

Characterisation of the Erodibility of Agricultural Soils Upstream of the Bandama Blanc Watershed, Northern Côte d'Ivoire

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Abstract

This study focused on characterising the erodibility of agricultural soils in the Bandama Blanc watershed in northern Côte d'Ivoire. The objective was to assess the susceptibility of soils to erosion based on farming practices. Soil data from the world and soil profiles were used to determine the physical and chemical parameters of the soils in the study area. These parameters were used to classify soil types using the Kohonen map and determine their erodibility. The erodibility map of the study area was obtained by inverse distance weighting (IDW). Analysis of the results showed Ferric Acrisol and Lixic Ferralsol in the agro-industrial environment (SUCAF 1 and 2) in Ferkessédougou. These soils have an average cation exchange capacity of 6.15 cmolc/kg and a high concentration of coarse elements. Ferric Lixisol is found in the rural environment, with an average cation exchange capacity of 10.29 cmolc/kg, covering the departments of Korhogo and Sinématiali. In addition, the erodibility of soils in the basin has shown that the agro-industrial environment is more susceptible to water erosion, with an average K value of 0.32 t-ha-h/MJ-mm, compared to 0.12 t-ha-h/MJ-mm in the farming environment. Finally, the greater vulnerability of soils in the agro-industrial environment to water erosion could be partly associated with agricultural practices, particularly when the intrinsic properties of the soils are relatively comparable.

Keywords

Water Erosion, Erodibility, USLE, Agricultural Watershed, Bandama Blanc

1. Introduction

Controlling soil erosion is one of the major concerns in rain-fed agriculture, particularly in tropical climates [1]. Côte d'Ivoire's agricultural dynamics, once based on the expansion of cash crops and food crops, have been achieved at the cost of putting significant pressure on natural resources. In the agricultural zone of the Bandama Blanc watershed, agriculture is characterised by low technicality in the department of Korhogo and high technicality in Ferkessedougou, with agro-industrial sugar plantations (SUCAF 1 and 2). This situation not only reduces soil fertility, but also leads to lower agricultural yields and biomass production in the agro-industrial zone [2]. Soil erodibility is one of the important components of water erosion. It provides information on the stability and capacity of soil to be easily transported by runoff water. Therefore, the agricultural techniques used in the departments of Korhogo and Ferkessedougou could have consequences on the resistance of soils to erosion. Indeed, the vast majority of the populations living there rely on agriculture as their main activity to secure income and combat food insecurity. In order to maintain sustainable agricultural development in this region, it is necessary to assess soil erodibility (K). [3] demonstrated the advantages of Geographic Information Systems (GIS) in assessing soil loss using the Universal Soil Loss Equation (USLE). One of these determining factors is soil erodibility, represented by the K factor in the [4] model, the most commonly used model worldwide [5]-[7]. The objective of this study is to assess the vulnerability of two sites to erosion (smallholder and agro-industrial plots) using the USLE, with satellite and field soil data.

2. Geographical Location of the Study Area

The Bandama Blanc watershed is located in northern Côte d'Ivoire, between longitudes 5°00'W and 6°30'W and latitudes 9°22'N and 10°26'N. The study area, covering approximately 3348 km², is located in the upper part of this basin and extends over the Poro, Tchologo and part of the Hambol regions. The capitals of these regions are, respectively, the cities of Korhogo, Ferkessedougou and Katiola (**Figure 1**). These regions are part of the Savanes District. In addition, the localities in the Hambol region that belong to the study area are the SUCAF framework village, Pangaladougou and Kouroukounan. The vegetation is of the Guinean savannah type and this watershed is drained by the White Bandama River and its main tributaries, Lafigué and Lopkoho. Average annual rainfall varies from 1100 to 1400 mm [8] and temperatures range from 24°C to 30°C. Geologically, the area contains magmatic and metamorphic rocks, which are formed from Acrisols and Ferric Lixisols.

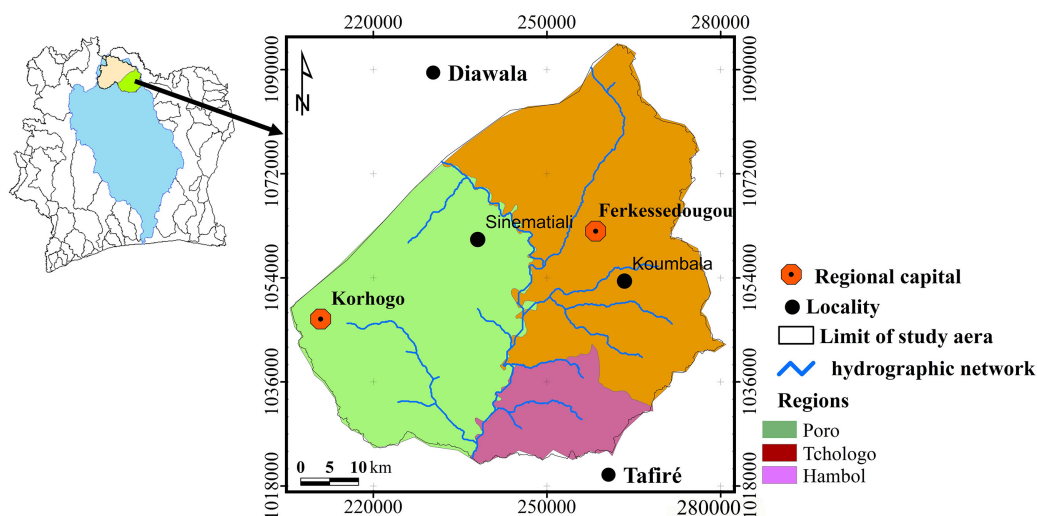


Figure 1. Geographical location map of the study area.

