Water and Soil Management and Modeling

Online ISSN: 2783 - 2546

University of Mohaghegh Ardabili

Linking soil erosion and food security in Kano State, Nigeria: A geospatial assessment using RUSLE and household surveys

Abdulazeez Hudu Wudil [1], Muttaka Idris[2]*, Akinola Adesuji Komolafe[3]

[1] Senior Lecturer, Department of Agricultural Economics and Agribusiness, Faculty of Agriculture, Federal University Dutse, Jigawa State, Nigeria
[2] PhD Candidate of Remote Sensing and GIS, Department of Remote Sensing and Geo-science Information System, School of Earth and Mineral Sciences, Federal University of Technology Akure, Nigeria.
[3] Associate Professor, Department of Remote Sensing and Geo-science Information System, School of Earth and Mineral Sciences, Federal University of Technology Akure, Nigeria.

Abstract

Soil erosion constitutes a significant environmental and agricultural obstacle that jeopardizes food security throughout Nigeria. This research delves into the correlation between the intensity of soil erosion and household food security in Kano State by employing the Revised Universal Soil Loss Equation (RUSLE) and the Household Food Consumption Score (HFCS). A multistage sampling technique was used to identify 600 respondents across four Local Government Areas categorized by varying levels of erosion severity (Very High, High, Low, and Very Low). The modeling of soil erosion was accomplished in Google Earth Engine by the integration of CHIRPS rainfall data, SRTM Digital Elevation Model (DEM), FAO soil classification maps, and Landsat satellite imagery. The findings derived from the Revised Universal Soil Loss Equation (RUSLE) model indicate that more than 90% of the study area is exposed to high and very high erosion risk; The result of the One-Way ANOVA analysis showed significant differences ($p < 0.001$) in caloric consumption relative to erosion classifications. While 30.36% of the households situated in areas characterized by very low erosion are found to consume between 2800 and 3200 kcal/day, only 12% were found to consume between 2800 and 3200 Kcal/person/day. Similarly, the percentage of households classified as food-secure was found to be high in areas with very low erosion (72%) as against 54.67% in very high erosion areas. Crop yields revealed that cowpea and millet exhibited pronounced sensitivity to erosion, with cowpea yields diminishing by as much as 38.42% when comparing very low to very high erosion zones. This research concludes that soil erosion considerably affects agricultural productivity and food security. It calls for prompt policy measures that support agroforestry, terracing, cover cropping, and sustainable land management methodologies to alleviate erosion and boost food resilience.

Keywords: Food Security, Geospatial analysis, Soil Erosion, Sustainable Land Management

Article Type: Research Article
Academic Editor: Raoof Mostafazadeh

*Corresponding Author, E-mail: muttakaidris@kustwudil.edu.ng, muttakaidris2018@gmail.com

Citation: Wudil, A.H., Idris, M., & Komolafe, A.A. (2026). Linking soil erosion and food security in Kano State, Nigeria: A geospatial assessment using RUSLE and household surveys. Water and Soil Management Modeling, 6(2) (Special Issue: New Approaches to Water and Soil Management and Modeling), 1-20.
doi: 10.22098/mmws.2025.18151.1650
Received: 22 August 2025, Received in revised form: 28 September 2025, Accepted: 28 September 2025, Published online: 03 June 2026
Water and Soil Management and Modeling, Year 2026, Vol. 6, No.2 (Special Issue), pp. 1-20
Publisher: University of Mohaghegh Ardabili

1.Introduction

Soil erosion is a pressing environmental issue that has profound implications for global food security (Kopittke, et al.,2019; Borrelli et al., 2020). It is estimated that approximately 80% of agricultural land globally suffers from erosion, underscoring its widespread impact and the urgency for effective mitigation strategies (Cerón-González et al., 2025). Ighodaro et al. (2016) reported that about 17% of the world's soils have already been eroded by wind and water, making it harder to produce enough food for ever the global population. Since World War II, 38% of the world's agriculture has degraded due to the annual loss of 75 billion tons of soil from farmlands and the destruction of 12 million hectares of cropping land (Dahl et al., 2013). Soil erosion in Nigeria represents a critical environmental challenge that has profound implications for the country's agricultural productivity and food security (Gomiero, 2016; Olagunju, 2015). Regional characteristics markedly influence the severity of soil erosion in Nigeria. In Northern Nigeria, desertification poses a major environmental issue, while the southern regions experience high torrential rainfall, are which are the main causes of soil erosion (Alumona & Onwuanabile, 2019; Muoghalu & Akanwa, 2021). The impact of soil erosion on agriculture in Nigeria is profound, as it directly affects food security and sustainable land management (Anabaraonye et al., 2021; Prince et al., 2023). Soil erosion leads to decreased soil fertility, making it difficult to sustain agricultural productivity, which is crucial for the livelihood of many communities (John et al., 2022). Erosion not only diminishes on-farm productivity but also creates off-site effects, such as sedimentation in waterways, which can disrupt local ecosystems and reduce the quality of water sources (Rashmi et al., 2022; Srivastava et al., 2023; Hayes et al., 2024; Quinton & Fiener, 2024). Several anthropogenic factors exacerbate soil erosion, including deforestation, overgrazing, and the use of inappropriate tillage methods. Climate change also plays a role, intensifying weather patterns that contribute to soil displacement. The National Bureau of Statistics reported that as of 2022, approximately 133 million Nigerians were living in multidimensional poverty, highlighting the severity of the food insecurity crisis (Kasuwa, 2024; Ukwe, 2025). Similarly, food insecurity in Nigeria is a pressing issue, with an estimated 33.1 million representing 16.5% of the population classified as food insecure as of the first quarter of 2024 (Ajetunmobi, 2024). As the population continues to grow, projected to reach between 377 million and 401 million by 2050, there are urgent calls for modernization within the agricultural sector to address these pressing challenges (Kedir & Kararach, 2019; Assan, 2023). This convergence of environmental degradation and socio-economic vulnerability underscores the critical necessity of this research.

The relationship between soil erosion and food insecurity is complex and multifaceted. While agricultural production is heavily dependent on soil quality, food insecurity is not merely a matter of production capacity, it is also a function of access, availability, and utilization of food. Given that soil erosion leads to declining crop yields, it can drive up food prices and disrupt local food systems, further entrenching poverty and food insecurity (Arega et al., 2024; Naqvi et al., 2024). A significant gap exists in directly linking soil erosion and food security through an integrated analytical framework. While numerous studies have independently assessed soil erosion or food security, few have explicitly connected the two phenomena quantitatively. For instance, Samarinas et al., (2024) estimated severe soil loss in the northern Greece using RUSLE, highlighting its threat to agricultural productivity but without quantifying subsequent food security impacts. Similarly, Wudil et al. (2023) developed a complete food security index for Kano state, Nigeria however, the study attributed food insecurity primarily to socio-economic factors, overlooking the foundational role of environmental challenges. Similarly, some studies have approached this link indirectly for example; Barbosa et al. (2024) found that declining crop yields in northwestern Brazil were correlated with degraded soils, while (Barrelli etal 2020; sartori et al., 2024) modeled the potential impact of erosion on future global food production. However, methodologies that integrates a geospatial erosion model like the Revised Universal Soil Loss Equation (RUSLE) with a localized Household Food Security Index (HFSI) at a precise study area level remains underdeveloped. This study aims to fill this gap by employing these integrated frameworks to explicitly examine the effects of soil erosion on food security. The Revised Universal Soil Loss Equation (RUSLE) is a widely used predictive model for estimating soil erosion rates based on various environmental factors. The model incorporates five primary components: rainfall erosivity, soil erodibility, slope length and steepness, cover management, and conservation practices (Benavidez et al., 2018; Pinson & AuBuchon, 2023). The Revised Universal Soil Loss Equation (RUSLE) is used to assess the extent to which soil erosion contributes to food insecurity in the study area by analyzing the impact of soil erosion on agricultural productivity and its effects on food supply. The Household Food Security Model Index (HFSI) is used to evaluate the relationship between soil erosion and household food security. The specific novelty of this study lies in the integration of these two distinct models. This integrated methodology allows for a more holistic assessment of how biophysical degradation translates into socio-economic vulnerability, providing evidence base for interventions that target both land management and livelihood support. This study contributes valuable knowledge that can guide targeted interventions to reduce food insecurity, with practical recommendations for policymakers and agricultural practitioners on sustainable land management practices that mitigate the impacts of soil erosion. This holistic approach is essential for designing effective strategies addressing the root causes of food insecurity in vulnerable communities, offering theoretical and practical contributions to the field. Hence the study is designed to capture the following objectives; 1) quantify annual soil loss rates in the study area using the RUSLE model; 2) assess the level of household food security using the HFSI; and 3) analyze the correlation between estimated soil erosion rates and household food security indices to determine the extent of their relationship.

