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Spatiotemporal Analysis of Potential Impact of Soil Erosion on Maize and Groundnuts Yield in Northern Ghana

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Abstract

Soil erosion is a threat to the viability of arable land, which has a relationship with crop productivity. This study was carried out in the Northern, North-East and Savannah Regions of Ghana, which have a high agricultural potential. The study examined erosion-yield relationship by comparing estimated erosion rates with maize and groundnut yields in a GIS environment. The study also projected soil erosion and determined its potential effect on the yield of maize and groundnuts. The soil erosion rates were found to be 4.2 t ha-1y-1, 5.1 t ha-1y-1 and 7.1 t ha-1y-1 for the Northern, North-East and Savannah Regions respectively.
Projections for the next 10 years showed that, soil erosion will averagely increase by about 12 %, which could reduce the yield of maize and groundnut by 21 % and 16 % respectively by the year 2031, should the current trend continue. The study also found out that crop (maize and groundnut) yield per land area is relatively lower in areas severely affected by soil erosion. Farmers in the study area and areas of similar ecology must be encouraged to adopt Soil and Water Conservation (SWC) strategies to enhance and sustain productivity.

Keywords: RUSLE, Northern Region, North-East Region, Savannah Region.

1. INTRODUCTION

One of the most important natural resources for humans is the soil. It is a limited, strategic resource of huge social, economic and environmental significance (Telles *et al.,* 2013). However, soil erosion continues to disrupts the natural balance which can lead to decrease in the productive potential of agricultural land (Pimentel *et al.,* 1995). Erosion results in the loss of topsoil layers and soil fertility, thereby leading to declining yield per unit of applied inputs (Telles *et al.,* 2011). Soil erosion is widely considered a serious threat to the long-term viability of agriculture in many parts of the world (El-Swaify and Moldenhauer, 1985).

Erosion results in the degradation of a soil's productivity in a number of ways; it reduces the efficiency of plant nutrient use, damages seedlings, decreases plants' rooting depth, reduces the soil's water-holding capacity, decreases its permeability, increases runoff, and reduces its infiltration rate (O'Geen *et al.,* 2001). Soil erosion greatly influences incomes and output from the agricultural sector as yields decline and input costs rise. The decreasing water holding capacity of the soil and loss of soil nutrients as well as changes that takes place in various soil properties (Oguz *et al.,* 2006) causes the destructive effect of the soil erosion. The erosion impact on agricultural land has negative effects on the productivity of the soil and eventually, on crop yield. The effect of erosion on crop yield, resulting in the decline in crop production, is complex and influenced by changes in soil quality variables (Obando and Stocking, 2001).

In Ghana, majority of the rural folks are farmers and are dependent on agriculture with about 70 % involved in the sector. Already, the contribution of the agricultural sector to Ghana's national output has dwindled compared to other sectors of the economy, meanwhile soil erosion continues to cause productivity decline and stagnated crop yield (Fredua 2014). Given that rapid rates of soil erosion are occurring on farms in the study area, a logical place to begin to look at the issue from an economic perspective is its effect on crop yield. This paper examines erosion-yield relationship by analyzing erosion and yield data of maize and groundnuts in three northern regions of Ghana.

2. MATERIALS AND METHODS

2.1 Description of Study Area

The study was conducted in the Northern Region (NR), North-East Region (NER) and the Savannah Region (SR) of Ghana (see Fig. 1). The regions share the same border and therefore has similar ecological and socio-cultural characteristics. The regions experience a single rainy season from May to October with erratic rainfall that averages between 800 - 1000 mmy^{-1} (Ghana Meteorological Service, 2012). The dry season occurs between November and April. The regions fall within the Guinea and Sudan Savannah Agro-ecological zones of Ghana, which consist of grasses with isolated short trees such as *Parkia biglobosa* (Dawadawa tree) and *Vitellaria paradoxa* (Shea tree). The regions are approximately 180 m above sea level and are located at latitudes 10° 38' N and 08° 0.8' N and longitudes 0° 48' W and 1° 7.2' W.

