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Contribution of Hierarchical Multi-Criteria Analysis (AHP) to the Evaluation and Spatialization of Soil Erodibility in Humid Mountainous Areas: Case of Bafou-North, Cameroon Western Highlands

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ABSTRACT

The agricultural basin of Bafou-North is part of the mountainous domain in Cameroon western highlands, with a humid tropical climate, subjected to intensive exploitation of the soil since the 1980s. This exploitation is followed by a reduction of the vegetation cover and the increased risk of erosion of these soils. In order to assess the extent of this risk, this study proposes to characterize and map the susceptibility of Bafou-North soils to erosion by the multi-criteria weight method under GIS of all the erodibility factors considered in this study. Among other parameters considered, it emerges that the topography through its slope component primarily influences (66.7%) the risk of soil erosion in Bafou-North, followed by pasture (55.87%) and tillage (27.93%). The spatialization of the erodibility factor (K) of Bafou-North soils, which translates the susceptibility to erosion, reveals that nearly 79.89% (6963.37 ha) of the surface area is subject to a risk ranging from moderately high to very high [$0.25< K\geq0.71$ t.h/(ha.N)] against 20.11% (1752,88 ha) for fairly resistant soils [$0.17<K\geq0.25$ t.h/(ha.N)]. This observation therefore challenges all farmers and authorities to further integrate soil conservation methods into their policies for the sustainable management of agricultural land.

1. Introduction

According to the report "State of the World's Soil Resources" (FAO, 2015), soil erosion is one of the ten major threats to soils. Erosion is the main form of land degradation in the tropics (Roose et al., 2015), and particularly water erosion (Roose and De Noni, 2004). Population growth and rising standards of living are driving increased demand for food, water and housing. This has led to the inappropriate use of certain agricultural practices, thus causing an upheaval in the natural balances which lead to soil degradation (Zékri and Tounkob, 2021). In Cameroon, and more specifically in the Cameroon Western Highlands, the high rainfall associated with the rugged terrain, the reduction in plant cover as well as inadequate cultivation practices (ridging along the steepest slope and cultivation flat) intensively, promote water erosion, which leads to the degradation of agricultural land and consequently a drop in production (Fotsing, 1993; Temgoua et al., 2000).

The results of Boukong (2000) on Oxisol reported an average annual departure of 2.61 and 5.23 mm/ha/year of soil for the ridges parallel to the main slope, respectively 9 and 20%. Several studies report that the quantification of soil losses is very often difficult due to the complex interaction of many factors such as climate, soil cover, topography and human activities (Lu et al., 2004; Jinghu and Yan, 2014). In order to determine the factor which would most influence the risk of soil erosion in tropical mountain areas, this study proposes an AHP which is based on the principle of comparison by pairs of the criteria then the solutions between them. AHP is a decision-making approach developed by Saaty (1980) which makes it possible to unify several criteria in a decision-making process. Subsequently, a modeling of the erodibility factor (K) which represents the susceptibility of a soil to undergo erosion will be carried out.

2. Materials

2.1. Study Area

The study was carried out in Bafou-North located in the south of Mount Bambouto which is in the central part of the Cameroon volcanic line. The area belongs to Cameroon Western highlands, between latitudes 5°33'00''N and 5°36'30' 'N and longitudes 10°03'00''E and 10°07'00''E (Fig. 1). This area, like the entire Bafou group, is subject to a humid tropical climate with high rainfall ranging between 1500 and 2000 mm/year (Tckékoté et al., 2018), mainly recorded between March and October, while the dry season goes from November to February with temperatures ranging between 13 and 28 °C (Temgoua et al., 2015). This locality has a rugged relief with steep slopes and high altitudes that can reach 2700 m in places.

The primary vegetation of the area is the natural vegetation essentially made of eucalyptus forest and gallery forests along water course made of knotty trees such as *Maesa lannceolata*, *Trema guineensis* et *Adenocarpus* (Tuebue et al., 2020), which has been strongly degraded by human activities and replaced secondary vegetation and farmlands. Bafou-North is highly anthropized with nearly 80% of the population mainly practicing agricultural activities (Temgoua et al., 2015) and 45% of young people between the ages of 25 and 45 (Ngimdoh et al., 2020).