2.0 Materials and Methods

2.1 Study area:

The state lies at latitude 10°45′00″N to 12°45′02″N and longitude 8°02′00″E to 10°44′00″E, situated within the Sudan savanna zone. Agriculture serves as a primary livelihood for the local population. The region's agricultural output includes millet, sorghum, maize, cowpea, peanuts, pepper, and onions, alongside livestock rearing. According to the 2006 National Population Census, the state's population was approximately nine million, with 4,957,952 males and 4,453,336 females. With an annual growth rate of 2.27% (Raimi et al., 2020).The estimated population has reached 13,895,104. The state encompasses 44 local government areas. There are two major seasons: the dry season, spanning from October to April, and the wet season, lasting from May to September. Annual rainfall varies between 687 and 860 millimeters, while average temperatures range from a minimum of 12°C to a maximum of 41°C (Tafida & Olayinka, 2021).

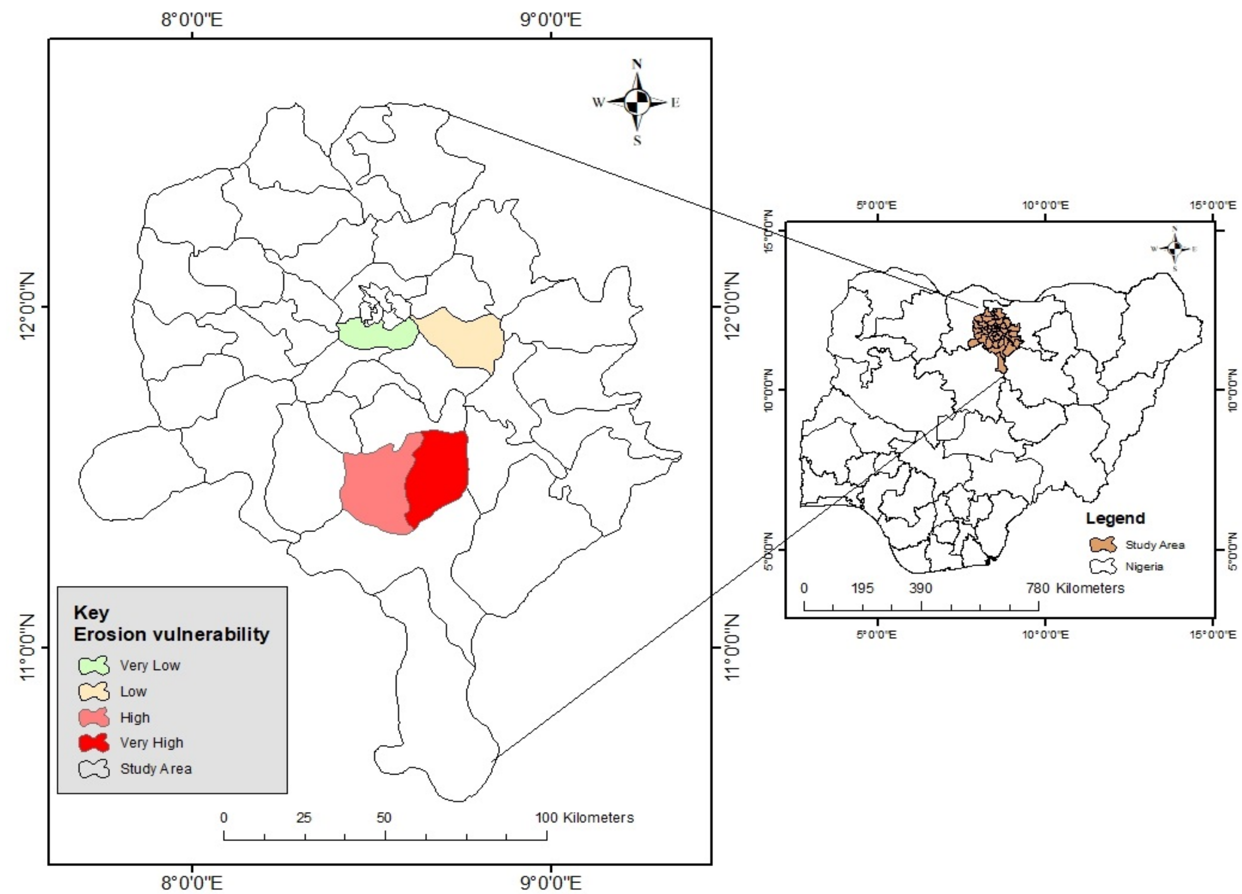

Figure 1: Geographical location of the study area

2.2 Sampling Procedure

A three-stage sampling technique was employed to select respondents for the study, specifically targeting Local Government Areas (LGAs) affected by varying intensities of soil erosion (very high, high, low, and very low). The erosion classification was derived using the RUSLE model, which categorized the study area based on erosion severity. In the first stage, cluster sampling was used to group the state into zones based on erosion intensity: very high, high, low, and very low. This approach enabled the study to assess how soil erosion influences respondents' food security. Based on this clustering, the following LGAs were selected for data collection. Table 1 presents clustered local governments study area based on the noticeable impact and intension of soil erosion.

Table 1: Clustered LGAs in Kano State based on the noticeable impact and intensity of soil erosion

Cluster	Local Government	Sample Size
Very high	Kibiya	160
High	Rano	160
Low	Warawa	160
Very low	Kumbotso	160

Source: Authors computation

In the second stage, due to the lack of a formal sampling frame, respondents were selected from lists of farmers provided by farmers' associations and agricultural officers at the state and local government levels. Initially, 640 respondents were targeted, but after data collection, 618 questionnaires were retrieved. Following data cleaning, 12 responses were discarded. To ensure balanced representation, a minimum of 150 valid responses from each LGA were retained, resulting in a final sample size of 600 respondents. Food security data were collected using semi-structured questionnaires. Soil erosion estimates were generated using the RUSLE model. The moderate erosion class was excluded from the analysis due to its scattered distribution across the state, preventing potential bias in the findings.

2.3 Method of Data Analysis

2.3.1 Household Food Consumption Score (HFCS)

The HHFCS is a continuous measure of the degree of food insecurity (access) in the household in the past 24 hours. According to (Wudil et al., 2023). The HFCS measures the access and availability dimension of food security. They further stress that, since HFCS measures nutrient adequacy, the index indirectly measures utilization. Similarly, the repeated measure of this method can also be used to assess stability. To measure the household food security in the study area, we conducted direct dietary intake surveys and compared the results with nationally defined adequacy standards. This method was previously applied in food security studies across Nigeria (Kehinde & Kehinde, 2020; Aminu, 2023; Mukaila et al., 2024) and Ethiopia (Allee, Lynd, & Vaze, 2021). We calculated the caloric content of commonly consumed foods using standardized conversion factors, converting edible portions into energy values. Where necessary, we cross-checked estimates with food calorie calculators to ensure accuracy. Household food security was measured by comparing actual consumption data against each family's specific dietary needs, accounting for age and gender differences. A household was classified as food insecure if its caloric intake fell below a minimum threshold (2700 Kcal/person/day), the food security line (Boliko, 2019; Wik, Pingali, & Brocai, 2012). We determined caloric adequacy by dividing the household's total calorie supply by its adult-equivalent family size (Coates et al., 2018). All statistical analyses were performed using SPSS Statistics (Version 25).

$$Z_i = \frac{HDPCCA}{HDPCCR} \ldots\ldots\ldots \qquad (1)$$

Where:

$HDPCCR =$ *Household's Daily Per Capita Calorie Requirement*

$HDPCCA =$ *Household's Daily Per Capita Calorie Avaibility*

Where Z_i denotes the status of i^{th} household food security (Z ≥1 food secure and Z<1 food insecure).

A household was defined as a group of individuals cohabiting and sharing meals. To assess food security, the study compared daily per capita calorie availability against dietary requirements, using the FAO's benchmark of 2,700 kcal/day for an adult male (30–60 years) as the reference standard for developing countries. Households were categorized as either Food-secure (meeting or exceeding the 2,700-kcal threshold) or Food-insecure (falling below this requirement). Food poverty was operationalized as the condition wherein an individual or household's consumption fell below the established food security line of 2,700 kcal per capita per day. The model used to measure soil erosion level and the link between soil erosion and the food security status of the respondents in the study area is presented in Fig 2.