2.2 Interpolation of Maize and Groundnut Yield

Maize and groundnut yield for the 2017 and 2018 farming seasons were collected from 795 farmers in the study regions. The average yield for the two farming seasons were interpolated, using the Inverse Distance Weighting (IDW) method in Geographical Information System (GIS) to generate maize and groundnut yield maps. The maps show the spatial distribution and variations of maize and groundnut yield in the study regions. The IDW is a method (Equation 1) that interpolates by estimating unknown values with specific search distances, closest points, power settings and barriers.

$$Z_p = \frac{\sum_{i=1}^{n}\left(\frac{z_i}{d_i^p}\right)}{\sum_{i=1}^{n}\left(\frac{1}{d_i^p}\right)} \qquad [1]$$

Where Z is the estimated value for prediction point, *Zi* is the measured value for sample point, *di* is the Euclidean distance between sample point and prediction point, *p* is a power parameter, and *n* represents the number of sample points. A main factor affecting IDW interpolation result is the *p* value. When the *p* value increases, the smoothness of IDW output surface increases.

2.3 Estimation of annual soil erosion rate

The quantitative annual soil erosion rate was estimated with the Revised Universal Soil Loss Equation (RUSLE) in a Geographical Information System (GIS). The RUSLE model works by multiplying five input factors (Renard *et al.,* 1997) as given in Equation (2). See Fig. 2 for flow chart diagram depicting the procedure of the soil erosion estimation.

$$A = R \times K \times LS \times C \times P \qquad [2]$$

Where:
- A = mean (annual) soil erosion rate ($t\ ha^{-1}y^{-1}$)
- R = rainfall erosivity factor ($MJ\ mm\ ha^{-1}h^{-1}y^{-1}$)
- K = soil erodibility factor ($t\ ha^{-1}h\ ha^{-1}MJ^{-1}mm^{-1}$)
- LS = slope length and steepness factor (unitless)
- C = cover management factor (unitless)
- P = land conservation factor (unitless).

Rainfall erosivity (R)

The R factor refers to the capacity of rainfall in a specific location to cause or influence erosion (Tamene *et al.,* 2017). It is a function of the intensity, quantity and duration of rainfall, as well as the energy of raindrop, pattern and resultant runoff rate (Farhan and Nawaiseh, 2015). An average 30-year (1990-2020) precipitation data from the study area was interpolated to give a rainfall map, which was employed in GIS with Equation (3) (Hurni, 1985) to generate the rainfall erosivity factor.

$$R = (0.562)\ P - 8.12 \qquad [3]$$

Where:
- R = rainfall erosivity ($MJ\ mm\ ha^{-1}h^{-1}y^{-1}$)
- P = precipitation (mmy^{-1})

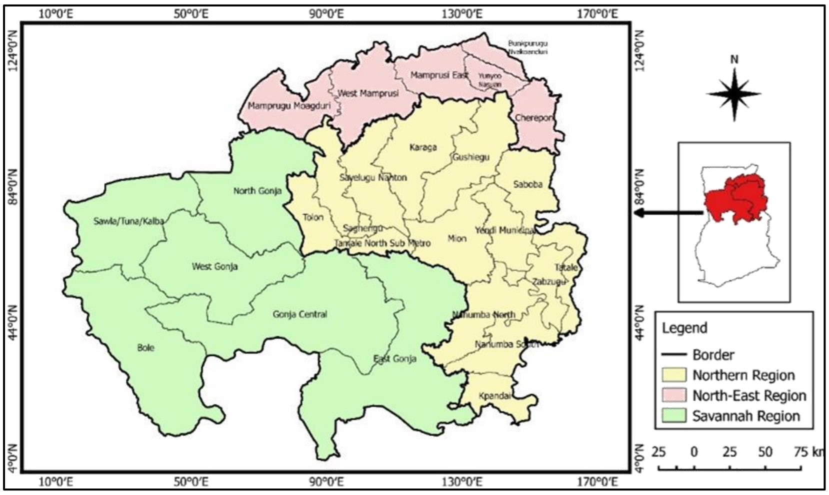

Fig. 1. Map of the study area, showing the three regions with their respective districts

Soil erodibility (K)

The K factor expresses soil vulnerability to erosion (Panagos *et al.,* 2015; Fenta *et al.,* 2016). It is a function of soil properties such as organic matter, texture, porosity, structure and the parent material. Equation (4) (Wischmeier and Smith, 1978; Renard *et al.,* 1997), was used to determine the K factor.

