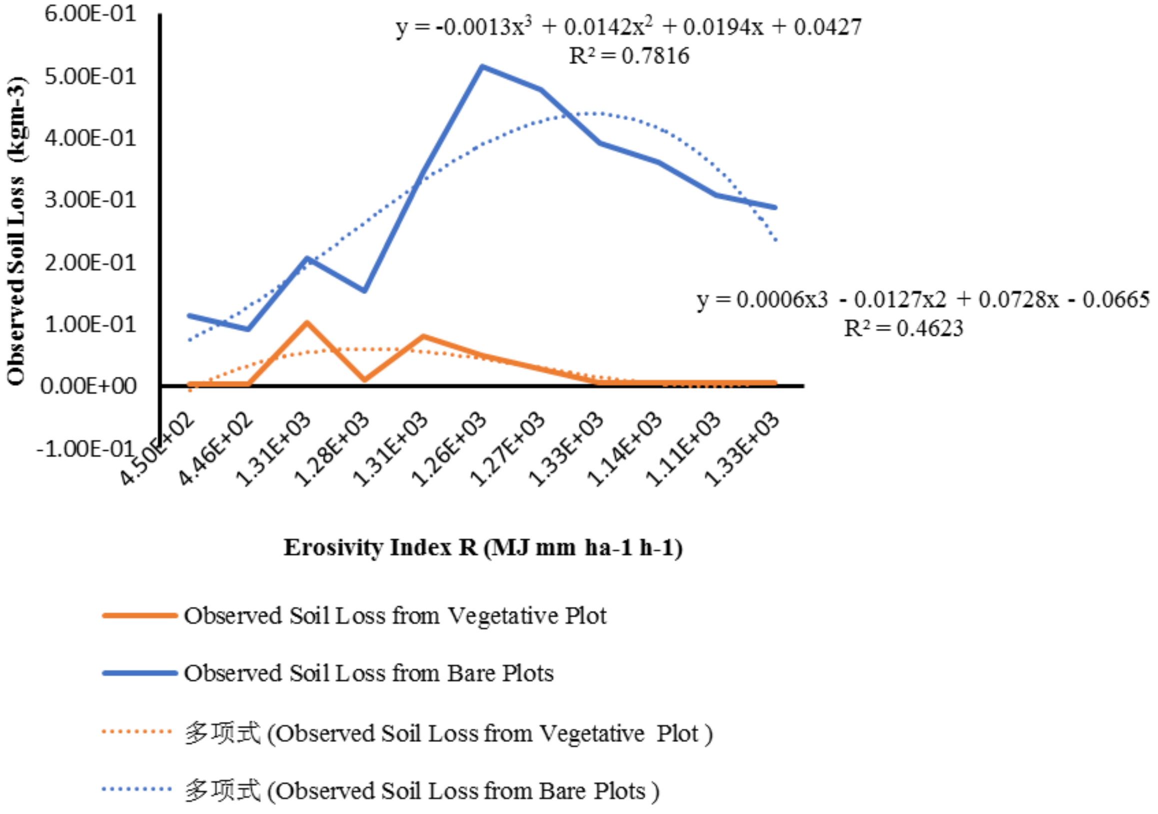

Figure 7 Graph of observed soil loss against erosivity index

It is important to note that data collected over a more extended period could improve the result and could be said to be more reliable (Adewumi, 2019).

4 Conclusion

The research validated the Universal Soil Loss Equation for a selected location in North Central Nigeria for both bare plot and vegetative plot using a rainfall simulator. There was a strong correlation over a short term between erosivity index, R, and observed soil losses from bare plots and a combination of both plots but not for vegetative plot over a short-term rainfall event.

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