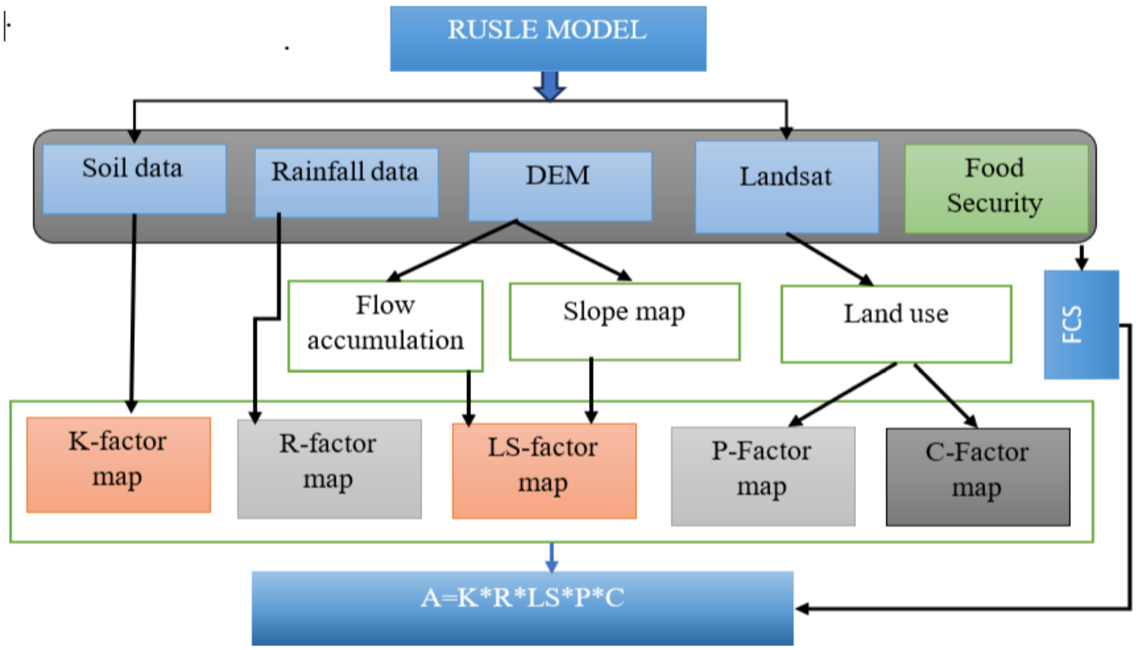

Figure 2: Model for the study linking RUSSLE Model with Food Security Model

2.3.2 Measuring the Effect of Soil Erosion on Food Security

To ascertain the causality between various levels of soil erosion and calorie intake, the study adopts one-way ANOVA. This method was conducted to compare the means of per-calorie intake across the four erosion levels (very high, high, low, and very low). Shapiro-Wilk was used to test the normality of the data, while Levene's test was used to test the homogeneity of variance. The ANOVA model is defined as:

$$Y_{ij} = \mu + \tau_i + \varepsilon_{ij} \qquad (2)$$

Where: Y is the dependent variable,
μ is the mean of all observation,
τ_i deviation from the mean, and
ε_{ij} is the random error

ANOVA is a hypothesis-testing approach that determines statistically significant differences between the means of three or more independent (unrelated) groups (Mooi et al., 2017). It is an expansion of the t-test, which is limited to comparing two groups. The primary notion of ANOVA is to compare the variation within and between groups. If the variation between groups is much greater than the variation within groups, it indicates that the group means are not uniform.

Hypothesis

- Null Hypothesis (H_0): All group means are equal.
  Alternative Hypothesis (H_1): At least one group mean is different from the others.

2.3.3 Soil Erosion Modeling Using RUSLE

The average annual soil loss *A* (t ha⁻¹ yr⁻¹) was calculated using the Revised Universal Soil Loss Equation (RUSLE) (Equation 3), where *R* is the rainfall-runoff erosivity factor (MJ mm ha⁻¹ h⁻¹ yr⁻¹), *K* is the soil erodibility.

factor (t h MJ⁻¹ mm⁻¹), *LS* is the slope length and steepness factor (dimensionless), *C* is the cover-management factor (dimensionless), and *P* is the support practice factor (dimensionless).

$$A = R \times K \times LS \times C \, X \, P \qquad (3)$$

The Revised Universal Soil Loss Equation (RUSLE) Table 2. was used to estimate soil erosion in the study area. The equation is expressed as:

Table 2: Data Sources and Processing Technique

Factor	Description	Data Source	Processing Method
R (Rainfall Erosivity)	Energy of rainfall in soil detachment	CHIRPS rainfall data (2024)	Derived using empirical equation based on annual precipitation
K (Soil Erodibility)	Susceptibility of soil to erosion	FAO soil map	Calculated based on soil texture and organic matter content
LS (Topographic Factor)	Influence of slope length and steepness	SRTM DEM (30m)	Computed using flow accumulation and slope gradient in GIS
C (Cover Management Factor)	Vegetation cover effect on erosion	Landsat 8 (2024)	Derived from NDVI-based classification
P (Support Practice Factor)	Effect of conservation measures	Land use data	Assigned based on land management practices

The RUSLE model was implemented using Google Earth Engine (GEE**)** Random Forest. Soil erosion rates were validated using field observations and literature.

2.3.3.1 Topographic Factor (LS)

The combined slope length and slope steepness factor (LS) was calculated according to (Rasanen et al., 2023) using Equation 4:

$$LS = \left(\frac{\lambda}{22.13}\right)^m \times (65.41 sin^2\theta + 4.56 sin\theta + 0.065) \quad (4)$$

where λ is the slope length in meters, θ is the slope angle in degrees, and m is a slope-length exponent. The value of m is determined by the slope gradient: 0.2 for slopes <1%, 0.3 for 1-3%, 0.4 for 3-5%, and 0.5 for slopes ≥5%

2.3.3.2 Rainfall-Runoff Erosivity Factor (R)

Rainfall-Runoff Erosivity Factor (R) represents the cumulative kinetic energy and intensity of rainfall to cause erosion. It was calculated as the annual sum of all storm events' $\sum(EI_{30})$ values (Equation 5), which is the product of a storm's total kinetic energy (E) and its maximum 30-minute intensity (I_{30}) (Raj et al., 2022)

$$R = \sum(EI_{30}) \quad (5)$$

2.3.3.3 Soil Erodibility Factor (K)

The soil erodibility factor (K) quantifies the inherent susceptibility of soil particles to detachment and transport by rain and surface runoff. It was determined based on soil properties using the formula established by (Wang et al., 2023) (Equation 6):

$$k = \frac{1.293.\left(\begin{array}{c}2.1 \times 10^{-4}.M^{1.14}.\\(12 - 0m) + 3.25(S - 2) + 2.5\,(P - 3)\end{array}\right)}{100} \quad (6)$$

where M is the particle-size parameter, OM is the percentage of organic matter, S is the soil structure code, and P is the permeability class.

2.3.3.4 Cover-Management Factor (C)

The cover-management factor (C) is a ratio that represents the effect of vegetation cover and land use practices on reducing soil erosion relative to bare, tilled soil. It was calculated using Equation 7 (Xiong et al., 2023).

$$C = \frac{Soil\ Loss\ uder\ Existing\ Cover}{Soil\ Loss\ under\ Bare\ Soil} \ldots \quad (7)$$

2.3.3.5 Support Practice Factor (P)

The support practice factor (P) is a ratio that represents the effect of conservation practices (e.g., contouring, terracing, strip-cropping) on reducing erosion compared to farming up and down the slope. It was calculated using Equation 8 (Marcinkowski, 2025).

$$\boldsymbol{C} = \frac{Soil\ Loss\ with\ Support\ Practice}{Soil\ Loss\ without\ Support\ Practice} \quad (8)$$

Values range from 0 (maximum conservation practice effectiveness) to 1 (no conservation practices) (Marcinkowski, 2025).

2.3.4 Evaluation of the Accuracy of the Model

The accuracy of the model was evaluated using equation 9. Predicted is the model output while the observed are the result of the fieldwork

$$\text{Accuracy Assessment} = \frac{\text{Predicted}}{\text{observed}} \text{X } 100 \quad (9)$$

Weakness: It failed to assess the accuracy of the moderately erosion areas because sheet erosions are not visible. The number of points can be added for better accuracy

Table 3: verification of the model Accuracy

Point (Lat, Lon)	Predicted Class	Observed Class	Match	Remarks
11.941030, 8.647986	Low	Low	✓	Vegetated farmland; minimal erosion with no visible rills
11.887517, 8.747722	Low	Low	✓	Grass cover; stable soil condition
11.518233, 8.654769	Very High	Very High	✓	Active gully erosion with sparse vegetation; matches prediction
11.536176, 8.665029	Very High	Very High	✓	Severe gully erosion; model prediction confirmed
11.570764, 8.588912	High	High	✓	Sparse vegetation; visible rill erosion
11.541178, 8.581542	High	High	✓	Exposed soil and slope gradient with visible rills

3.0 Results and Discussion

Figure 3. present the RUSLE factors include Rainfall Erosivity (R), which measures the effect of precipitation intensity on soil detachment; Soil Erodibility (K), reflecting soil vulnerability to erosion; Topographic (LS), accounting for slope length and steepness effects; Cover Management (C), indicating vegetation's role in reducing erosion; and Support Practice (P), representing conservation measures like contour farming. These factor maps are combined in RUSLE to estimate soil loss and guide erosion control strategies.