$$K = \frac{2.173[2.1\times10^{-4}\times M^{1.14}\times(12-a) + 3.25\times(b-2) + 2.5\times(c-3)]}{100}$$
[4]

Where:
K = soil erodibility (t $ha^{-1}h\ ha^{-1}MJ^{-1}mm^{-1}$)
M = $(\%\ silt + fine\ sand) \times (100 - \%\ clay)$
a = $\%\ organic\ matter\ (\%\ C\ \times 1.724)$; C is organic carbon
b = soil structure code number
c = soil permeability class number

The variables *b* and *c* were derived from the soil map of the study area. The *b* code ranges from 1 to 4 (1= very good granular, 2= fine granular, 3= medium or coarse granular and 4= block, platy or solid) and the *c* code ranges from 1 to 6 (1= extremely fast, 2= medium to quick, 3= mild, 4= slow to moderate, 5= very fast, 6= very slow) (Kim and Julien, 2006). The Sequence Alignment by Genetic Algorithm (SAGA) in GIS was used to derive the average soil structure and permeability based on the sand, silt and clay maps.

Slope length and steepness factor (LS)

The LS factor expresses the combined influence of slope steepness and length on soil erosion (Renard *et al.,* 1997). Equation (5) was used to derive the LS factor (Moore and Wilson, 1992) from Digital Elevation Model (DEM) (Mitasova and Mitas, 1999; Simms *et al.,* 2003).

$$LS = \left(\frac{\beta\chi}{22.13}\right)^{0.5} \times \left(\frac{\sin\theta}{0.0896}\right)^{1.3} \quad [5]$$

Where:
LS = Slope length and steepness factor (Unitless)
β = flow accumulation
χ = cell size
θ = slope angle

Cover management factor (C)

The The C factor is the effect of different LULC on soil erosion (Renard *et al.,* 1997). It is the impression of cropping on erosion and depends on the type, growth and cover of vegetation (El Jazouli *et al.,* 2017). The C factor was derived from Normalized Difference Vegetative Index (NDVI) using Equation (6) (Jong *et al.,* 1998). The C factor map was reclassified and assigned to values between 0 – 1 that correspond to various land cover types as shown in Table 1.

$$C = 0.431 - 0.805\ (NDVI) \quad [6]$$

Where C is the cover management factor and the NDVI is the indicator for the level of live-green vegetation in land-use and landcover.

Land conservation factor (P)

The P factor is the proportion of soil erosion for any ground conditions to soil erosion in ploughed conditions (Renard *et al.,* 1997; Kunta, 2009). It is the effect of land conservation on soil erosion. The P factor was generated from the land cover map of the study area, which was reclassified and assigned to values between 0 - 1 that correspond to various land-use types (Table 1).

Table 1: Description of landuse/cover types with corresponding C and P factor values

			Factors	
No.	**Land use/cover**	**Description**	**C**	**P**
1	Urban area (dense)	An 80 – 100 % developed areas with < 20 % vegetation	0.8	0.01
2	Urban area (less dense)	A 30 – 80 % vegetated developments with about 20 – 70 % un-vegetated cover	0.9	1
3	Urban-forest area	Designated forest with about 25 – 100 % non-natural woody vegetation	0.05	0.7
4	Tree groves	Settlement areas, undeveloped private land with extensive tree coverage	0.05	0.1
5	Marshlands	Intermittently salt and water-saturated areas	0.001	0.01
6	Water	Moving and still water (e.g. ponds, lakes, rivers etc)	0	0
7	Bare soil	Developments bare areas. Exposed cover-free soils. Gravel and sand-wined pits	1	1
8	Paved Roads	Asphalt, bituminize and concrete roads	0.7	0.01
9	Unpaved Road	Non-paved roads	1	1
10	Forest	Disturbed and inaccessible forest dominated with about 25 – 100 % trees	0.003	0.1
11	Farmlands	Fallow lands, farmland with 75-100 % cover, grass with sparse trees	0.5	0.4
12	Tree-mosaic	Shrubs dominated with trees	0.003	0.1

Sources: (Prasannakumar, *et al.,* 2012; Kusimi *et al.,* 2016; Panagos, *et al.,* 2015)