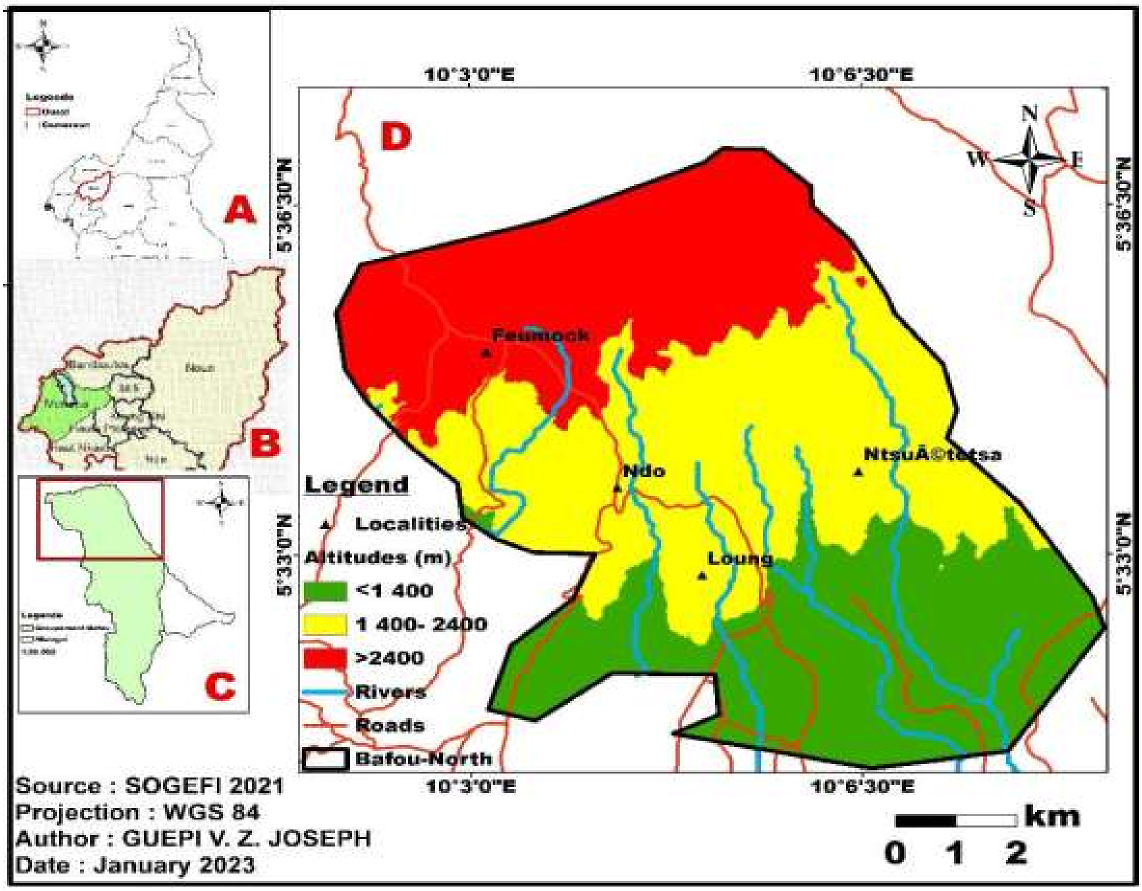

Fig. 1. Location of the study area. (A) Location of West Region in Cameroon; (B) Location of Dchang in Menoua Division; (C) Location of Bafou North in Bafou Locality; (D) Geomorphological Map of Bafou North

The main activities of the local population are farming, breeding, small business and hunting. Concerning anthropic species, they are different crops essentially carrots, potatoes, apples, maize and other parts of this area is occupied by tea plantation. The main rivers draining the Bafou area are Mia-mezo, Mianou, Mia-melieu, Mia-meloung and Atioyem, and together constitute a radial drainage system. The substratum is essentially trachyte. It drowns islets of basalts, rhyolites, phonolytes, and pyroclastites (Youmen, 1994 in Tuebue, 2020) which overlie the pre-Cambrian granite-gneiss basement. The main soil types are aluandic-ferralsols, ferralsols on volcanic rocks according to Tematio et al. (2009).

3. Methodology

3.1. Evaluation of Erodibility

The work consisted prior to the collection of samples in the field. A set of 48 points were randomly sampled to a depth of 20 cm using a manual auger and the samples carefully stored and transported to the laboratory. After analysis and determination of the organic matter content, the percentages of the clay, silt and sand fractions, the erodibility factor K was calculated using the equation of Wischmeier and Smith (1978) including the steps described by Auerswald et al. (2014).

$$K = K_1 * K_2 + 0.043 * (A - 2) + 0.033 * (P - 3) \quad (1)$$

$$\text{Avec } K_1 = 2.77 * 10^{-5} * (f_{Si + vfSa} * (100 - f_{Cl}))^{1,14} \text{ et } K_2 = (12 - f_{OM})/10 \quad (2)$$

with K expressed in [t.h/(ha.N)]
fsi+vfsa: mass fraction (%) of [silt (2 to 50 µm) + fine sand (50 to 100 µm)]
fCl: mass fraction (%) of clay (< 2 µm)
fOM: mass fraction (%) of organic matter
A: soil structure code (1, 2, 3 or 4) used in the classification
P: profile permeability class (1, 2, 3, 4, 5 or 6)

The structure code (A) was assigned using the diagram the structure code based on textural classification (Ontario Center for Soil Resource Evaluation, 1993 in Romba, 2016). The permeability code was determined from the clay and sand contents of each sample according to Table 1.

Table 1. Soil permeability according to textural class (King and Le Bissonnais, 1992)

No	Texture class	Permeability (P)
1	Clay <18% et Sand>65%	Rapid
2	18%<Clay< 35% et Sand >15% ou 15%<Sand<65% et Clay <18%	Medium to rapid
3	Clay <35% et Sand <15%	Medium
4	35%<Clay<60%	Slow to medium
5	Clay >60%	Slow

To assess the nature of the soils, Bolline and Rosseau (1978) established a classification grid (Table 2).

Table 2. Classification of soil erodibility according to Bolline and Rosseau (1978)

Erodibility (K)	Soil class
< 0.10	Soil very resistant to erosion
0.10 à 0.25	Soil fairly resistant to erosion
0.25 à 0.35	Soil moderately resistant to erosion
0.35 à 0.45	Sensitive soil resistant to erosion
> 0.45	Very sensitive soil resistant to erosion

3.2. Spatialization of the Erodibility Factor (K)

The results obtained were then imported into the Arcgis 10.3 software and the ordinary kriging method was applied. This is a commonly used approach that considers the trend to be constant but only at the level of a local neighborhood. This hypothesis is therefore interesting because it ensures that locally observable variations are considered. This method thus makes it possible to predict the value of a variable of interest at positions where no sample is available.

The principle consists of repeating the operation in each node X0 of a regular grid covering the area studied. Indeed, for a set of n data points X from a neighborhood centered around a point X0, the estimation mesh can be constructed, neglecting the estimation variance to thus make it possible to find the N weighters λi. The latter, called kriging weights, give the smallest possible estimation variance called kriging variance.