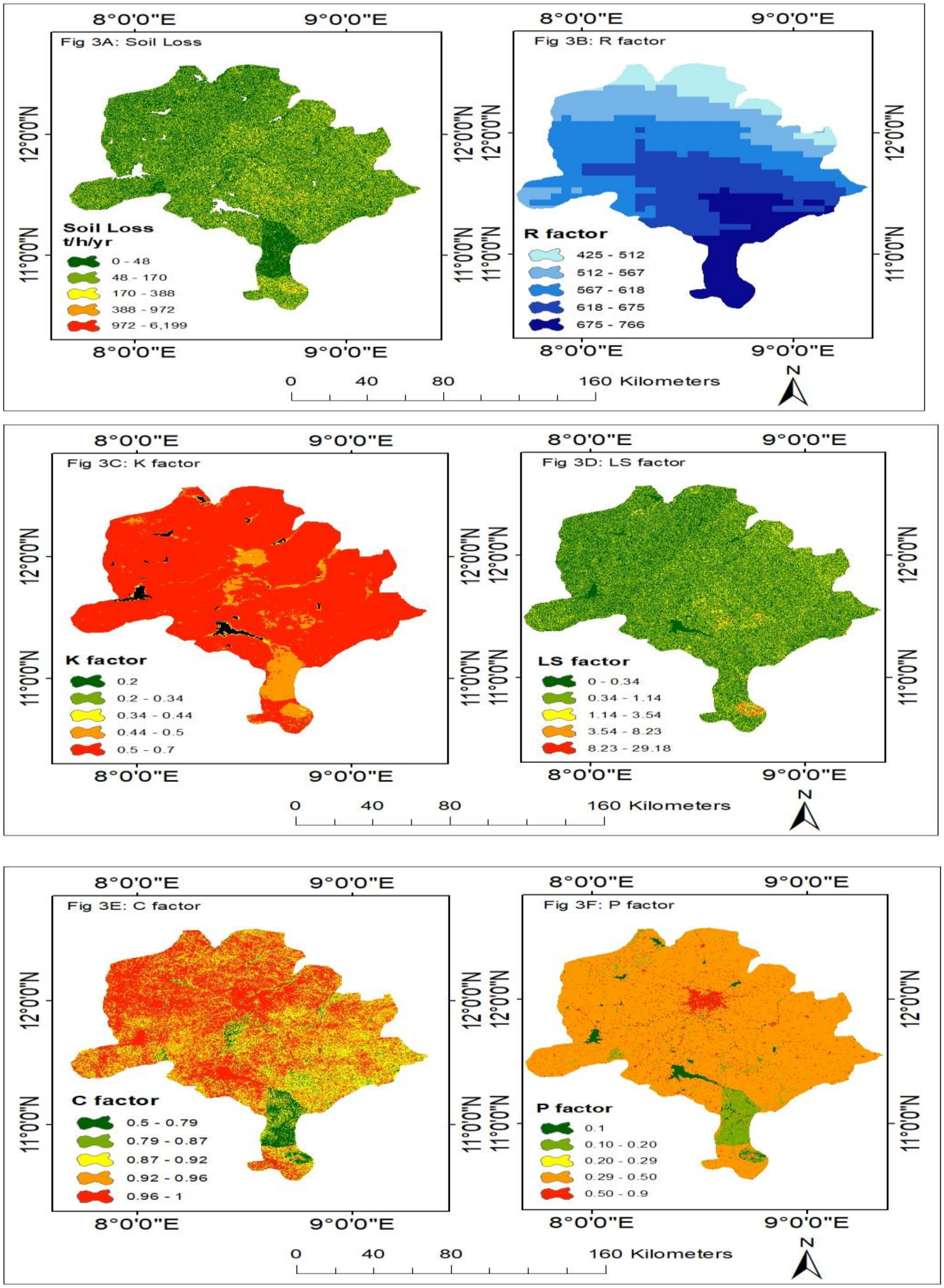

Figure 4 represents the distribution of soil erosion risk across five categories: Very Low, Low, Moderate, High, and Very High. The results are presented in t/ha and percentages.

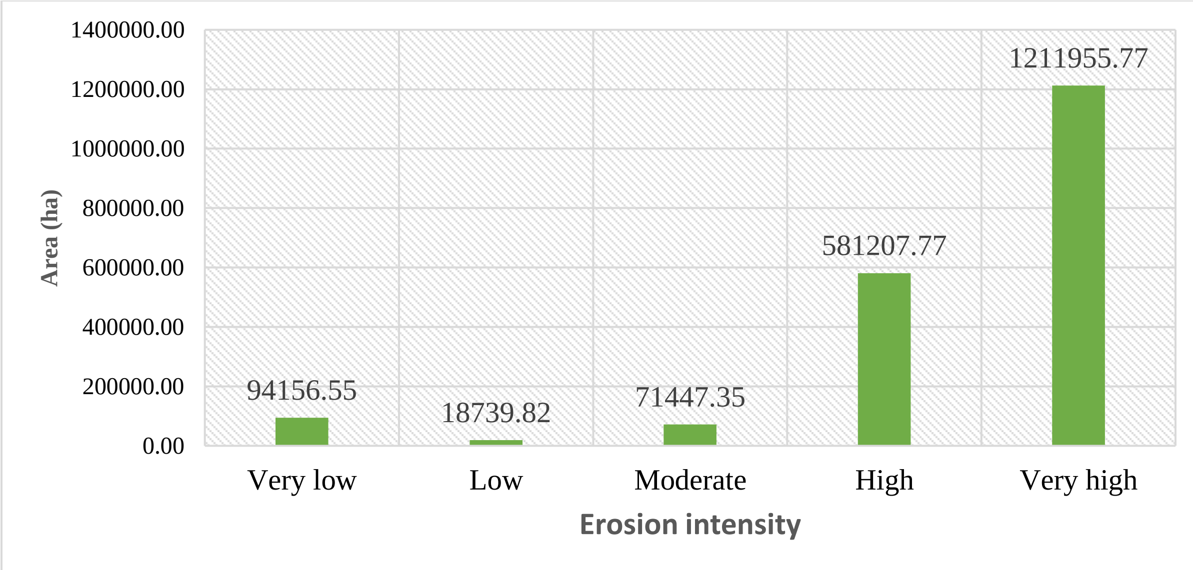

Figure 4: Distribution of the study area by erosion intensity classes

3.1 Intensity of soil erosion in the study area

The result (Figure 4) indicates that Very Low accounts for 94,156.55 ha (4.76%) of the total area. Low represents 18,759.82 ha (0.95%). Moderate encompasses 71,447.35 ha (3.61%), High covers an area of 581,207.77 ha (29.40%), while "Very High" dominates with 1,211,955.77 ha (61.28%). From the findings, it can be observed that 1,793,163.54 ha (90.68%) of the total area is prone to very high or high erosion risk, which is detrimental to the livelihood of the farming household in the study area. This result is in agreement with that of Mwanake et al. (2023) who showcased that a large area of the African soil is devastated by high erosion levels. Another study by Igwe, Onuigbo, Chinedu, Ezeaku, and Muoneke (2017) outlined that in southwestern Nigeria, soil loss due to erosion exceeds 50 tons per hectare annually, with deforestation, poor farming practices, and heavy rainfall as the major contributors. Lal (2015) reported that, across Sub-Saharan Africa,

soil erosion has been identified as a major environmental challenge, with an estimated 65% of agricultural lands affected by moderate to severe degradation. Similarly, a study conducted by Nyssen et al. (2015) reported that in Ethiopia's highlands, over 90% of the land is prone to erosion primarily due to unsustainable land management combined with steep slopes.Table 4 presents a cross-tabulation between Soil Erosion Level and Calorie Intake (Kcal). The values outside the parentheses represent the frequencies, while the percentages are the figures in parentheses.