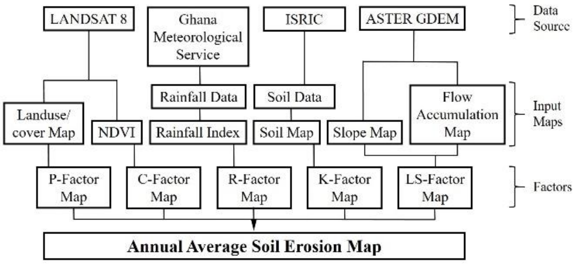

Fig. 2 Flow Chart depicting the procedure of soil erosion rate estimation

2.4 Relationship between soil erosion and the yield of maize and groundnuts

Sampled georeferenced data points were taken from the yield (maize and groundnut) and the soil erosion maps and carefully checked to ensure conformity of the spatial characteristics. The R statistical computing software, version 3.4.4 was used to calculate Pearson's Correlation Coefficient to determine the relationship between the yield (maize and groundnuts) and soil erosion. An analysis of regression was done to determine the numeric relationship between the yield (maize and groundnuts) and soil erosion.

2.5 Projection of soil erosion rate

The The rate of change of soil erosion due to changes in land-use/landcover (LULC) over the last 30 years (1988 to 2018) was determined by assuming that the non-human induced factors (rainfall erosivity, soil erodibility and the slope length and steepness factors) were constant. This is due to the fact that non-human induced factors only change significantly over a long-term relative to the LULC (i.e. cover management and land conservation)

factors. The erosion change in the last 30 years was determined by the expression given in Equation (7), whilst the rate of erosion change was determined using Equation (8). The projection for a particular year was determined using Equation (9).

$$Erosion\ change\ (t\ ha^{-1}y^{-1}) = Erosion_{2018} - Erosion_{1988} \quad [7]$$

$$Erosion\ change\ rate\ (t\ y^{-1}) = \frac{Erosion\ change}{30y} \quad [8]$$

$$Projected\ erosion\ (tha^{-1}y^{-1}) = \sum(erosion\ rate_{previous\ years} + erosion\ change\ rate) \quad [9]$$

3. RESULTS AND DISCUSSION

3.1 Maize and groundnut yield

The spatial distribution of the RUSLE factors is shown in Fig. 4. Table 3 also presents the mean and standard deviation of the factors. The spatial distribution of the rainfall erosivity and the estimated soil erosion show a direct positive relationship, as higher erosion rates were observed in areas of high rainfall erosivity. According to the erosivity map of Ghana and West Africa produced by Oduro-Afriyie (1996) and Roose (1977), erosivity of R ≤ 2,452 MJ mm $ha^{-1}h^{-1}y^{-1}$, constitute low erosivity, hence the erosivity of the study regions were generally low.

The soil erodibility factor similarly showed a direct positive relationship with the soil erosion rate. High erosion rates were observed in areas of high soil erodibility, hence suggesting that, high erodible areas exposed the soil particles to much particle detachment due to the impact of raindrops. The spatial variability of the soil erodibility could be due to the soil textural classes, or silt content in the soil, as soil erodibility generally depends on the contents of silt, irrespective of the amount of fraction of clay and sand (Mhangara *et al.,* 2012).

The slope length and steepness (LS) factor also revealed a direct positive relationship with soil erosion rates, as higher erosion rates were observed in areas of high LS factor. This suggests the significance of topography in erosion process, hence, the need for the implementation of conservation measures to reduce the adverse effect. According to Tosic *et al.* (2011), high LS factor values of LS ≥ 5, correspond to mountainous areas whilst lower LS values of LS < 5, correspond to relatively flat regions. Based on this assertion, about 98 % of the study regions are generally low-lying or flat.

The crop management and land conservation factors on the other hand were inversely proportional to the soil erosion rates. High erosion rates were observed in areas of low or weak crop management and land conservation factors. In relative terms, the rainfall erosivity and slope length and steepness factors were the main driving factors of soil erosion in the study regions.

