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Study of a Toposequence of West Mayo-Kani Soils (Far North Cameroon)

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Abstract

The soils of Gadas, object of the present study, are identified on the macromorphological, physico-chemical level and the indices of erodibility are related to their physico-chemical properties. The physico-chemical analyzes were carried out by standard methods. The macromorphological analysis of a toposequence made it possible to identify five types of soils: the lithosols which occupy the high zones of the landscape, the colluvial soils (arenosols, regosols) which are located high on the piedmont, alluvial soils (fluvisols) which are located at the bottom of the slope in the alluvial plain and are the most extensive, topomorphic vertisols, and brown soils formed on granite are located either between a colluvial soil and alluvial soil. Physico-chemical analyzes of the soils of Gadas show that these soils are weakly acidic to neutral, sandy to sandy-clayey, saturated, low in nitrogen and organic matter and characterized by average proportions of exchangeable bases. The study of soil erodibility, based on the use of erodibility indices, showed that alluvial soils and brown soils formed on granites are the most susceptible to erosion, whereas vertisols and colluvial soils are the least vulnerable to erosion.

Keywords

Far North Cameroon, West Mayo-Kani, Gadas, Soils, Erodibility

1. Introduction

The soils of the Far North of Cameroon are diversified and are of capital importance for its population. Knowledge of these soils is a prerequisite for their development and sustainable management. It makes it possible to provide decision-makers with a database allowing them to define guidelines for sustainable soil management. Hence the need to characterize the soils on the macromorphological, physico-chemical and erodibility levels. The soils of North Cameroon are generally very fragile, of light texture, with an average fertility potential; when exposed, they are very sensitive to erosion [1] [2]. The use of these soils, in particular their cultivation, increases in the long term either their erodibility [3] [4] or their depletion in nutrient elements [5] [6] and further compromises the agricultural production [7] [8]. This is the case of the soils of the western mayo-kani. Unfortunately, these soils remain very little known both in terms of their typology, their erodibility and their valuation. However, the first soil inventories in northern Cameroon date from the 1960s [9]. A small-scale soil synthesis was carried out in the 1980s [10]. More recently, some large-scale work has been carried out for the recognition of these soils in specific sectors [1] [2] [11]. It is therefore interesting to characterize the soils of Gadas and to determine their erodibility.

2. Location of the Study Area

Located in the province of Far North Cameroon, the region of Gadas is part of the district of Kaélé, department of Mayo-kani Ouest. It is located in the NW part, twelve kilometers from Kaélé. The study area is between 10˚13' and 10˚23' North latitude and 14˚23' and 14˚28' East longitude (**Figure 1**). It enjoys a

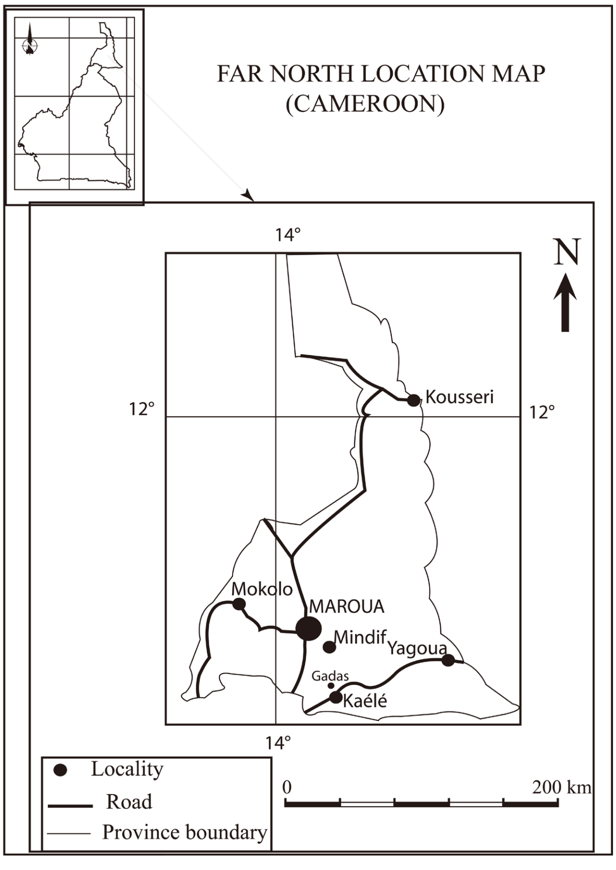

Figure 1. Location map of Gadas.