Where the λi are weights to be assigned to the data points and where µ is a Lagrange parameter that comes into play for algebraic reasons. The left member of the system contains the covariances between the data points, while the right member contains the covariances between each data point and the estimation point X0. This system, once solved, makes it possible to transfer to the point X0 information coming from the neighboring data points, by the calculation x0 of a weighted average.

By performing the matrix multiplication, we can rewrite the system in the form:

$$\sum_{i=1}^{N} \lambda_i \, C(x_\alpha - x_i) + \mu = C(x_\alpha - x_0), \qquad \alpha = 1 \text{ à } N$$
$$\sum_{i=1}^{N} \lambda_i = 1 \quad (3)$$

So, the kriging system is as follows:

$$\begin{vmatrix} C(x_1 - x_1) & C(x_1 - x_2) & \ldots\ldots & C(x_1 - x_n) & 1 \\ C(x_2 - x_1) & \ldots\ldots & \ldots\ldots & C(x_2 - x_n) & 1 \\ \ldots\ldots & \ldots\ldots & \ldots\ldots & & \ldots \\ C(x_n - x_1) & C(x_n - x_2) & \ldots\ldots & C(x_n - x_n) & 1 \\ 1 & 1 & 1 & 1 & 0 \end{vmatrix} \begin{vmatrix} \lambda_1 \\ \lambda_2 \\ \ldots \\ \lambda_n \\ \mu \end{vmatrix} = \begin{vmatrix} C(x_1 - x_0) \\ C(x_2 - x_0) \\ \\ C(x_N - x_0) \\ 1 \end{vmatrix} \quad (4)$$

The estimate is therefore determined using the formula opposite:

$$Z_v^*(x_0) = \sum_{i=1}^{N} \lambda_i Z(x_i) \quad (5)$$

The kriging estimate variance is then calculated as follows:

$$\sigma_{ord}^2 = C(0) - \sum_{i=1}^{N} \lambda_i C(x_0, x_i) - \mu \quad (6)$$

The model retained in this study is the Gaussian model because it allowed, following various comparisons, to better predict the unknown values of the other points.

3.3. Study of the Level of İnfluence of Each Factor

The study of the level of influence of each factor was done using the method of Hierarchical Multi-criteria Analysis (AHP). Soil erosion depends on several factors that act simultaneously. For the case of this study, the following factors were taken into account on the basis of their importance in the risk of soil erosion and knowledge of the field: topography, land use and climate. These parameters represent in the AHP process, the criteria. From these evaluation criteria, a hierarchical structure was developed (Fig. 2).

The slope, altitude, forest, fallow, pasture, tillage and precipitation represent the alternatives in this model. The next step is to compare the different parameters with each other at a hierarchical level in order to determine the importance of this level in solving the problem. To do this Saaty (1980) developed a scale of relative importance (Table 3).

Based on this table, a binary comparison matrix was then developed, specifying for each parameter a scale ranging from 1-9 depending on the importance of the criterion (Table 3). The weights of the criteria were assigned on the basis of a good knowledge of the terrain and the mastery of the importance of the factors in the process of erosion.

Once the matrix has been developed, a consistency ratio (CR) should be calculated to indicate the reliability of the judgments of the calculated matrix (Saaty, 1977). To show that the matrix is coherent, the value of (CR) must be less than 0.1 (10%). This consistency ratio (CR) is calculated using the following equation:

$$CR = CI/RI \tag{7}$$

With (CR) consistency ratio, (RI) random index developed by Saaty (1977) (Table 2) and (CI) the consistency index calculated by the equation below.

$$CI = \lambda max - n/n-1 \tag{8}$$

λ_{max}: maximum eigenvalue of each factor in the array of the matrix and n the size of the matrix.

4. Results

4.1. Erodibility Factor (K)

From the results of the percentages of sand and clay, all the points were projected in the textural diagram in order to determine the code on the structure of each sample. The result is shown in Fig. 3. It is observed that 11 samples hold the code 1, for example samples E3, E12, E13 and E29. The majority of samples belong to codes 3 and 4. These results were then used for the approximation of the K-factor.

The approximation of K gives us the results of Table 11 (appendix).

The descriptive statistics carried out led to the results opposite.

This table shows that the K factors obtained are between 0.17 and 0.71 t.h/(ha.N) for a general average of 0.37 t.h/(ha.N). The Sk value (0.93>0) obtained shows that there is asymmetry to the left with a more or less flattened and pointed distribution peak (K>0.37) compared to normal. The general table of the K factors of all the samples is presented in the appendix. It emerges from this table that the majority of the soils of Bafou-North are classified in the interval of soils prone to a risk of erosion, with the exception of soils E4, E18, E35 and E42 whose values of the K factor are included. Between 0.10 and 0.25; classified as fairly resistant to erosion. This represents only about 8.3% of the surface of Bafou-North against 91.6% for areas with medium to very high sensitivity.