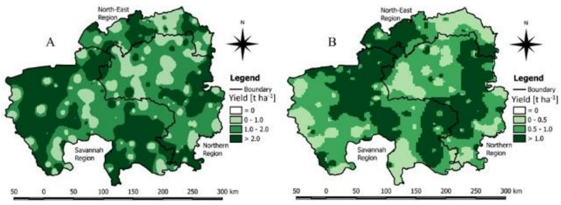

Fig. 3. Spatial distributions of (A) maize and (B) groundnut yield in the three regions

Table 2. Minimum, maximum, mean, and standard deviation values of maize and groundnut yield

Yield ($t\ ha^{-1}$)	NR		NER		SR	
	M	G	M	G	M	G
Min.	0.4	0.2	0.5	0.2	0.3	0.2
Max.	3.9	2.4	3.6	2.8	4.6	2.5
Mean	1.2	0.4	0.9	0.4	1.4	0.5
S D	1	0.5	1.1	0.5	1.2	0.5

M = Maize, G = Groundnuts, SD = Standard Deviation

3.2 Soil erosion factors

The spatial distribution of the RUSLE factors is shown in Fig. 4. Table 3 also presents the mean and standard deviation of the factors. The spatial distribution of the rainfall erosivity and the estimated soil erosion show a direct positive relationship, as higher erosion rates were observed in areas of high rainfall erosivity. According to the erosivity map of

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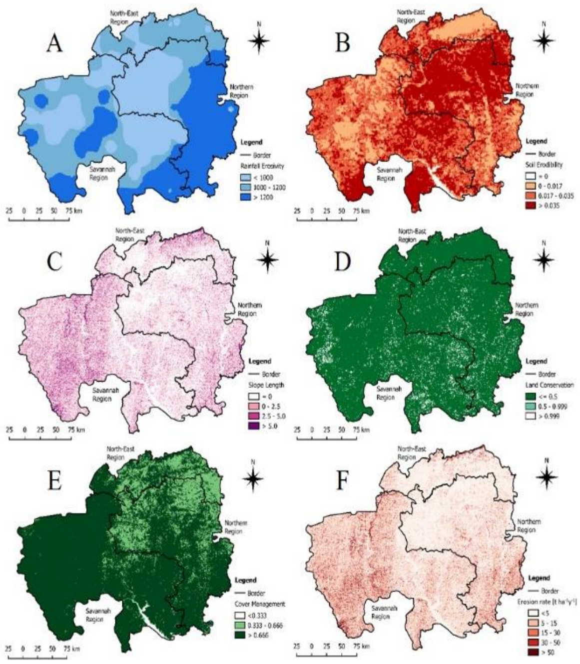

Fig. 4. Spatial distributions of Rainfall Erosivity (A); Soil Erodibility (B); Slope length and Steepness (C); Cover Management (D) Land Conservation (E) and Annual Soil Erosion Rate (F)

Table 3. Mean and standard deviation of RUSLE factors and annual soil erosion rate

Factors	Mean	SD
R factor (MJ mm $ha^{-1}h^{-1}y^{-1}$)		
Northern Region	565	582
North-East Region	494	544
Savannah Region	579	555
K factor (t ha h $ha^{-1}MJ^{-1}mm^{-1}$)		
Northern Region	0.018	0.019
North-East Region	0.016	0.018
Savannah Region	0.019	0.018
LS factor (Unit less)		
Northern Region	0.3	1.3
North-East Region	0.4	3.2
Savannah Region	0.4	2.1
C factor (Unit less)		
Northern Region	0.33	0.35
North-East Region	0.05	0.18
Savannah Region	0.41	0.40
P factor (Unit less)		
Northern Region	0.23	0.26
North-East Region	0.20	0.24
Savannah Region	0.27	0.28
Annual soil erosion rate (t $ha^{-1}y^{-1}$)		
Northern Region	4.2	21
North-East Region	5.2	35
Savannah Region	7.1	25