3. Materials and Methods

Soil erodibility (K) from the Universal Soil Loss Equation (USLE) developed by [4] was assessed for soil types in the study area based on smallholder and agro-industrial plots.

3.1. Materials

The equipment included tools for opening and analysing soil profiles (tape measure and zip-lock plastic bags) during the field campaign. The campaign, carried out from 8 to 14 March 2023, enabled soil profiles to be opened and photographs to be taken at each profile. Next, a single-ring infiltrometer and a stopwatch were used to measure hydraulic conductivity. A Garmin handheld GPS was used to locate the sampling points. A magnetic stirrer was used to homogenise the soil solution during measurement using the pH with a HANNA HI 991001 pH meter. In addition, soil data from the Digital SoilGrids 250 m (<https://soilgrids.org>) the WRB and USDA soil classification systems were used to compare the results obtained [9] and [10]. Finally, the spatialisation of the sampling points and the development of thematic maps were carried out using QGIS 2.18 software. Matlab 6.1 was then used to determine the soil types.

3.2. Methods

3.2.1. Classification of Soil Types

Soil types were determined using an artificial neural network (ANN) model based on unsupervised learning and agglomerative hierarchical clustering (AHC). The input data for the model consisted of physical and chemical soil parameters, including coarse fragments, particle-size distribution, soil water content at field capacity and permanent wilting point (pF 2.5 and pF 4.2), organic matter (OM) content, total nitrogen, available phosphorus, and cation exchange capacity (CEC) for calcium, magnesium, sodium, and potassium. These data were obtained from the

analysis of 88 soil samples collected from the horizons of 28 soil profiles established along toposequences in agro-industrial and smallholder farming plots. The analyses were carried out at the SUCAF (CASTEL) laboratory in Ferkessedougou (**Figure 2**). The soil classes obtained through multivariate analysis of soil properties were then compared with the reference soil classes derived from SoilGrids at a spatial resolution of 250 m and expressed according to the Reference Soil Groups of the World Reference Base for Soil Resources (WRB) [9] [10] for the study area. Furthermore, the SOM identifies observations with similar physicochemical characteristics and projects them onto a neuron grid. Similar observations are mapped onto neighboring neurons, whereas highly dissimilar observations are mapped onto more distant neurons. This property makes it possible to explore the natural structure of the soil dataset. This approach has previously been used specifically for the classification of soil samples based on physical and chemical parameters, including texture, pH, and nutrient contents [11]. Thus, since water erosion primarily affects the soil surface, only organic matter content, silt percentage, fine sand percentage, soil structure, and permeability were used to calculate the soil erodibility factor (K) for each soil profile. These parameters were determined from the surface horizons of the 28 soil profiles.

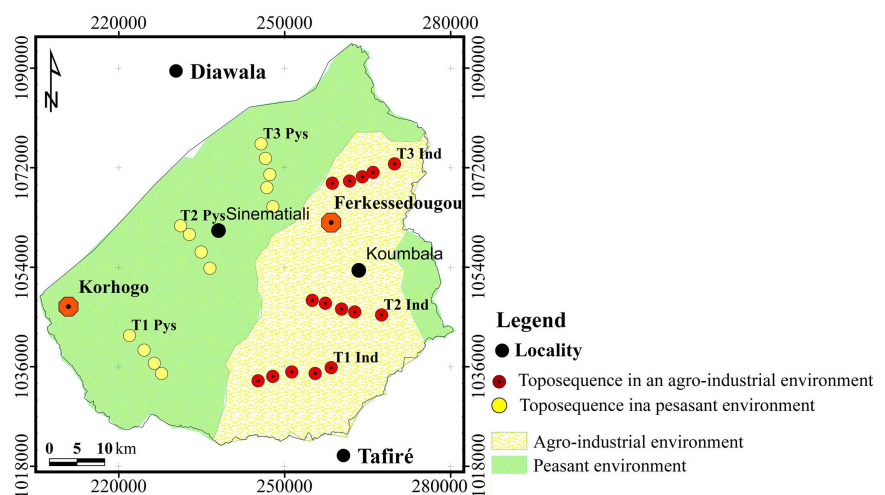


Figure 2. Distribution of sampling points upstream of the Bandama Blanc watershed.

3.2.2. Determination of Physical Soil Parameters

Physical parameters such as grain size distribution, field capacity moisture content (pF 2.5) and permanent wilting point (pF 4.2) of the soil were determined using the methods below. The method [12] was used to determine grain size distribution. Field capacity (pF 2.5) and permanent wilting point (pF 4.2) were obtained by extracting water under pressure using the [13] membrane used by [14]. These measurements were carried out at the SUCAF soil laboratory (CASTEL) in Ferkessedougou. The particle size distribution was used to determine the texture code of the soil samples collected. In addition, soil permeability was determined using Darcy's law by measuring the rate of gravitational water infiltration into the

soil ($\text{cm}\cdot\text{s}^{-1}$) (Equation (1)):

$$Q = K \times S \times \frac{\Delta h}{L} \quad (1)$$

Where Q : Fluid volume flow rate, K : permeability coefficient (m/s), Δh : Height of the water column, L : Length of the soil sample (m).