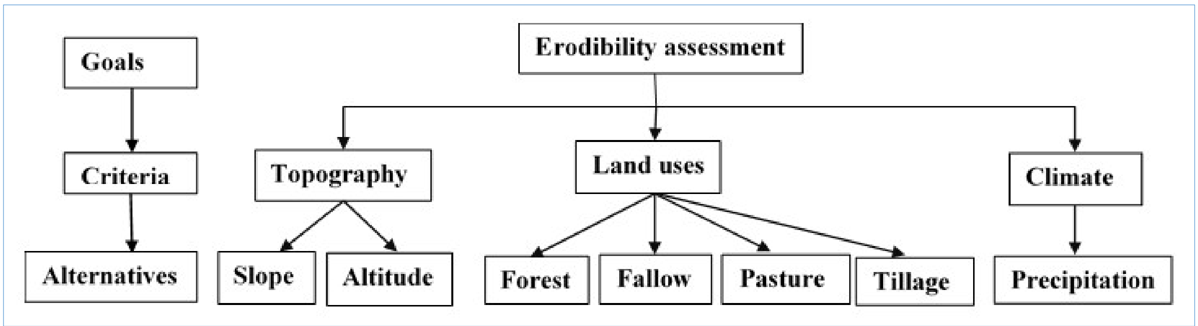

Fig. 2. Hierarchical structure used in the model

Table 3. Thomas Saaty scale of importance (Saaty, 1984)

Degrees of importance	Explication
1	Equal importance: two characteristics contribute in the same way
3	Low importance: experience and personal appreciation personnelle slightly favor one characteristic over another
5	Strong or decisive importance: experience and appreciation strongly favor one characteristic over another
7	Very strong or attested importance: a characteristic is strongly favored and its dominance is attested in practice
9	Absolute importance: the evidence favouring one characteristic over another is as compelling as possible
2, 4, 6, 8	Values associated with judgments when compromise is needed.

Table 4. Comparison matrix produced by the AHP method

Criteria	Topography	Land uses	Climate
Topography	1	5	6
Land uses	1/5	1	3
Climate	1/6	1/3	1

Table 5. Random consistency index (RI) for n=1, 2, ……8 (Saaty, 1977)

Parameter	Value							
n	1	2	3	4	5	6	7	8
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41

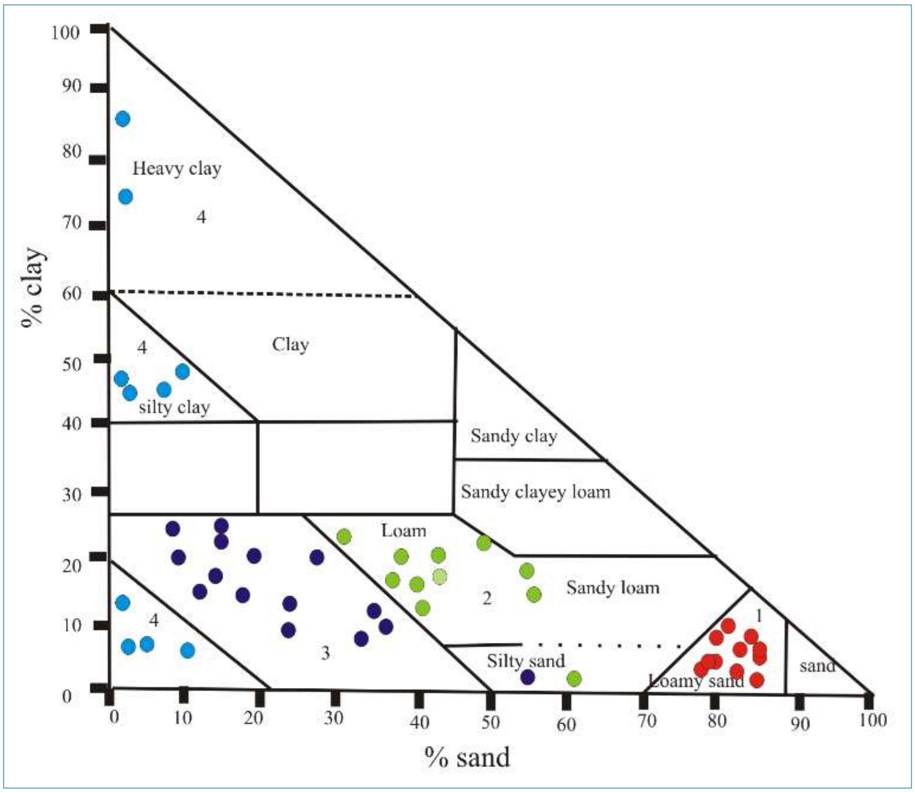

Fig. 3. Representation of the different soil samples on the textural triangle in reference to Ontario Center for Soil Resource Evaluation (1993) in Romba (2016).

Table 6. Descriptive statistics of the erodibility factor K in [t.h/(ha.N)]

Parameters	Values
N	48
Min	0.17
Max	0.71
Median	0.33
Mean	0.37
Standard deviation	0.12
Skewness (Sk)	0.93
Kurtosis (K)	0.37

4.2. Analytical Hierarchical Process (AHP)

Table 4 above presenting the comparison matrix developed by the method of Saaty (1980) allowed us to determine the coherence index (CI) and the coherence ratio (CR) taking into account the value 0.58 as corresponding to the random index (RI) because for this study, three criteria were taken into account. The results are recorded in Table 7. The CR value obtained being less than 0.10, it was concluded that the ranking process is reliable. Thus, the weights of the criteria obtained were used for decision-making in the calculation of the relative weights of the alternatives identified in Fig. 3.

It appears from Table 4 that the topography would be responsible for 70.66% of the risk of soil erosion in Bafou-North, primarily thanks to its alternative slope which contributes 66.67% of this percentage. This criterion is followed by land use (20.13%) and pasture (55.87%) as the main alternative, then tillage (27.93%).

Fig. 4 presents the different classes of slopes and the land cover map of the study area.