SD = Standard Deviation

3.3 Estimated soil erosion rate

The spatial distribution of the annual soil erosion rate is shown in Fig. 4 (F). The soil erosion rates ranged from 1 t $ha^{-1}y^{-1}$ in the flat areas to over 100 t $ha^{-1}y^{-1}$ in the extensively sloppy areas of the regions. However, the average erosion rate for the study regions was 5.5 t $ha^{-1}y^{-1}$. Suggesting a generally low soil erosion rates in the study regions. This phenomenon could be attributed to the low-laying nature of the regions coupled with the relatively low rainfall rates. Fredua (2014) obtained an average erosion rate of 11 t $ha^{-1}y^{-1}$ in the study regions, which is on a high compared to the average rate of 5.5 t $ha^{-1}y^{-1}$ obtained in this study. On regional basis, the Savanna Region had the highest average erosion rate of 7.1 t $ha^{-1}y^{-1}$, followed by the North-East and Northern Regions with average erosion rates of 5.2 t $ha^{-1}y^{-1}$ and 4.2 t $ha^{-1}y^{-1}$ respectively (Table 3). The higher erosion rate observed in the Savannah Region was probably due to the relatively higher rainfall rates and the lengthy and steeper slopes in the region.

The average soil erosion rates in the study area were classified into severe (> 30 t $ha^{-1}y^{-1}$), moderate (30 - 15 t $ha^{-1}y^{-1}$) and low (< 5 t $ha^{-1}y^{-1}$) based on a criterion adopted from Haregeweyn *et al.* (2017); Yesuph and Dagnew (2019). It is noticeable from the classification that, the erosion rates are generally low in the Northern and North-East Regions and then moderate to low in the Savannah Region (Table 4).

Table 4: Percentage erosion severity

Erosion Rate ($t\ ha^{-1}\ y^{-1}$)	NR	NER	SR
Severe (> 30)	5	4	11
Moderate (30 - 15)	13	9	21
Low (<15)	82	87	69

3.4 Projection and potential effect of soil erosion on maize and groundnut yield

The projected soil erosion rate for the next 10 years (2021 - 2031), based on LULC change is presented in Fig. 5. Under normal conditions, soil erosion rate in the Northern Region will increase from 4.20 to 4.70 t ha y^{-1} (11 % increase) and from 5.2 to 6.03 t $ha^{-1}y^{-1}$ (13 % increase) in the North-East Region. While that of the Savannah Region will increase from 7.1 to 7.87 t $ha^{-1}y^{-1}$ (11 % increase).

Increase in erosion rates could significantly decrease maize and groundnut yield by 18 % and 16 % respectively in the Northern Region; 21 % and 15 % respectively in the North-East Region; and 24 % and 18 % respectively in the Savannah Regions should the current trend remain for the next 10 years.

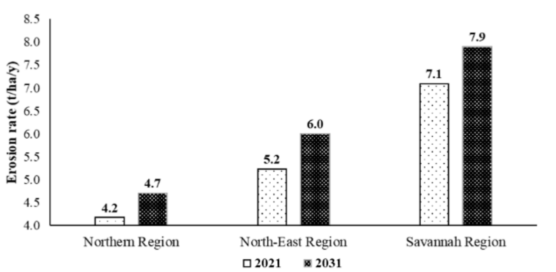

Fig. 5: Projected soil erosion rates for the year 2031 (i.e., 10 years from 2021)

3.5 Relationship Between Soil Erosion and Yield (Maize and Groundnuts)

A graphical display of the relationship between yield (maize and groundnut) and soil erosion is presented in Fig. 6. Table 5 shows the regression equations of yield (maize and groundnut) and soil erosion. There was a negative correlation between yield (maize and groundnuts) and soil erosion, as soil erosion rate increased, yield (maize and groundnut) decreased. The negative relationship is expected as soil erosion leads to the loss of top soil and plant nutrient needed for improved yield.

The maize – erosion curve is steeper compared to the groundnut – erosion curve, suggesting a higher resilience of groundnuts to soil erosion relative to maize. There were significant differences in yield of maize and groundnut for different soil erosion classes. At a soil erosion rate of about 1.0 t $ha^{-1}y^{-1}$, the average maize yield was about 3.0 t ha^{-1}, and that of groundnut was about 1.5 t ha^{-1}. At erosion rate of about 10 t $ha^{-1}y^{-1}$, average maize and groundnut yields reduced to about 2.3 t ha^{-1} and 1.2 t ha^{-1} respectively. Whilst at erosion rate of 30 t $ha^{-1}y^{-1}$, maize yield and groundnut yields were about 1.4 t ha^{-1} and 0.7 t ha^{-1} respectively. This indicates a yield loss of about 0.1 t and 0.04 t of maize and groundnuts for every ton increase of annual soil erosion.