This made it possible to estimate the permeability codes needed to evaluate the erodibility factor (K) of the universal soil loss equation [4]. In addition, the content of coarse elements with a diameter greater than 2 mm was determined at the soil laboratory of the Centre de Recherche Ecologique (CRE) at the University of Nangui-ABROGOUA, using soil samples taken from all soil profiles. The coarse elements were obtained by washing with water. These coarse soil elements were dried in an oven at 105°C for 48 hours and weighed [15]. They were passed through a column of square mesh sieves of 2, 3, 4, 5 and 10 mm. The masses of the different sieve refusals, relative to the total mass of the sample, gave the rates corresponding to the size classes of 2 - 3, 3 - 4, 4 - 5 and 5 - 10 and >10 mm [16] (Equation (2)).

$$\text{Coarse} = \frac{\text{Screen reject mass}}{\text{Total mass of soil dried in the open air}} \times 100 \quad (2)$$

The method [17] was used to determine the total nitrogen content. The assimilable phosphorus content was obtained by colorimetry, using ammonium fluoride and hydrochloric acid according to the Olsen method modified by [18]. The potassium, calcium, magnesium and sodium contents were determined using a flame photometer after extraction with acetic acid. The [19] was used to determine the organic carbon content in the soil samples. This technique uses a cold sulphochromic attack to oxidise the organic carbon present in the sample and determine its content by titration. The organic carbon content was used to determine the organic matter content by multiplying it by 1.724. Organic matter is useful in assessing the erodibility factor (K) of soils. The cation exchange capacity was also determined after drying the soil samples in the open air. Then, a sodium chloride solution was used to saturate the soil exchange sites with Na^+ . Next, an ammonium acetate solution was added to these soil samples to replace the adsorbed ions with NH_4^+ ions. Finally, the cation exchange capacity was obtained by measuring the saturating cations in the filtrate using atomic absorption spectrometry [20]. In addition, the pH_{eau} was determined in a soil suspension obtained with distilled water in a ratio of 1/2.5 using a glass electrode of a pH meter [21].

3.2.3. How Kohonen Maps Work

The Self-Organising Maps (SOM) method, or Kohonen map [22] based on artificial neural networks (ANN) with unsupervised learning (Figure 3), was used. It is a multivariate statistical analysis model that compares data to identify similarities and differences. The data used in this study are the physico-chemical parameters of the soils evaluated above. The steps involved in using the Kohonen map

are: training the Kohonen map, the learning algorithm and hierarchical ascending classification.

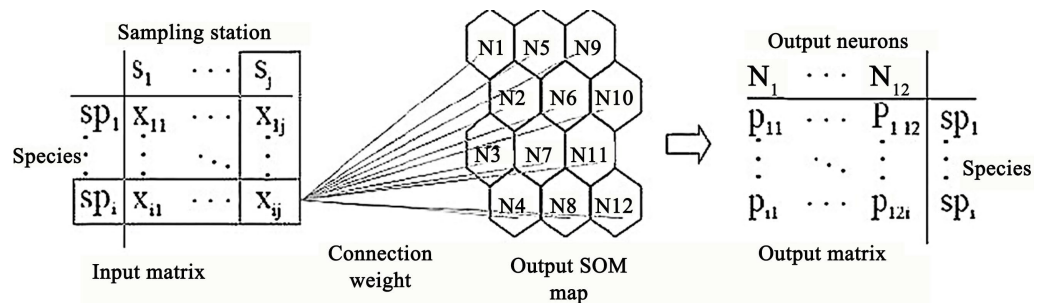


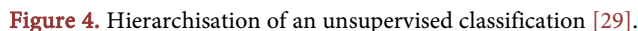
Figure 3. Simplified diagram of the self-organising map (SOM) [23].

1) Learning and size of the Kohonen map

Learning makes it possible to define the architecture of an artificial neural network (ANN) through careful selection of the input vector, the size of the network (or total number of layers and neurons) and the structure of the network. This involves defining the type of interconnection between the layers of neurons and transfer functions, without a standard procedure [24]. This is done by calculation ($S = 5\sqrt{N}$), where N is the number of soil samples entering the artificial neural network (ANN) and S is a value close to the product of the number of cells or neurons in a column by the number of cells in a row in the matrix representing the size of the Kohonen map [24]. The calculation required several iterations, with different combinations of this product, in order to select the Kohonen map that simultaneously minimises quantisation errors (QE) and topography errors (TE) [25] [26]. The learning process maps the input space of the map. Its purpose is to adapt the proportions of the soil samples so that examples that are close in the input space are associated with the same neurons or with contiguous neurons on the map. The different parts of the algorithm were virtual objects initialised by objects taken at random from the dataset. A real object was chosen at random and presented to the input layer, and the distance between this object and each virtual object was calculated. The closest virtual object was declared the “winning neuron” or “Best Matching Unit (BMU)” and all neurons in the vicinity of the BMU were modified (reordered and adjusted) [27].