Table 4: Cross tabulation of the Soil Erosion Levels and Calories Intake

Erosion Level	Calorie intake (Kcal)				Total
	1600 – 2000	2001- 2400	2401-2800	2801-3200	
Very high	42(28.00)	76(50.67)	14(9.33)	18(12.00)	150
High	56(37.33)	42(28.00)	33(22.00)	19(12.67)	150
Low	28(18.67)	48(32.00)	49(32.67)	25(16.67)	150
Very low	19(12.67)	33(22.00)	52(34.67)	46(30.67)	150
Total	145(24.16)	199(33.17)	148(24.67)	108(18.00)	600

3.2 Cross tabulation of the Soil Erosion Levels and Calories Intake

The result indicates that some 28% of the respondents in the very high erosion area consumed on average 1600 to 2000 kcal/p/day. Similarly, some 50.67% consumed an average of 2001 to 2400 Kcal, and only 12% consumed above 2800 Kcal. In the high erosion areas, the result indicates that more than one-third of the respondents (37.33%) consumed between 1600 to 2000 Kcal/p/day, 28% of the households consumed an average of between 2001 and 2400. However, those that consumed an average of between 2401 to 2800Kcal/p/day and 2801 to 3200Kcal/p/day were found to be 22 and 12.67% respectively. Meanwhile, in the low erosion area, 32.67% of the respondents consumed between 2401 and 2800 Kcal/p/day. Some 32.00 % of the respondents consumed between 2001 and 2400 Kcal/p/day. The result also indicates that 18.67 % and 16.67% consumed between 1600 to 2000 Kcal and 2801 and 3200 Kcal/person/day. Lastly, in the very low erosion areas, the results indicate that 34.67% of the farming households consumed between 2401 and 2800 Kcal/p/day. Some 30.67% consumed between 2801 and 3200 Kcal/person/day. The result also indicates that 22% and 12.67% consumed between 2001 to 2400 Kcal and 1600 and 2000 Kcal/p/day. Table 5 presents the results of a one-way analysis of variance (ANOVA) followed by post-hoc pairwise comparisons (Table 6) to examine the relationship between soil erosion levels and average calorie intake of the households across the various categories of the erosion-prone areas.

Table 5: Relationship between Soil Erosion levels and Average Calorie Intake of the Farming households

Calorie intake	Sum of Squares	df	Mean Square	F	Sig
Between Groups	16031654.297	3	5343884.766	34.771	.000
Within Groups	91599353.036	596	153690.190		
Total	107631007.333	599			

Table 6: post-hoc pairwise comparisons

Control		Mean difference	Standard Error	Significant
Very High	High	-106.12597	44.74929	.084NS
	Low	-307.52031*	45.19910	.000***
	Very low	-417.39869*	45.43615	.000***
High	Very high	106.12597	44.74929	.084NS
	Low	-201.39435*	45.12688	.000***
	Very low	-311.27273*	45.36431	.000***
Low	Very high	307.52031*	45.19910	.000***
	High	201.39435*	45.12688	.000***
	Very low	-109.87838	45.80807	.078NS
Very low	Very high	417.39869*	45.43615	.000***
	High	311.27273*	45.36431	.000***
	Low	109.87838	45.80807	.078NS

3.3 Soil Erosion levels and Average Calorie Intake of the Farming households

From the Analysis of Variance result (ANOVA) in Table 5, the test is statistically significant ($p < 0.001$), indicating that at least one erosion level group has a significantly different mean daily calorie intake. In addition, the pairwise comparisons between the Very High Erosion (VHE) and the Low and very low soil erosion levels show a significant mean difference ($p < 0.01$), indicating that very high erosion areas have significantly lower calorie intake than low/very low erosion areas. The result further indicates that there is a significant mean difference ($p <$ 0.000) between the high erosion area and the low and very low erosion areas. In contrast, the results show no significant difference between low and very low erosion areas, and also there was no significant difference between very high and high erosion areas. This result can be concluded to say that the calorie intake of the household can be reduced due to erosion, but at a certain threshold below which there might be a stable calorie intake. Stocking (2003) reported that moderate to low soil erosion may not necessarily affect food intake unless it reaches a mechanical injury threshold.

Table 7: Food Security status across different erosion classes

Erosion Levels	Food Secure	Food insecure	Total
Very high	82 (54.67)	68(45.33)	150
High	96 (64.00)	54(36.00)	150
Low	107(71.33)	43(28.67)	150
Very low	108(72.00)	42(28.00)	150
Total	379(63.17)	221(36.83)	600

3.4 Food Security status across different erosion classes

Table 7 reveals that 72% of farming households in areas with very low soil erosion levels are food secure. Similarly, 71.33% of households in regions with low erosion levels are food secure. In contrast, only 54.67% of respondents in areas with very high erosion are food secure, while 64% in high-erosion zones are food secure. This indicates a notable 17.33% disparity between the extremes (very high vs. very low erosion). These findings align with Tully, Sullivan, Weil, and Sanchez (2015), who observed that soil degradation could increase food insecurity by 20–30%. Additionally, the marginal difference between low and very low erosion areas suggests that once erosion falls below a certain threshold, its impact on food security becomes negligible. Ighodaro et al. (2016) reported that farmers in soil erosion-prone areas of South Africa lose more than 21% of their crops due to erosion, and some 55% reported that erosion affects their food availability.

Table 8: Pairwise comparisons of mean crop yields across soil erosion severity classes.

		Rice			**Millet**			**Sorghum**			**Cowpea**		
Control Groups	Treatment groups	Mean diff.	Std Err.	Sig	Mean diff.	Std Err.	Sig	Mean diff.	Std Err.	Sig	Mean diff.	Std Err.	Sig
Very High	High	239.23	29.89	0.00***	-160.13	8.00	0.00***	31.88	13.26	0.077	-47.92	7.69	0.00***
	Low	59.98	30.19	0.194	-285.70	8.08	0.00***	-61.68	13.39	0.00***	-176.93	7.76	0.00***
	Very low	-65.36	30.34	0.138	-363.87	8.13	0.00***	-98.33	13.46	0.00***	-207.06	7.80	0.00***
High	Very high	-239.23	29.89	0.00***	160.13	8.00	0.00***	-31.88	13.26	0.077	47.92	7.69	0.00***
	Low	-179.26	30.14	0.00***	-125.58	8.07	0.00***	-93.56	13.37	0.00***	-129.01	7.75	0.00***
	Very low	-304.59	30.30	0.00***	-203.74	8.11	0.00***	-130.21	13.44	0.00***	-159.14	7.79	0.00***
Low	Very high	-59.98	30.19	0.194	285.70	8.08	0.00***	61.68	13.39	0.00***	176.93	7.76	0.00***
	High	179.26	30.14	0.00***	125.58	8.07	0.00***	93.56	13.37	0.00***	129.01	7.75	0.00***
	Very low	-125.34	30.59	0.00***	-78.17	8.19	0.00***	-36.65	13.57	0.04**	-30.13	7.87	0.00***
Very low	Very high	65.36	30.34	0.138	363.87	8.13	0.00***	98.33	13.46	0.00***	207.06	7.80	0.00***
	High	304.59	30.30	0.00***	203.74	8.11	0.00***	130.21	13.44	0.00***	159.14	7.79	0.00***
	Low	125.34	30.59	0.00***	78.17	8.19	0.00***	36.65	13.57	0.04**	30.13	7.87	0.00***

3.4 Effect of Erosion Severity on Crop Yields

The analysis of variance revealed a significant effect of erosion severity on the yields of millet, sorghum, and cowpea ($p < 0.001$), while rice yields demonstrated a more complex and less consistent response (Table 8). Post-hoc pairwise comparisons are detailed below. Millet yield exhibited a strong inverse relationship with erosion severity. Yields declined steadily and significantly ($p < 0.001$ for all comparisons) as erosion intensity decreased from 'Very Low' to 'Very High'. The most substantial yield difference was observed between the 'Very Low' and 'Very High' classes (Mean diff. = -363.87 kg). Notably, even a single-step increase in severity, such as from 'High' to 'Very High', resulted in a significant yield reduction of 160.13 kg ($p < 0.001$). This high sensitivity indicates that millet productivity is directly compromised by the loss of topsoil and soil fertility, consistent with reports that each centimeter of topsoil lost can reduce millet yields by up to 37% (Nishigaki et al., 2019; Bright et al., 2017). Sorghum yield was significantly affected by erosion, but the response pattern was not as linear as for millet. While yields in 'Very Low' erosion areas were significantly higher than in 'Very High' areas (Mean diff. = 98.33 kg, $p < 0.001$), no significant difference was found between the 'Very High' and 'High' classes ($p = 0.077$). This indicates that sorghum may tolerate initial increases in erosion severity better than millet, but significant yield penalties occur once erosion passes a moderate stage (e.g., 'Low' to 'High' classes). This complex response may be influenced by seasonal rainfall, where the improved drainage of moderately eroded soils can be beneficial in wet years, a phenomenon noted by Kubiku et al. (2022) and Seid (2021). Among the four crops studied, cowpea was the most sensitive to soil erosion. Every pairwise comparison between erosion classes showed a highly significant difference in yield ($p < 0.001$). The yield gap between 'Very Low' and 'Very High' erosion classes was the largest of all crops (Mean diff. = -207.06 kg), and a clear stepwise decline was evident with each increase in erosion severity. This extreme sensitivity is likely due to the plant's reliance on nitrogen fixation and a shallow root system, making it highly vulnerable to the loss of organic matter and topsoil. Our results, showing yield reductions exceeding 38%, confirm previous studies that reported cowpea declines of 22-45% on eroded soils due to reduced nutrient availability and root exposure (Zougmoré et al., 2000; Agyare et al., 2021).