Table 7. Calculated values of CI and CR

RI	CI	CR
0.58	0.051098710	0.088101224

Table 8. Calculated weights of the different criteria and alternatives retained in this study

Criteria	Weights	Alternatives	Weights
Topography	0.7066	Slope	0.6667
		Altitude	0.3333
Land uses	0.2013	Forest	0.0698
		Fallow	0.0922
		Pasture	0.5587
		Tillage	0.2793
Climate	0.0921	Precipitation	0.0921

It is observed that this area is highly subject to human activities and has very high slopes (>30%) in places. The map of precipitation over a period of 10 years was obtained by natural division and presents 5 classes. These classes are very low, low, moderate, high and very high (Fig. 5).

4.3. K-factor Interpolation

The interpolation of the erodibility factor by the ordinary Kriging method with the model adopted as the Gaussian model allowed us to obtain the following results.

Following the classification of Cambardella et al. (1994), the spatial dependence between soil properties is strong when SD<25%, moderate when SD is between 25% and 75% and very strong when SD>75%.

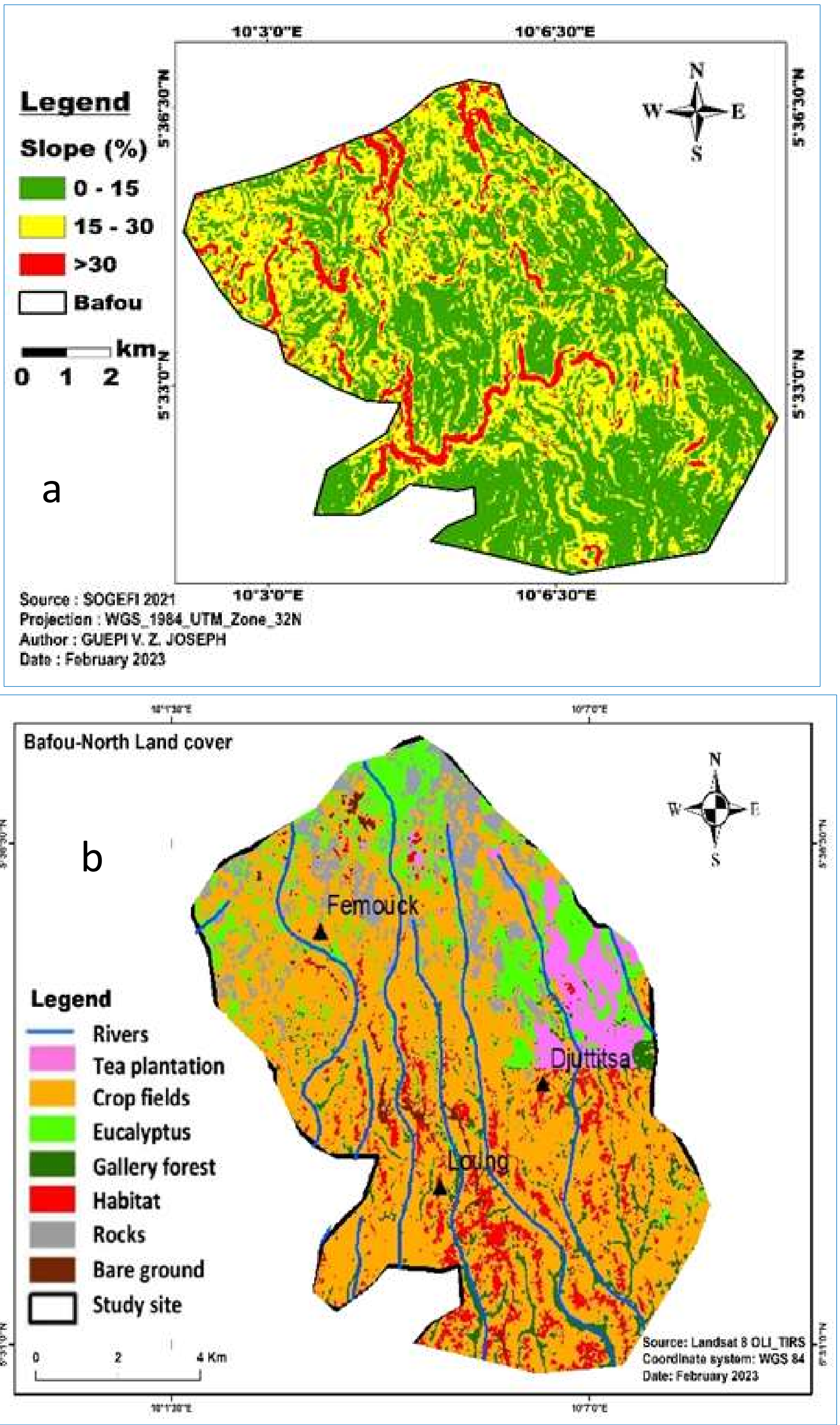

Fig. 4. Different classes of slopes and the land cover map of the study area

It is observed that there is a strong spatial dependence (SD=6.87%) between the values of the factor K at different points in space. This model is represented by the semi-variogram (Fig. 2) whose regression function is as:

$$X_0 = 0,7131 * x + 0,0977 \quad (9)$$

With regard to the semi-variogram above, there is a spatial structuring between the different sampling points because the majority of the points are located below the range. This made it possible to proceed with the loss of the variable at the places not sampled. Once the model was specified, the interpolation was therefore carried out and the following spatialization map (Fig. 8) was generated.

It emerges from this interpolation that the soils classified as fairly resistant to erosion occupy an area of 1752.88 ha or 20.11% (Table 10) of the total area (8716.25 ha) of this zone, while the major part (6963.37 ha) or 79.89% is located in the moderately to very sensitive classes.