2) Ascending hierarchical classification

The neurons obtained from the map were grouped using a hierarchical agglomerative clustering (HAC) procedure. This unsupervised classification aims to identify groups of soil samples exhibiting similar behavior across the set of variables, thereby providing a clearer overall representation of the SOM [28]. In this study, a Self-Organizing Map (SOM) consisting of 48 neurons arranged in a 6×8 grid was used to analyze 88 soil samples. This configuration allows the multidimensional variability of soil properties to be represented while providing a sufficient number of prototypes to identify similarity patterns among the samples. The resulting neurons were subsequently subjected to hierarchical clustering to iden-



Soil erodibility (K) was calculated after determining soil texture, structure codes and permeability codes. These parameters are included in the equation developed by [30] [31]. The erodibility obtained is a component of [4] Universal Soil Loss Equation (USLE).

The fine grain size was determined using the [12] on soil samples taken from soil profiles in the study area. This made it possible to obtain the proportions (%) of clay, silt and sand. By plotting these proportions on the USDA soil texture diagram (Figure 5), the structure codes (S) (1, 2, 3 and 4) can be deduced. Code 4 corresponds to fine-textured clayey, silty-clay soils. The full range of grain sizes (sand, clay) can be included in each of the codes 1, 2 or 3, depending on the size of the aggregates. The size of the aggregates in each soil was assessed in relation to the organic matter content.

[4] and [32] described the correspondence between soil permeability and codes 1, 2, 3, 4, 5 and 6 (**Table 1**).

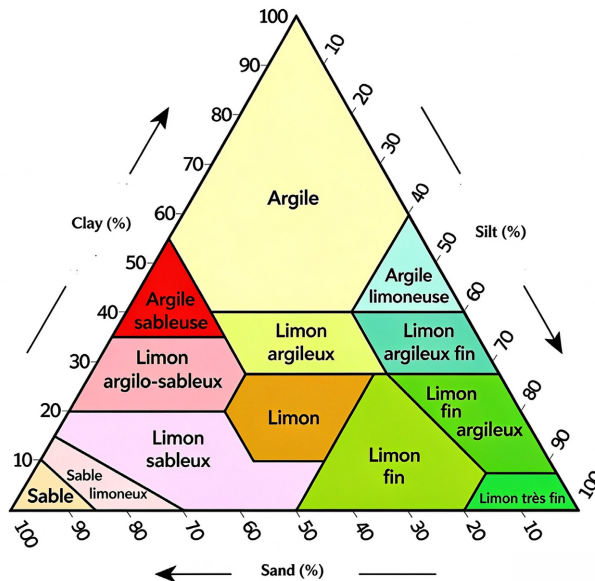


Figure 5. Textural classification of soils according to the USDA [32].

Table 1. Hydraulic conductivity of soil types and permeability codes [33].

Types of soil permeability	Permeability (code P)	Permeability (cm/h)	Permeability class
Very low permeability	6	<0.4	Very slow
Low permeability	5	0.4 - 2	Slow
Moderately low permeability	4	2 - 20	Slow to moderate
Medium permeability	3	20 - 40	Moderate
High permeability	2	40 - 60	Moderate to fast
Very high permeability	1	>60	Fast

3) Calculation of soil erodibility (K)

The erodibility (K) of 28 samples taken from the top 40 centimetres of soil was calculated. This factor is an indicator of how easily soil particles detach. It depends on the structure, texture, organic matter content and permeability of the soil. The factor (K) (t·h/MJ·year) was calculated using Equation (3) [30] [31].

$$\text{Erodibility} = \frac{2.1 \times 10^{-4} (10 - MO) M^{1.14} + 3.25(S - 2) + 2.5(P - 3)}{100} \quad (3)$$

Where MO : soil organic matter content, M : the product of primary particle fractions, $M = (\% \text{ silt} + \% \text{ fine sand}) \times (100 - \% \text{ fine sand})$, S : structure code and P : permeability code.

4. Results and Discussion

4.1. Results

4.1.1. Soil Types

The soil type map is obtained from the Kohonen map, the ascending hierarchical

classification and the distribution followed by the counting of soil samples from the study area.

1) Size of the Kohonen map

After several iterations during training on artificial neural networks, the Kohonen map of 48 cells arranged in 6 rows $\times$ 8 columns (**Figure 6**) was selected to show the soil types in the study area. This map gave the lowest quantification errors (QE = 0.41) and topology errors (TE = 0.00) with the 88 soil samples from the study area (**Table 2**).

Table 2. Estimation of quantisation errors and topology of different sizes of Kohonen map.

Card size	Quantisation errors (EQ)	Topology errors (ET)
8 $\times$ 6	0.46	0.01
6 $\times$ 8	0.41	0.00
2 $\times$ 23	0.42	0.04
23 $\times$ 2	0.42	0.03

The selected matrix is in bold.

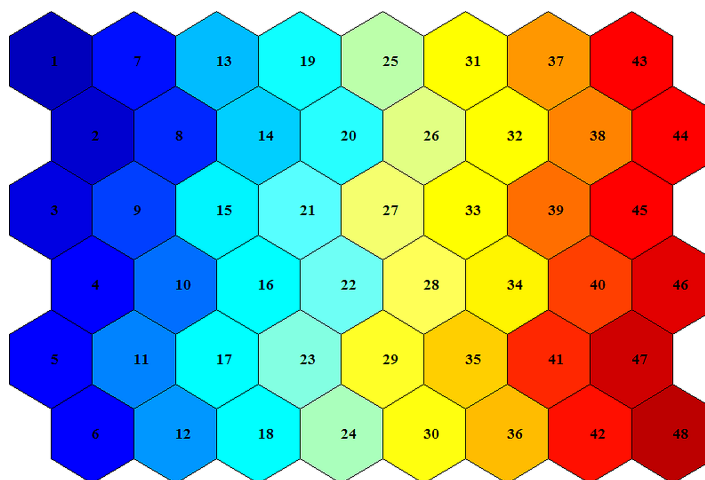


Figure 6. Kohonen map of the physical and chemical parameters of soils.