Contrary to the other crops, rice yield did not follow a systematic pattern of decline with increasing erosion severity. No significant yield difference was found between 'Very High' and 'Low' ($p = 0.194$) or 'Very High' and 'Very Low' ($p = 0.138$) erosion classes. A significant difference was only observed between the most severe classes, 'Very High' and 'High' (Mean diff. = 239.23 kg, $p < 0.001$). This suggests that lowland paddy rice is resilient to moderate erosion, likely until a critical threshold of soil loss or physical disruption is crossed. This finding aligns with existing literature which posits that paddy yields are only significantly impacted when erosion leads to gully formation, disrupts hardpans crucial for water retention, or exceeds a soil loss rate of approximately 12 Mg ha^{-1} yr^{-1} (Lal, 2006; Valentin et al., 2005; Smith et al., 2021).

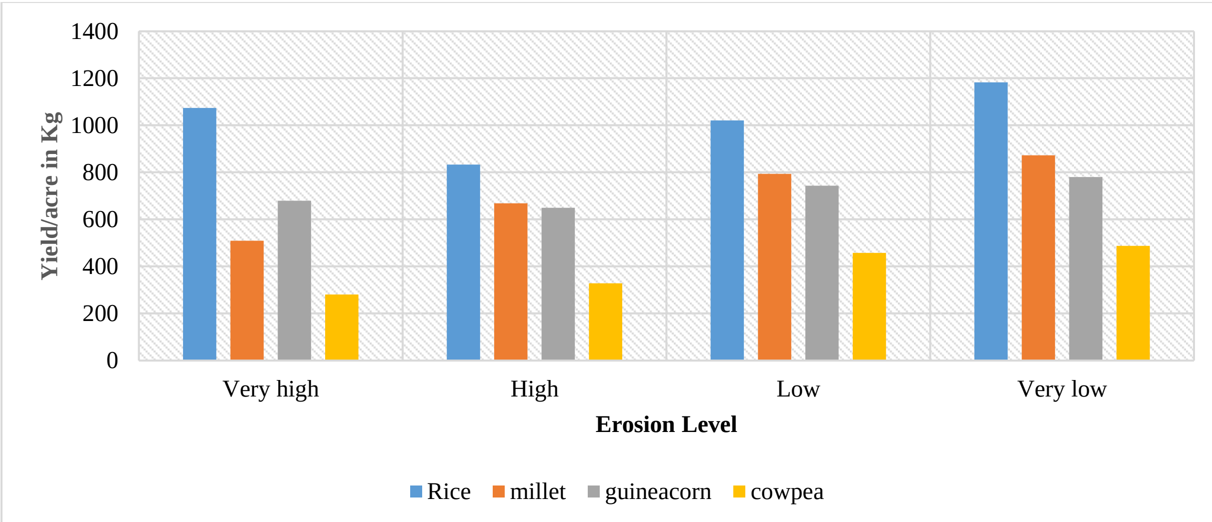

Figure 5: Average Yield of some cereals per acre across different erosion levels

3.6 Average yield per acre across different erosion levels

From the result, (Fig.5) the average yield of paddy per acre of the very low erosion area was the highest (1125.44kg/acre), which is closely followed by the very high erosion area with an average of 1060.43kg/acre. The areas with the high and low erosion levels have the mean output of 818.65kg and 998.36kg/acre, respectively. For the millet, the average output of the highly vulnerable area was found to be 510.12kg/acre, as against 668.55kg, 794.13kg, and 872.29kg for high, low, and very low erosion levels, respectively. This result showcased that erosion harms the production of millet. The result in Figure 1 further shows that the average yield of sorghum in the very high erosion area was 679.32kg/acre, and that of the high erosion area was 649.73 kg/acre. Similarly, the average yield of the low and very low erosion areas was 743.28kg and 779.93kg, respectively. This result shows that very high and highly vulnerable areas have virtually the same yield level, and areas with low and very low erosion have outputs that are virtually the same. The average yield gap between the two extremes was found to be 100.62kg, representing 12.9%. Lastly, the result shows that the average yield of cowpea ranges between 281.57kg/acre to 457.19kg/acre for very high erosion level and a very low erosion area, respectively. This shows a difference of 175.62kg/acre, representing 38.42%. For the high and low erosion areas, the average yields were 328.18kg/acre and 457. 19kg/acre respectively. This finding is in line with that of Pimentel and Burgess (2013), who reported that soil erosion could reduce crop yield by 20 to 50%, depending on the severity.

4.0 Conclusion

Environmental problems include soil erosion, which is made worse by unsustainable land use and climate change. The purpose of the study was to calculate the extent of soil erosion and how it affected the food security of households in Kano State. The home food security index and the RUSTLE model are used in the study. According to the study, soil erosion severely affects a sizable amount of the study area's agricultural land. This study is essential for policy recommendation in Nigeria in the following ways: The geospatial erosion risk map enables precise targeting of conservation resources (e.g., subsidies for agroforestry, terracing) to the specific LGAs and watersheds with "High" and "Very High" erosion severity, maximizing impact and cost-effectiveness. In addition, the proven link between erosion and reduced yields of staples like cowpea and millet mandates the integration of soil conservation into national food security policy, making Sustainable Land Management a core pillar of agricultural programming.

4.1 Summary of the Findings

This study yielded three primary and interconnected findings. Firstly, the geospatial analysis revealed the alarming scale of the issue, with over 90% of the study area being at high to very high risk of erosion. This widespread degradation had a direct human cost, as evidenced by a strong negative correlation ($p < 0.001$) between erosion severity and household food security. Ultimately, this decline in food security was driven by the significant sensitivity of key crop yields to erosion, particularly for cowpea and millet, which saw drastic reductions in productivity.

4.2 Limitations of the Study

The study's findings are subject to several important limitations. The first limitation concerns model generalization; the RUSLE model, while robust, is an empirical model that estimates potential soil loss, and actual sediment yield can be influenced by factors not fully captured, such as subsurface processes. A second limitation involves the spatial and temporal scope of the study, which was confined to a specific timeframe and four LGAs in Kano State, thereby limiting the generalizability of the findings to other agro-ecological zones or climatic conditions. Finally, a third limitation stems from the use of cross-sectional data. The household survey provides only a snapshot in time, whereas a longitudinal design would be necessary to more definitively establish causality between erosion and food security over time.

4.**3 Recommendations for future research direction**

Future studies should integrate the RUSLE model with a sediment delivery ratio (SDR) or process-based models like SWAT to better quantify actual sediment yield. Consequently, future study should be expanded to wider geographical areas across Nigeria's agro-ecological zones and incorporate multi-year data to properly assess long-term trends and climate impacts.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions: First Author: Study conception, Data analysis, and original manuscript preparation. Second Author: Supervision, data cleaning, and Critical revision of the manuscript. Third Author: Study design, Methodology, and Analytical review.

Data availability: Available on request.

Funding: This research received no specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

Agyare, W. A., Amponsah, W., Forkuo, E. K., Opoku, A., Quansah, E., Bessah, E., ... & Adeyewa, D. (2023). Soil Carbon Sequestration and Crop Production Course Module. https://cgspace.cgiar.org/items/5eb719fa-2ddf-4dc7-983b-fbeecee48b74.

Ajetunmobi, O. (2024). Socio-economic impact of food insecurity on vulnerable population in Nigeria. *Journal of Agriculture, Food Systems, and Community Development, 13*(4), 13–18. https://www.foodsystemsjournal.org/index.php/fsj/manuscriptguidelines.