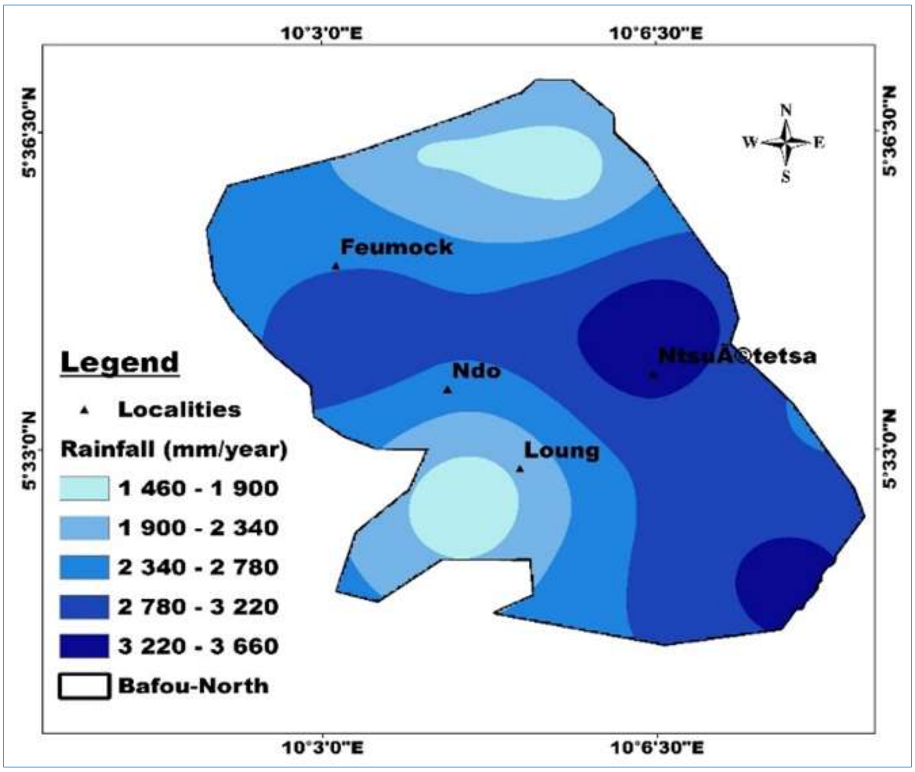

Fig. 5. Distribution of annual total precipitation (2012-2021)

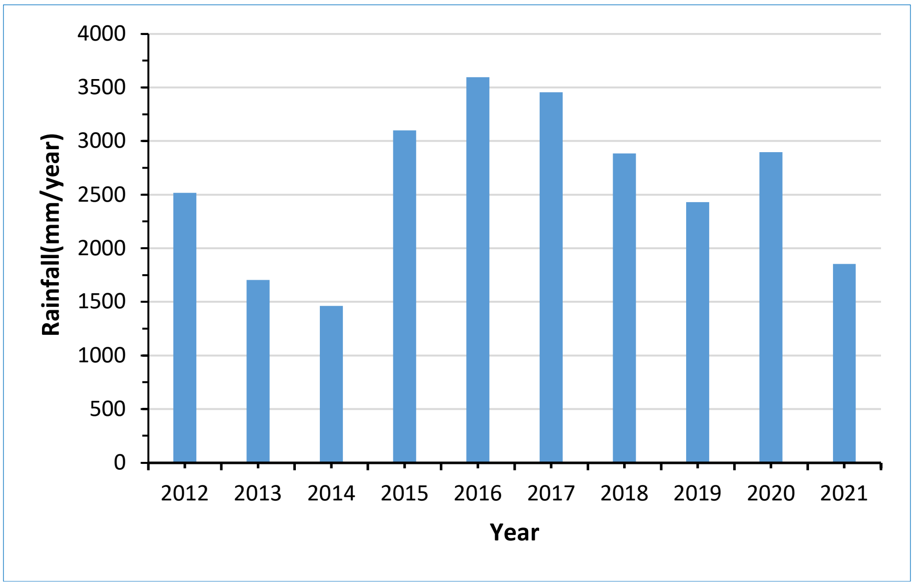

Fig. 6. Annual precipitation histogram (2012-2021)

1. Discussion

Bafou-North is located at a high altitude with more or less high slopes. Combined with the decrease in vegetation cover recorded in recent years and the potential aggressiveness of the rain, the soils of this territory are prone for the most part to erosion. Indeed, the approximation of the erodibility factor which expresses the susceptibility of a soil to erosion, reveals values which oscillate between 0.17 and 0.71 t.h/(ha.N).

Table 9. Model parameters

Parameters of kriging	Values
Nugget	0.0013
Major Range	0.0478
Partial Sill	0.0177
Sill	0.0190
Spatial Dependence (SD)	0.0687
Root-Mean-Square	0.0629

These values are for the most part included in the class of soils subject to the risk of erosion according to the classification of Bolline and Rosseau (1978).

Faced with the problem of food self-sufficiency, these areas are increasingly developed by a rural population that lives mainly from agriculture. It would therefore be advisable to seek solutions for adapting this agriculture in order to reduce soil erosion in this territory as much as possible, rather than thinking of recommending that the populations abandon the so-called marginal areas. The search for these solutions requires identifying the main factors that can condition this phenomenon in this environment.

The AHP carried out in this study reveals that the slope contributes 66.67% to the risk of soil erosion in Bafou-North. Several studies indeed present the slope as one of the main factors of soil erosion and demonstrate that soil loss varies exponentially with the inclination of the slope (Tardy, 1993; Paul-Hus, 2011; Payet et al., 2012; Mayima et al., 2019).

Work carried out by Ebog (2010) on abandoned tracks in a forest in central Cameroon showed that soil losses on a 20% slope (35.21 t/ha) were significantly higher than those obtained on slopes of 5 and 10% (9.73 and 10.42 t/ha, respectively).