2) Ascending hierarchical classification of soil physico-chemical parameters on the Kohonen map

The dendrogram resulting from the ascending hierarchical classification yielded four groups of soil samples at a Euclidean distance of 1.5 (**Figure 7**). This distance allows cells to be grouped in pairs of groups with the same ancestors, thus presenting a strong relationship.

3) Distribution and enumeration of soil samples on the Kohonen map

Figure 8 shows a total of 88 soil samples summarised in **Table 3** and **Table 4**. These tables show a homogeneous appearance of soils III and II. Soil III is characterised by the grouping of 100% of samples from soil profiles in the agro-industrial environment in Ferkessedougou. This soil is characterised, at 51%, by 4-horizon

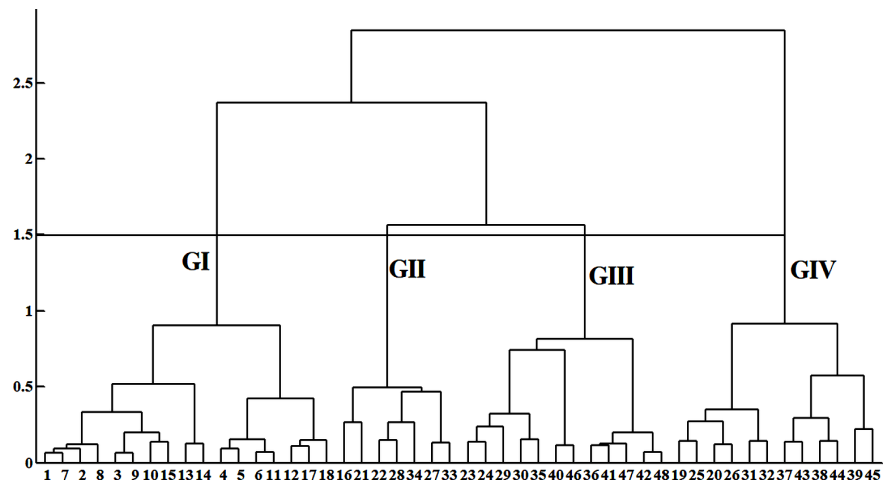
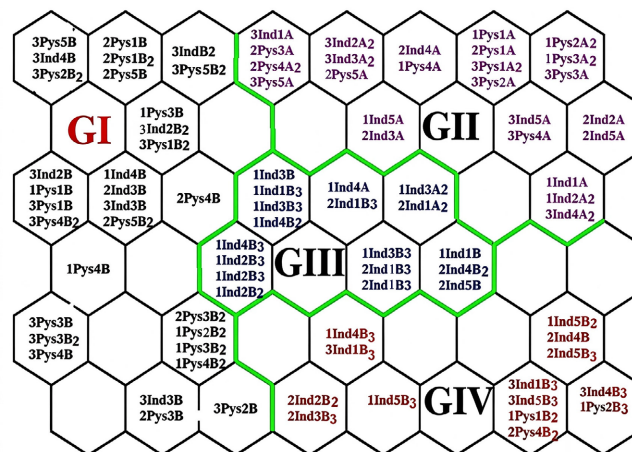


Figure 7. Ascending hierarchical classification dendrogram of Kohonen map cells based on soil physicochemical parameters.

profiles (A, B1, B2 and B3) and dominated by toposequence 1. Soil II consists of almost equal proportions of 52% and 48%, respectively, of soils from rural and agro-industrial environments. It is 99% horizon A, 32% of which has 2 horizons. Soils I and IV are heterogeneous, as they consist of both samples of soil profiles from farming and agro-industrial environments. Nevertheless, specific characteristics were observed depending on the toposequences and horizons. Soil I consists mainly of soils from toposequence 3, dominated by 3-horizon profiles, A1, A2 and B at 61% and A, B1 and B2 at 39%, which are clearly distinct and account for 74% of soils in the farming environment, while soil IV is codominant with soil samples from toposequence 2 and 3 in the agro-industrial environment at 78%, accounting for 72% of profiles, with 4 horizons (A, B1, B2 and B3).



Legend: GI: Group I; 1Pys1A: Toposequence 1, Peasant, Profile 1 and Horizon A; 2Ind3B: Toposequence 2, Agro Industrial, Profile 3 and Horizon B.

Figure 8. Distribution of soil samples on the Kohonen map by soil type.

Table 3. Count of soil samples upstream of the Bandama Blanc watershed by soil type and toposequence on the Kohonen map.