Allee, A., Lynd, L. R., & Vaze, V. (2021). Cross-national analysis of food security drivers: comparing results based on the Food Insecurity Experience Scale and Global Food Security Index. *Food Security, 13*(5), 1245-1261. https://link.springer.com/article/10.1007/s12571-021-01156-w

Alumona, I. M., & Onwuanabile, K. M. (2019). Environmental insecurity in Nigeria. *Internal Security Management in Nigeria: Perspectives, Challenges and Lessons*, 181-213. doi:10.1007/978-981-13-8215-4

Aminu, F. O. (2023). Agrarian Households Vulnerability to Food Insecurity in Ogun

State Nigeria. *Journal of Agriculture, Food, Environment and Animal Sciences*, *4*(2), 214-229. http://www.jafeas.com, ISSN: 2757-5659

Anabaraonye, B., Okafor, J. C., Ewa, B. O., & Anukwonke, C. C. (2021). The impacts of climate change on soil fertility in Nigeria. *Climate Change and the Microbiome: Sustenance of the Ecosphere*, 607-621. https://link.springer.com/chapter/10.1007/978-3-030-76863-8_31

Arega, E., Deribew, K. T., Moisa, M. B., & Gemeda, D. O. (2024). Assessment of soil erosion and prioritization of conservation and restoration measures using RUSLE and Geospatial techniques: the case of upper Bilate watershed. *Geomatics, Natural Hazards and Risk, 15*(1), 2336016. doi:10.1080/19475705.2024.2336016

Assan, N. (2023). Sustainable small-scale animal agriculture and food security in Africa. doi: 10.54517/ssd. v1i2.2342

Barbosa, W. C. D. S., Guerra, A. J. T., & Valladares, G. S. (2024). Soil erosion modeling using the revised universal soil loss equation and a geographic information system in a watershed in the northeastern Brazilian Cerrado. *Geosciences*, *14*(3), 78. doi:10.3390/geosciences14030078

Benavidez, R., Jackson, B., Maxwell, D., & Norton, K. (2018). A review of the (Revised) Universal Soil Loss Equation ((R) USLE): With a view to increasing its global applicability and improving soil loss estimates. *Hydrology and Earth System Sciences, 22*(11), 6059-6086. doi:10.5194/hess-22-6059-2018

Boliko, M. C. (2019). FAO and the situation of food security and nutrition in the world. *Journal of nutritional science and vitaminology, 65*(Supplement), S4-S8. doi:10.3177/jnsv.65. S4

Borrelli, P., Robinson, D. A., Panagos, P., Lugato, E., Yang, J. E., Alewell, C., … & Ballabio, C. (2020). Land use and climate change impacts on global soil erosion by water (2015–2070). *Proceedings of the National Academy of Sciences, 117*(36), 21994-22001. doi:10.1073/pnas.2001403117

Bright, M. B., Diedhiou, I., Bayala, R., Assigbetse, K., Chapuis-Lardy, L., Ndour, Y., & Dick, R. P. (2017). Long-term Piliostigma reticulatum intercropping in the Sahel: crop productivity, carbon sequestration, nutrient cycling, and soil quality. Agriculture, ecosystems & environment, 242, 9-22. doi: 10.1016/j.agee.2017.03.007

Cerón-González, A., Ng, H., Ivelic-Saez, J., Vega-Aguilar, A., Agbor, D. T., Pacci, S., & Glina, B. (2025). Securing the future of soil science: Addressing global demographic barriers to engage youth and accelerate early careers. Geoderma, 455, 117220.

Coates, J., Patenaude, B. N., Rogers, B. L., Roba, A. C., Woldetensay, Y. K., Tilahun, A. F., & Spielman, K. L. (2018). Intra-household nutrient inequity in rural Ethiopia. Food Policy, 81, 82-94. doi: 10.1016/j.foodpol.2018.10.006

Dahl, M.-P. J., Gauer, P., Kalsnes, B. G., Mortensen, L. E., Jensen, N. H., & Veihe, A. (2013). Numerical runout simulation of debris avalanches in the Faroe Islands, North Atlantic Ocean. Landslides, 10, 623-631.

Gomiero, T. (2016). Soil degradation, land scarcity and food security: Reviewing a complex challenge. Sustainability, 8(3), 281. doi:10.3390/su8030281

Hayes, E., Higgins, S., Mullan, D., & Geris, J. (2024). High-resolution assessment of riverbank erosion and stabilization techniques with associated water quality implications. International Journal of River Basin Management, 22(4), 611-625. doi:10.1080/15715124.2023.2214866

Ighodaro, I. D., Lategan, F. S., & Mupindu, W. (2016). The impact of soil erosion as a food security and rural livelihoods risk in South Africa. Journal of Agricultural Science, 8(8), 1-12. doi:10.5539/jas. v8n8p1

Igwe, P., Onuigbo, A., Chinedu, O., Ezeaku, I., & Muoneke, M. (2017). Soil erosion: A review of models and applications. International Journal of Advanced Engineering Research and Science, 4(12), 237341. https://dx.doi.org/10.22161/ijaers.4.12.22

Jackie, A. J. (2024). The influence of human activity and environmental factors on gully erosion. *INOSR Experimental Sciences, 13*(1), 80–85. doi:10.59298/INOSRES/2024/13.1.8085

John, J., Rosamma, C. N., & Thampi, S. G. (2022). Assessment and prediction of soil erosion and its impact on the storage capacity of reservoirs in the Bharathapuzha River Basin, India. Environmental Modeling & Assessment, 27(1), 77–103. doi:10.1007/s10666-021-09789-z.

Kaira, P., Tamta, N., Pant, N., Joshi, J., & Deepak. (2025). Impact of climate change adaptation on the millet crops: As a climate resilient and sustainable crops of Uttarakhand Himalaya. In *Climate change impact on Himalayan biodiversity* (pp. 353–372). Springer. https://www.springer.com/example-book-link

Kasuwa, P. F. (2024). Nigeria: Hungry Nation in a Land of Plenty. *Przegląd Prawno-Ekonomiczny*, (3), 9–32. doi:10.31743/ppe.17613 czasopisma.kul.pl

Kedir, A. M., & Kararach, G. (2019). *Rethinking agricultural transformation and food security in Africa: Hunger and malnutrition as major challenges of the 21st century* (pp. 373–410). doi:10.1142/10980

Kehinde, A. D., & Kehinde, M. A. (2020). The impact of credit access and cooperative membership on food security of rural households in southwestern Nigeria. *Journal of Agribusiness and Rural Development, 57*(3), 255–268. doi: 10.22004/ag.econ.356107

Kopittke, P. M., Menzies, N. W., Wang, P., McKenna, B. A., & Lombi, E. (2019). Soil and the intensification of agriculture for global food security. *Environment International, 132*, 105078. doi: 10.1016/j.envint.2019.105078

Kubiku, F. N., Mandumbu, R., Nyamangara, J., & Nyamadzawo, G. (2022). Sorghum (Sorghum bicolor L.) yield response to rainwater harvesting practices in the semi-arid farming environments of Zimbabwe: A meta-analysis. *Heliyon, 8*(3). doi: 10.1016/j.heliyon. 2022.e08974

Kumar, S., Kumar, A., Sen, H., Janeja, H. S., Maity, S., Banerjee, S., ... Channapur, A. M. (n.d.). Small millets: A multifunctional crop for achieving sustainable food security under climate change. World, 718, 863. doi:10.14719/pst.4113

Lal, R. (2006). Enhancing crop yields in the developing countries through restoration of the soil organic carbon pool in agricultural lands. *Land Degradation & Development, 17*(2), 197–209. doi:10.1002/ldr.696

Lal, R. (2015). Restoring soil quality to mitigate soil degradation. *Sustainability, 7*(5), 5875-5895. doi:10.3390/su7055875

Marcinkowski, P. (2025). Unveiling the Potential of Agricultural Soil Loss Mitigation in Poland: Assessing Conservation Management and Support Practices. *Agronomy, 15*(6), 1290. doi:10.3390/agronomy15061290

Masaka, J., Dera, J., & Muringaniza, K. (2020). Dryland grain sorghum (Sorghum bicolor) yield and yield component responses to tillage and mulch practices under subtropical African conditions. *Agricultural Research, 9*(3), 349-357. doi:10.1007/s40003-020-00485-6

Mooi, E., Sarstedt, M., & Mooi-Reci, I. (2017). Hypothesis testing & ANOVA. In *Market Research: The Process, Data, and Methods Using Stata* (pp. 153-214). Singapore: Springer Singapore. https://link.springer.com/chapter/10.1007/978-981-10-5218-7_6

Mukaila, R., Falola, A., Omotesho, A. O., Akanbi, S.-U. O., Egwue, L. O., & Aidi, H. O. (2024). Effects of COVID-19 on food security status of rural farming households: Evidence from Nigeria. *Journal of Agricultural Sciences (Belgrade), 69*(1). https://aseestant.ceon.rs/index.php/jas/article/view/33039.