Fonteh et al. (1998), showed that when the slope varies from 0.89 to 2.69% erosion would increase 34 times compared to the first slope in this region. Confirming the results of other researchers, in particular those of Djoukeng et al. (2016) who revealed a loss of soil (approximately 35 t/ha) on a 29% slope, greater than that obtained on an 11% slope (approximately 20 t/ha).

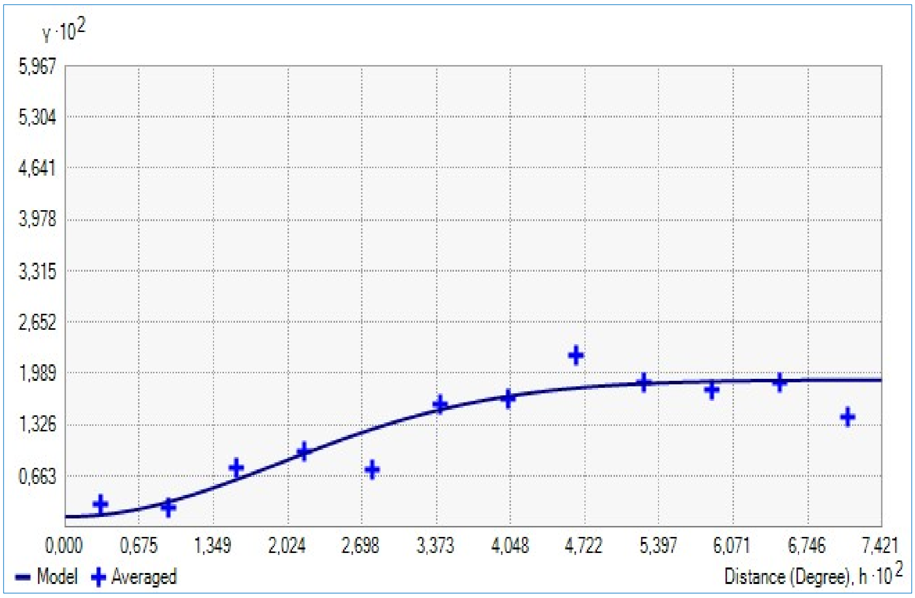

Fig. 7. Modeling of the estimated semi-variogram for ordinary kriging

In addition, Leumbe et al. (2012) had been able to demonstrate that by halving the inclination of the slopes, the erosion rates drop by around 70%, which is in agreement with the studies of Roose (1981) and the results obtained in this work. Uncontrolled land use would also be a real problem in this environment. It can be seen that through its grazing component, land use would influence the risk of erosion by nearly 55.87%. Intensive grazing or overgrazing is the cause of the reduction of plant cover by trampling and soil compaction (Boughalem, 2013), which increases the rate of runoff leading to soil erosion, particularly in tropical environments.

Conversely, the forest presents the area least susceptible to erosion with a percentage of 6.98%. This highlights the major role of plant cover in soil protection. The vegetation will in fact protect the soil by limiting the impact of raindrops on the aggregates and thus limit the creation of very fine soil promoting slaking (SOLAG, 2019), slow down runoff and erosion (Fletcher, 2017). The work of Amani et al. (2022)

carried out in the West Cameroon highlands showed a soil loss of 1.52 ±1.61 t/ha for covered soil against 3.76 ±5.98 t/ha for bare soil. This supports the results of this study as shown in Fig. 8.

The study of Roose (1981) has shown that erosion under cultivation is 1000 times higher than under forest, whatever the slope. Also, climatic factors, in particular rainfall, would contribute very little (9.21%). It has been demonstrated by Zékri and Tounkob (2021) that in mountain areas, the erosivity of rainfall is not a determining factor in the risk of erosion, but rather the susceptibility of the land (steep slopes, soft substrates and plant cover degraded) and inappropriate human practices which are the major causes. This is consistent with the relatively low percentage of climate action obtained in this study. As for plowing, it is mainly done with a hoe in this area and determines the erodibility of the soils of Bafou-North at nearly 27.93%. This technique increases the detachability of the aggregates and therefore the risk of erosion in the long term. This results in considerable losses upstream of the slopes and a strong accumulation at the bottom of the slopes.