Soil types	Number of samples	Farmers (%)	Agro-industrial (%)	Total (%)	Toposequences per sample majority
I	31	74	26	100	T3 (Pys)
II	25	52	48	100	T1, T2, T3 (Pys) et T1, T2, T3 (Ind)
III	18	0	100	100	T1 (Ind)
IV	14	22	78	100	T2 et T3 (Ind)

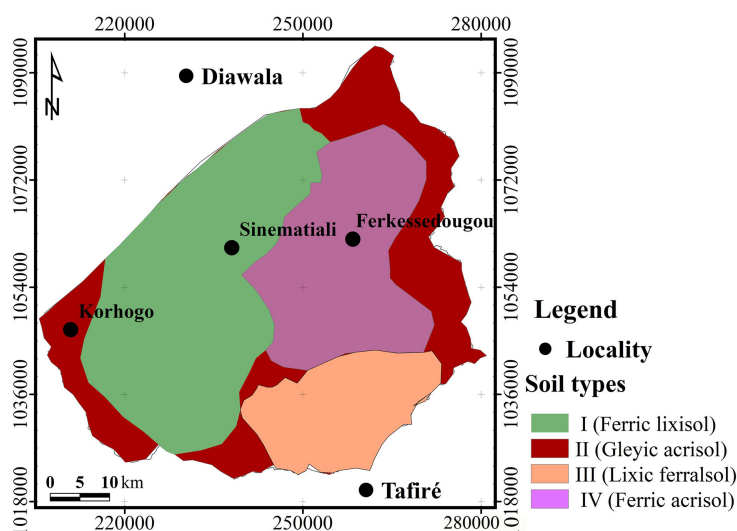
T = Toposequences; Pys = Peasant; Ind = Agro-industria.

Table 4. Number of soil samples upstream of the Bandama Blanc watershed, by horizon and soil type on the Kohonen map.

Soil type	Number of samples	Horizon A1 and 2 (%)	Horizon B1 (%)	Horizon B2 and 3 (%)	Total %
I	31	0	61	39	100
II	25	67 - 32	0	1	100
III	18	16	16	17 - 51	100
IV	14	0	21	7 - 72	100

4) Spatial distribution of soil types

The Kohonen map made it possible to distinguish three significantly different soil types: types I, III and IV. **Figure 9** shows that the study area is dominated by Acrisols. Soil I is Ferric Lixisol, with the toposequences T1Pys, T2Pys and T3Pys. The T3Pys toposequence is more representative. These soils are located in rural areas and their cation exchange capacity varies between 4 and 16.44 cmolc/kg, with a pH of 5.6. The agro-industrial environment was characterised by the presence of soils III and IV, with a pH of 6.2. Soil III is a Lixic Ferralsol. It only contains the T1Ind toposequence, while soil IV is a Ferric Acrisol, with the T2Ind and T3Ind toposequences. These toposequences are not significantly different, and their cation exchange capacity varies between 1.73 and 13.35 cmolc/kg.

**Figure 9.** Map of soil types and toposequences upstream of the Bandama Blanc watershed.

4.1.2. Soil Erodibility in the Bandama Blanc Watershed

Erodibility was assessed based on soil type, using texture derived from grain size composition, structure code deduced from texture, organic matter content and soil permeability in the Bandama Blanc watershed.

1) Soil texture, organic matter, structure and permeability

The results of the granulometric composition (**Table 5**) of the soils in the study area showed that the soil toposequences (I) in the farming environment were predominantly silty-clay-sandy in texture. The average organic matter content of this environment varies between 1.24% and 1.95% across all toposequences. Furthermore, in the agro-industrial environment, soils (III) and (IV) have a predominantly sandy-silty texture on toposequences T1 Ind and T2 Ind. The average organic matter content on these toposequences is between 0.84% and 1.96%. On the other hand, the T3 Ind toposequence of soil (IV) in the agro-industrial environment is dominated by a silty-clay-sandy texture, rather than a sandy-clay-silty texture, with an average organic matter content of 1.15%. It was found that, across all soil types in the agro-industrial environment, there was more sand and an average of 1.3% organic matter. In contrast, rural areas are characterised by a silty-clay texture with an average of 1.68% organic matter per toposequence. So, the soils in the agro-industrial environment are coarser than those in the farming areas. **Table 5** shows the structure codes obtained through soil texture classification and the permeability classes obtained from the permeability values of the different soil types. Soils (III) and (IV) located in the agro-industrial environment have a particulate structure. This was highlighted by structure code 1, which is predominant in the T1 Ind and T2 Ind toposequences, with an average permeability of 0.41 cm/s, corresponding to an average permeability class of 2. However, the T3 Ind toposequence of soil type (IV), from the same environment, is characterised by fairly structured soil. It is therefore characterised by a predominant structure code 2 and an average permeability of 0.32 cm/s, corresponding to permeability class 3. Furthermore, soil (I), from the agricultural environment, and the soils of the three toposequences T1 pys, T2 Pys and T3 Pys are poorly structured. They correspond to structural code 3, which is predominant across all toposequences. The average permeability obtained for these toposequences is 0.09 cm/s, corresponding to an average permeability class of 5. Soils in agro-industrial areas have a predominantly particulate structure with moderate permeability, while those in rural areas have a compact structure with low permeability.

2) Soil erodibility

The erodibility values K for the different soil groups in the upper reaches of the Bandama Blanc watershed are shown in **Table 6**. Soils (III) and (IV) in agro-industrial areas have average erodibility (K) values of 0.30 and 0.34 t·ha·h/MJ·mm, respectively. This erodibility varies from 0.23 to 0.41 t·ha·h/MJ·mm for soil (III) and from 0.24 to 0.39 t·ha·h/MJ·mm for soil (IV). For soil (I) in a farming environment, erodibility varies from 0.05 to 0.14 t·ha·h/MJ·mm, with an average of 0.12 t·ha·h/MJ·mm. In addition, soil erodibility (K) trends show higher values in agro-industrial environments than in farming environments.