Muoghalu, L., & Akanwa, A. (2021). Ecological intensification for sustainable agriculture: The Nigerian perspective. In *Ecological Intensification of Natural Resources for Sustainable Agriculture* (pp. 521-564). https://link.springer.com/chapter/10.1007/978-981-33-4203-3_15

Mwanake, H., Mehdi-Schulz, B., Schulz, K., Kitaka, N., Olang, L. O., Lederer, J., & Herrnegger, M. (2023). Agricultural practices and soil and water conservation in the transboundary region of Kenya and Uganda:

Farmers' perspectives of current soil erosion. Agriculture, 13(7), 1434. doi:10.3390/agriculture13071434

Naqvi, S. A. A., Tariq, A., Shahzad, M., Khalid, S., Tariq, Z., Salma, U., ... Soufan, W. (2024). Predicting soil erosion risk using the revised universal soil loss equation (RUSLE) model and geo-spatial methods. *Hydrological Processes, 38*(8), e15248. doi:10.1002/hyp.15248

Nishigaki, T., Ikazaki, K., Shinjo, H., Tanaka, U., Fatondji, D., & Funakawa, S. (2025). Pearl millet yield reduction by soil erosion and its recovery potential through fertilizer application on an Arenosol in the Sahel. *Soil and Tillage Research, 246*, 106324. doi: 10.1016/j.still.2024.106324

Nyssen, J., Poesen, J., Lanckriet, S., Jacob, M., Moeyersons, J., Haile, M., ... Adgo, E. (2015). Land degradation in the Ethiopian highlands. In *Landscapes and Landforms of Ethiopia* (pp. 369-385). https://link.springer.com/chapter/10.1007/978-94-017-8026-1_21

Olagunju, T. E. (2015). Drought, desertification and the Nigerian environment: A review. *Journal of Ecology and the Natural Environment, 7*(7), 196-209. doi:10.5897/JENE2015. 0523

Pimentel, D., & Burgess, M. (2013). Soil erosion threatens food production. *Agriculture, 3*(3), 443-463. doi:10.3390/agriculture3030443

Pinson, A. O., & AuBuchon, J. S. (2023). A new method for calculating C factor when projecting future soil loss using the Revised Universal Soil Loss Equation (RUSLE) in semi-arid environments. *Catena, 226*, 107067. doi: 10.1016/j.catena.2023.107067

Prince, A. I., Obiorah, J., & Ogar, E. (2023). Analyzing the critical impact of climate change on agriculture and food security in Nigeria. *International Journal of Agriculture and Earth Sciences, 9*, Article 42023. D.O.I: 10.56201/ijaes.v9.no4.2023.pg1.27

Quinton, J. N., & Fiener, P. (2024). Soil erosion on arable land: An unresolved global environmental threat. *Progress in Physical Geography: Earth and Environment, 48*(1), 136-153. doi:10.1177/03091333221140130

Raimi, M. O., Muhammadu, I. H., Udensi, L. O., & Akpojubaro, E. H. (2020). Assessment of safety practices and farmers' behaviors adopted when handling pesticides in rural Kano State, Nigeria. *Arts & Humanities Open Access Journal, 4*(5), 191-201. doi: 10.1016/j.ahoa.2020.100191

Raj, R., Saharia, M., Chakma, S., & Rafieinasab, A. (2022). Mapping rainfall erosivity over India using multiple precipitation datasets. *Catena, 214*, 106256. doi: 10.1016/j.catena.2022.106256

Räsänen, T. A., Tähtikarhu, M., Uusi-Kämppä, J., Piirainen, S., & Turtola, E. (2023). Evaluation of RUSLE and spatial assessment of agricultural soil erosion in Finland. *Geoderma Regional, 32*, e00610. doi: 10.1016/j.geodrs.2023.e00610

Rashmi, I., Karthika, K., Roy, T., Shinoji, K., Kumawat, A., Kala, S., & Pal, R. (2022). Soil erosion and sediments: A source of contamination and impact on agriculture productivity. In *Agrochemicals in Soil and Environment: Impacts and Remediation* (pp. 313-345). https://link.springer.com/chapter/10.1007/978-981-16-9310-6_14

Samarinas, N., Tsakiridis, N. L., Kalopesa, E., & Zalidis, G. C. (2024). Soil loss estimation by water erosion in agricultural areas introducing artificial intelligence geospatial layers into the RUSLE model. *Land, 13*(2), 174. doi:10.3390/land13020174

Sartori, M., Ferrari, E., M'Barek, R., Philippidis, G., Boysen-Urban, K., Borrelli, P., ... & Panagos, P. (2024). Remaining loyal to our soil: A prospective integrated assessment of soil erosion on global food security. *Ecological Economics, 219*, 108103. doi: 10.1016/j.ecolecon.2024.108103

Sartori, M., Ferrari, E., M'Barek, R., Philippidis, G., Boysen-Urban, K., Borrelli, P., … & Panagos, P. (2024). Remaining loyal to our soil: A prospective integrated assessment of soil erosion on global food security. *Ecological Economics, 219*, 108103. doi: 10.1016/j.ecolecon.2023.108103.

Seid, Y. (2024). Assessing land use/cover dynamics on soil erosion and sediment yield in Barkana Watershed, Northeast Ethiopia (Doctoral dissertation). [University], [Location]. [URL if available]

Smith, B., Douangsavanh, S., & Dubois, M. (2024). Synthesis report 2024 on co-designing agroecology innovations for Lao PDR. https://scholar.google.com/scholar?hl=en&as_sdt=0%2C5&as_ylo=2020&as_yhi=2025&q=Smith%2C+B.%2C+Douangsavanh%2C+S.%2C+%26+Dubois%2C+M.+%282024%29.+Synthesis+report+2024+on+co

Srivastava, S., Basche, A., Traylor, E., & Roy, T. (2023). The efficacy of conservation practices in reducing floods and improving water quality. *Frontiers in Environmental Science, 11*, 1136989. doi:10.3389/fenvs.2023.1136989

Stocking, M. A. (2003). Tropical soils and food security: the next 50 years. *Science, 302*(5649), 1356-1359. doi:10.1126/science.302.5649

Tafida, I., & Olayinka, S. (2021). Analysis of gender roles in goat production management in Kano State, Nigeria. *Journal of Agripreneurship and Sustainable Development, 4*(1), 228–241. doi:10.59331/jasd.v4i1.201

Tully, K., Sullivan, C., Weil, R., & Sanchez, P. (2015). The state of soil degradation in Sub-Saharan Africa: Baselines, trajectories, and solutions. *Sustainability, 7*(6), 6523-6552. doi:10.3390/su7066523

Ukwe, C. (2025). Nigeria and food security challenges: Intertwining of climate change and non-state armed groups and policy interventions. DOI: 10.5772/intechopen.1006922

Valentin, C., Poesen, J., & Li, Y. (2005). Gully erosion: Impacts, factors and control. *Catena, 63*(2-3), 132-153. doi:10.1016/j.catena.2005.02.015

Wang, S., Fan, Y., Liu, L., & Qu, J. (2023). Transport/detachment regimes of different size class sediment particles and enlightenments for transport capacity prediction for rain-induced overland flow erosion. *Sustainability, 15*(10), 7906. doi:10.3390/su15107906.

Wik, M., Pingali, P., & Brocai, S. (2012). Global agricultural performance: past trends and future prospects: World Bank. https://documents1.worldbank.org/curated/en/099804004242540454/pdf/IDU-a5bc39e9-8073-48c9-9052-5d569d4dfc4b.pdf

Wudil, A. H., Ali, A., Aderinoye-Abdulwahab, S., Raza, H. A., Mehmood, H. Z., & Sannoh, A. B. (2023). Determinants of food security in Nigeria: Empirical evidence from beneficiaries and non-beneficiaries rice farmers of the Kano River Irrigation Project. *Frontiers in Sustainable Food Systems, 7*, 999932. doi:10.3389/fsufs.2023.999932

Xiong, M., Leng, G., & Tang, Q. (2023). Global analysis of the cover-management factor for soil erosion modeling. *Remote Sensing, 15*(11), 2868. doi:10.3390/rs15112868

Zougmore, R., Kambou, F., Ouattara, K., & Guillobez, S. (2000). Sorghum-cowpea intercropping: An effective technique against runoff and soil erosion in the Sahel (Saria, Burkina Faso). *Arid Soil Research and Rehabilitation, 14*(4), 329-342. doi:10.1080/08903060050136441