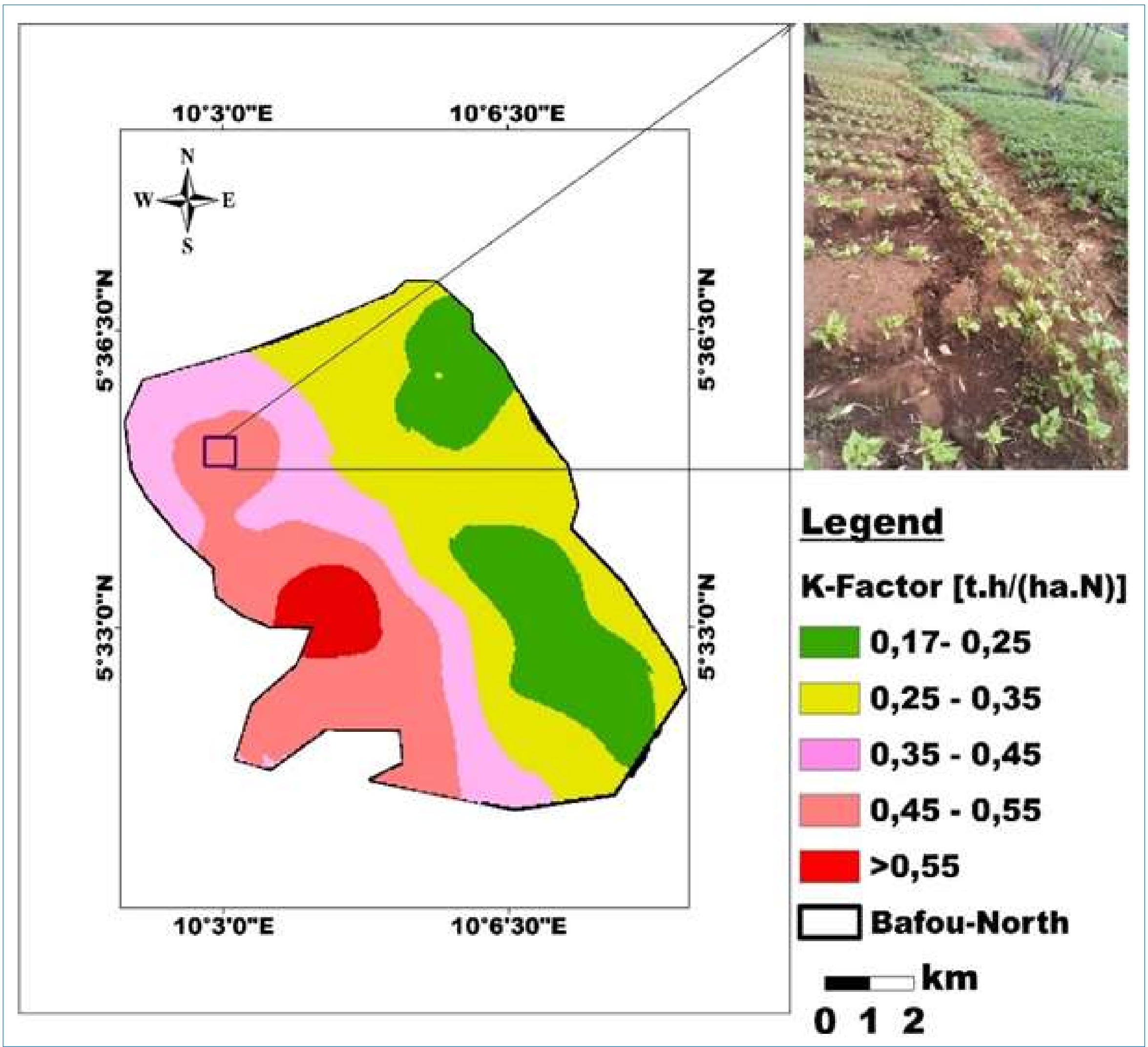

Fig. 8. Spatial variability of soil erodibility in Bafou-North

Table 10. Distribution of erodibility classes in Bafou-North

Erodibility class	Area (ha)	Total (ha)	Percentage (%)
0.17 – 0.25	1752.88	1752.88	20.11
0.25 – 0.35	2822.89	6963.37	79.89
0.35 – 0.45	1737.74		
0.45 – 0.55	2035.56		
>0.55	367.18		

Interpolation is an important method in the management of environmental ecosystems. It allows decision-making on the basis of the spatialization of a specific phenomenon. Several studies indicate that the integration of a GIS facilitates the planning and execution of decisions in several areas Azizi et al. (2014). This study made it possible to highlight all the areas potentially sensitive to erosion and presents Bafou-North as a territory whose risk of erosion is quite high. 79.89% of the area of this zone is indeed exposed to this risk. This result fairly reflects the reality observed in the field and corroborates with the results of several researchers who have shown that the risk of erosion is a function of several parameters, in particular the slope. Indeed, the areas at very high risk of erosion in Bafou-North are on slopes with a slope of between 20 and 25%.

4. Conclusion

The problem of erosion addressed in this study through the method of AHP coupled with a GIS, reveals that among the parameters retained (topography, land use and climate) as influencing the susceptibility of a soil to erosion, topography is most important. It alone determines 70.66% of the risk of soil erosion in Bafou-North, particularly through the slope factor. Land use is the main secondary parameter that increases the risk of erosion in this territory. However, it emerges that only grazing (55.87%) and plowing (27.93%) have a considerable influence on soil erosion in Bafou-North, while the forest has more of an advantage in terms of soil protection. The ordinary kriging method with the Gaussian model as the model used allowed the spatialization of the calculated K factor. The results obtained in the form of a soil erodibility map of Bafou-North show that the major part (6963.37ha) or 79.89% of the total area (8716.25ha) of this territory is subject to sensitivity to erosion which is between medium to very high. The results obtained in this work represent an important contribution in the search for appropriate solutions for the protection and restoration of this natural environment.

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Appendix

Table 11. Values of the erodibility factor (K) [t.h/(ha.N)]

Samples	K-Factor	Samples	K-Factor	Samples	K-Factor	Samples	K-Factor
E1	0.59	E13	0.38	E25	0.32	E37	0.71
E2	0.38	E14	0.28	E26	0.32	E38	0.33
E3	0.32	E15	0.32	E27	0.32	E39	0.29
E4	0.17	E16	0.28	E28	0.34	E40	0.27
E5	0.28	E17	0.47	E29	0.34	E41	0.56
E6	0.46	E18	0.25	E30	0.56	E42	0.25
E7	0.28	E19	0.43	E31	0.47	E43	0.43
E8	0.37	E20	0.55	E32	0.30	E44	0.47
E9	0.34	E21	0.44	E33	0.47	E45	0.59
E10	0.33	E22	0.27	E34	0.28	E46	0.31
E11	0.31	E23	0.27	E35	0.25	E47	0.41
E12	0.30	E24	0.41	E36	0.56	E48	0.27