Table 5. Structure code and permeability class of soil types upstream of the Bandama Blanc watershed.

Type Soil	Toposequence	Profile	Texture	Structure code	Permeability class	Organic matter %	Permeability cm/s
I	T1.Pys	1 to 4	Clay-loam	3	5	2.12	0.03
			Loam-clay-sand	3	5	1.92	0.09
			Sandy-clay-loam	3	6	1.76	0.11
			Sandy-clay-loam	3	5	1.67	0.12
	T2.Pys	1 to 4	Clayey	4	5	1.79	0.07
			Sandy loam	3	5	1.15	0.08
			Sandy clay	2	5	1.09	0.09
			Sandy loam	1	5	0.95	0.15
	T3.Pys	1 to 5	Clay-loam	3	5	2.21	0.08
			Loam-clay-sand	3	5	2.09	0.12
			Loam-clay-sand	3	5	1.24	0.1
			Loam-clay-sand	3	5	1.25	0.13
			Loam-clay-sand	3	5	0.5	0.12
III	T.Ind	1 to 5	Sandy loam	3	1	0.91	0.18
			Sandy loam	3	1	1.33	0.41
			Sandy silt	1	3	0.72	0.83
			Sandy	1	2	0.52	0.83
			Sandy silt	1	3	0.72	0.7
IV	T2.Ind	1 to 5	Sandy	1	2	0.18	0.21
			Sandy-loam	1	3	1.18	0.27
			Sandy-loam	1	3	1.2	0.33
			Sandy-clay	2	1	1.47	0.20
			Clay-sandy	1	1	2.47	0.15
	T3.Ind	1 to 5	Sandy loam	3	2	0.88	0.18
			Sandy clay loam	3	4	1.2	0.34
			Sandy loam	1	3	0.79	0.8
			Sandy clay loam	2	2	1.4	0.13
			Loamy sandy clay	2	4	1.46	0.16

Table 6. Erodibility of soil groups upstream of the Banadama Blanc watershed.

Soil type	Toposequence	Profile	Average soil erodibility (t·ha·h/MJ·mm)
I	T1.Pys	1 to 4	0.131
	T2.Pys	1 to 4	0.10
	T3.Pys	1 to 5	0.12
III	T1. Ind	1 to 5	0.301
IV	T2. Ind	1 to 5	0.33
	T3. Ind	1 to 5	0.34

T = toposéquence; Ind = Industrial and Pys = Peasant.

3) Spatialisation of soil erodibility

The erodibility results obtained were spatialised (**Figure 10**). The erodibility map shows a general variation in the erodibility factor (K) from 0.05 to 0.41 t·ha·h/MJ·mm. Two major areas of different erodibility were identified on this map. The Korhogo and Sinématiali area is characterised by low erodibility ranging from 0.120 to 0.14 t·ha·h/MJ·mm, with an average of 0.12 t·ha·h/MJ·mm. On the other hand, the Ferkessedougou area is marked by erodibility values ranging from 0.23 to 0.41 t·ha·h/MJ·mm, with an average of 0.32 t·ha·h/MJ·mm. The light brown colour indicates high erodibility and the dark brown colour indicates very high erodibility. These two colours are both found in agro-industrial areas. The soil was characterised by medium to coarse grain size, with structure codes indicating good permeability due to its predominantly sandy texture.

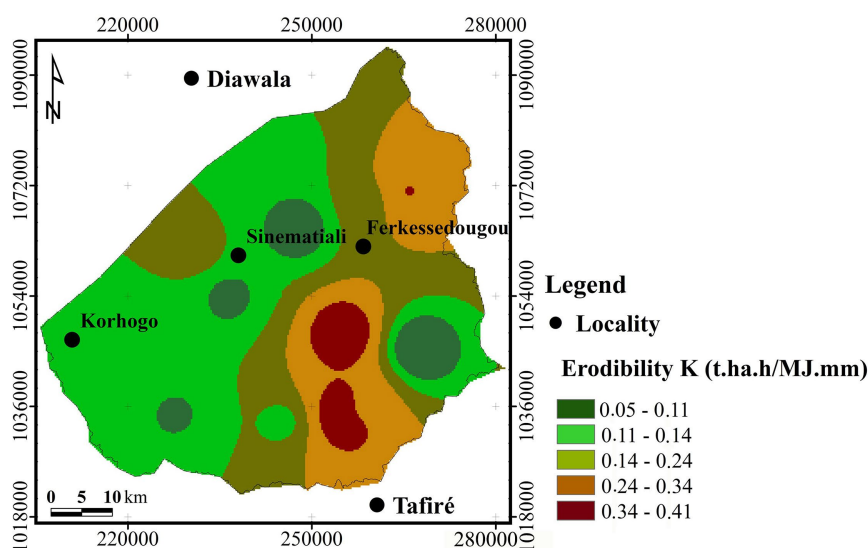


Figure 10. Erodibility map (K) upstream of the Bandama Blanc watershed.