At areas, with severe erosion class (> 50 t $ha^{-1}y^{-1}$), The average maize and groundnut yields were respectively 0.9 t ha^{-1} and 0.4 t ha^{-1}. Average maize and groundnut yield in areas with moderate erosion class (15 – 30 t $ha^{-1}y^{-1}$) were 1.1 t ha^{-1} and 0.5 t ha^{-1} respectively. Whilst in areas with the low erosion class (< 15 t $ha^{-1}y^{-1}$) maize and groundnut yields were 1.7 t ha^{-1} and 0.8 t ha^{-1} respectively. This results therefore indicates that, in areas with severe soil erosion class, maize yield decreased by about 18 % and 47 % compared to the areas with moderate and low erosion classes respectively. Whilst yield of groundnut in areas with the severe erosion class decreased by about 33 % and 45 % compared to the areas with moderate and low erosion classes respectively.

Overall, about 28 % and 24 % of maize and groundnut yield losses respectively, could be attributed to soil erosion and this could make a significant difference in profit margin of maize and groundnut cultivation. Increased soil erosion which resulted in a decreased top soil, soil nutrients and soil properties (i.e., soil structure organic matter, soil texture etc.), led to the maize and groundnut yield losses in the areas with severe erosion rates.

In a study on the effect of soil erosion on crop yield and soil properties in Turkey by Oguz *et al.* (2006), yield of sugar beets and wheat were found to be significantly higher on slightly eroded areas compared to moderately eroded areas. Similarly, a study on maize field in the Michigan state, by Mokma and Sietz (1992), observed that slightly eroded sites produced about 21% more yield compared to the severely eroded sites. The effect of erosion on crop yield, resulting in the decline in crop production, is complex and influenced by changes in soil quality variables (Obando and Stocking, 2001).

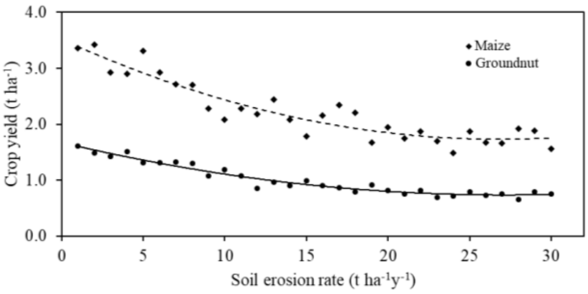

Fig. 6: Relationship between yield (maize and groundnuts) and soil erosion

Table 5: Regression equations of maize and groundnut yields

Regression equation	R^2
$MY = 0.0025se^2 – 0.1331e + 3.5183$	0.877
$GY = 0.0013se^2 – 0.0693e + 1.6721$	0.950

MY=Maize Yield, GY=Groundnuts Yield, e=erosion

4. CONCLUSION AND RECOMMENDATIONS

This study investigated the impact of soil erosion on the yield of maize and groundnut in the Northern, North-East and Savannah Regions of Ghana. The analysis procedure confirmed a negative relationship between soil erosion and crop yield, and further quantified the relationship for maize and groundnut yield specifically.

Dynamics of the soil erosion rates suggest rainfall erosivity coupled with slope length and steepness factors as the main erosion-drivers, due to high erosion vulnerability in areas with high rainfall erosivity and steep-lengthy slopes. The study has also established that, depleting rate of LULC in the three regions could cause soil erosion rates to increase by about 12 % of the current average rate of 8.0 t ha y^{-1}, by the year 2031. This phenomenon could eventually reduce maize and groundnuts yield by 21 % and 16 % respectively. The study found that crop (maize and groundnuts) productivity per land area is relatively lower in areas severely affected by soil erosion thereby posing adverse consequences for the average farmer's survival, which could ultimately influence his livelihood.

Given the rural populations' dependence on agriculture in the study regions, adequate agricultural strategies are required to limit the impact of soil erosion on crop production. To achieve this, farmers should be encouraged to adopt erosion-limiting soil and water conservation (SWC) measures that involve soil fertility enhancement to reduce soil erosion and improve crop yield.

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