4.2. Discussion

The study area has three types of soils significantly different. Ferric Acrisol and Lixic Ferralsol dominate in the agro-industrial environment (SUCAF 1 and 2) in Ferkessedougou. These soils have an average cation exchange capacity of 6.15 cmolc/kg. Ferric Lixisol is found in rural areas, with an average cation exchange capacity of 10.29 cmolc/kg, covering the departments of Korhogo and Sinématiali. According to [34], the cation exchange capacity of soils is low in rural areas and very low in agro-industrial areas. The difference between these soils can be explained by their nature and anthropogenic practices. Their cation exchange capacities are consistent with the results of [35] and [10], which showed that Acrisols and Lixisols have a cation exchange capacity of less than 24 cmolc·kg⁻¹. Furthermore, the soils derived from these groups showed little difference between them in terms of physical and physico-chemical properties. In addition, the soil profiles of both environments showed, in places, coarse, ferruginous elements (concre-

tions, nodules) and crusts or armour. According to [36], there is a high degree of similarity between the soils of the departments of Boundiali, Korhogo and Ferkessédougou. [37] made the same observation about the soils in this part of the White Bandama watershed. The difference between soils I, II, III and IV is due to their content of coarse elements, fine elements, field capacity and permanent wilting point moisture content, and organic matter due to their cultivation. Indeed, high levels of fine elements and moisture content at field capacity and permanent wilting point were observed in the soils of farming environment I. This area still has natural vegetation and uses more manual farming techniques, which reduces soil degradation. In agro-industrial areas III and IV, SUCAF 1 and 2 in Ferkessédougou, high levels of fine sand and coarse elements as well as low water content were observed. The cultivation techniques used on the soils of the SUCAF farms in Ferkessédougou could explain this observation, rather than the nature of the soils in this environment, which are highly resistant to erosion [38] [39]. These soils are regularly reworked by machines and overexploited for sugar production. These machines generate coarse elements by crushing rocks such as laterite and granite in tropical soils during ploughing [40]. The presence of coarse particles is linked to the leaching of fine particles (clay and silt) from the soil, as well as organic matter, under the action of water erosion caused by extreme rainfall and sugar cane irrigation water. According to [41] and [42], as the structural characteristics of soils deteriorate due to rain, there is an increase in erosion, both in terms of quantity, due to increased soil loss, and in terms of quality. This increasingly removes fine elements (clay, silt, organic matter), which are essential for soil fertility. These coarse elements may also explain the good permeability of soil in agro-industrial environments. According to [16], coarse elements on the soil surface reduce runoff and, as a result, promote water infiltration into the soil. In addition, these agricultural practices explain the high erodibility of soils obtained in agro-industrial environments (SUCAF) in Ferkessédougou, according to the classification of [43]. This is because soils III and IV have erodibility values ranging from 0.23 to 0.41 t·ha·h/MJ·mm, with an average of between 0.32 t·ha·h/MJ·mm. These soils are more susceptible to water erosion. [41] showed that as soil erodibility increases, erosion increases, the average solid load of water increases accordingly, and suspended particles become increasingly finer. As far as the rural environment is concerned, soil type I is characterised by a high abundance of fine soil particles. This area is dominated by small farms, with moderate reworking, which largely preserves the natural character of the soil in this environment. In fact, it has an average organic matter content of 1.68%, compared to 1.3% in agro-industrial areas. This also explains the low erodibility values (K) obtained on these soils. They vary from 0.05 to 0.14 t·ha·h/MJ·mm, with an average of 0.12 t·ha·h/MJ·mm. According to the classification of [43], the smallholder environment is moderately sensitive to soil loss through water erosion. This result can be explained by the fact that fine-grained clay is naturally more easily washed away by rainwater and transported by runoff, but develops internal cohesive forces after becoming saturated with water. It is then able to resist the detachment of its particles more

strongly. The soils in this environment are poorly structured, with fine granules, a structure code of 3 and low water permeability. This contradicts the findings of [44], who estimated that the value of K is linked to soil structure and would be low for fine soil, moderate for medium-fine soil and high for soils rich in silt. Ultimately, this study shows that the erodibility of tropical soils is more related to anthropogenic practices than to soil type. This is in agreement with [45], who say that in reality, there is no erodibility index by soil type, but that this index changes over time depending on soil moisture, roughness, vegetation cover, slope and organic matter content.

5. Conclusion

This study highlighted three (3) major soil types in the upper part of the Bandama Blanc watershed, dominated by the Acrisol group. Meanwhile, Ferric Acrisol and Lixic Ferralsol are located in the agro-industrial area (SUCAF 1 and 2) of Ferkess édougou. The Ferric Lixisol is found in the farming environment (Korhogo and Sinématiali). The soils in the SUCAFCI agro-industrial environment (Ferk essédougou) have a high content of coarse elements and fine sand, with an average cation exchange capacity of 6.15 cmolc/kg, while the content of fine elements and moisture is high, with an average cation exchange capacity of 10.29 cmolc/kg in the farming environment. These cation exchange capacities indicate that these soils have very low fertility. In addition, the erodibility of the soils in the basin showed that the agro-industrial environment is more sensitive to water erosion, with an average erodibility of 0.32 t·ha·h/MJ·mm, compared to 0.12 t·ha·h/MJ·mm in the farming environment. Furthermore, the greater vulnerability of soils in the agro-industrial environment to water erosion appears to be more strongly associated with agricultural practices and land-use intensity than with differences in the intrinsic properties or soil types themselves.

Author Contributions

Coulibaly Léréya, assisted with equipment during field sampling; Ouattara Ismail, Data processing using MATLAB 6 for SOM application; Ouedraogo Mohamado, reading and proofreading; Kouassi Tehua, Pascal Angui, participated in sampling and proofreading.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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