Sudano-Sahelian climate and is characterized by a long dry season of seven to eight months (early October to late April to early May) and a short rainy season of three to four months. The wind direction is characteristic of the seasons: the S-SW wind with a speed varying from 8.10 to 15.20 m/s characterizes the rainy season and the S-N wind, reaching speeds of 9.50 at 14.10 m/s, the dry season. The locality of Gadas is covered by a more or less wooded savannah and a thorny steppe. The river encountered is not very ramified, it is the Mayo Zapili. Their drainage is seasonal only in the rainy season; the drainage is towards the Mayo-Kani (see sampling map, **Figure 2**). Gadas is a plain in which stands a massif of granite rocks (Mount Gadas). Mount Gadas is a calc-alkaline granite massif 650 m above sea level.

3. Study Methods

3.1. In the Field

The location of the study area is made possible by the use of the topographic map of Maroua 1b (sheet NC-33-XV-1b) at a scale of 1/50.000. Indeed, several visits to the field have were carried out during which a GPS, a penetrometer, etc. were used. At the end of these field campaigns, 6 (six) soil pits were opened and exploited. These wells were dug following the NE-SW toposequence. Six successive profiles GF1, GF2, GF3, GF4, GF5, GF6 were made from the foot of the granite massif to Mayo Zapili (**Figure 2**). Indeed, Mount Gadas is a granite massif of 650 m altitude and steep slope, almost abrupt towards the SW side. The more or less steep inclination of the slopes led to this direction being chosen for the construction of the sampling wells; this in order to study the lateral variations of the soils. The detailed description of the profiles was made using soil pits (determination of depth, color, texture, structure, biological activity, etc.). After the

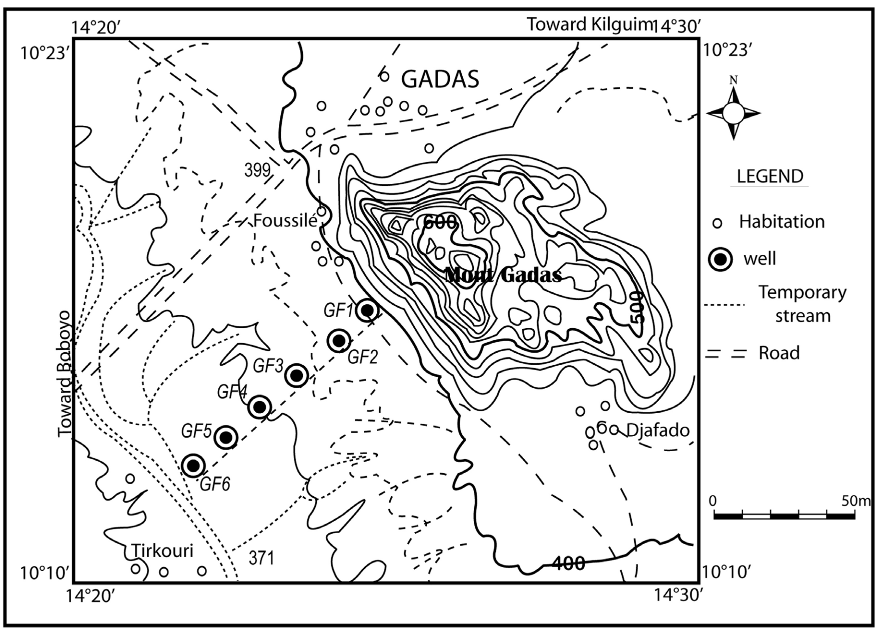

Figure 2. Gadas soil sampling map.

description of the different horizons, sampling is carried out, which consists of taking 0.5 kg of soil from each horizon, which is labeled and packed in a plastic bag for laboratory analysis (The figure below shows the soil sampling points along the slope).

3.2. In the Laboratory

The main analyzes carried out in the laboratory are physico-chemical analyses. Soil samples were air dried, then crushed and sieved to 2 mm. The fine earth thus obtained was used for particle size analysis, determination of organic carbon, total nitrogen, exchangeable bases, pH and residual humidity. The physicochemical analyzes were carried out in the soil laboratory of the Agronomic Research Institute for Development (IRAD) of Nkolbisson in Yaoundé and in the soil analysis and environmental chemistry laboratory of the Faculty of Agronomy, and Agricultural Sciences (FASA) from the University of Dschang.

3.3. Estimation of Soil Erodibility

To assess soil erodibility, two methods are used: the direct method or rain simulation consists of producing an artificial downpour on a micro-plot in order to measure runoff and induced soil losses [12] and the indirect or analytical or laboratory method, which consists in evaluating the erodibility of soils using erodibility indices which are calculated from physico-chemical soil data. The indirect method developed by [13] [14] [15] [16] [17] is the one we will use to assess the erodibility of the soils of Gadas.

The equations used are:

$$\text{CDR} = \frac{\text{WDC}(\%)}{\text{TC}(\%)} \quad (1)$$

$$\text{CA} = \text{TC}(\%) - \text{WDC}(\%) \quad (2)$$

$$\text{DR} = \frac{\text{WDC}(\%) + \text{WDS}(\%)}{\text{TC}(\%) + \text{TS}(\%)} \quad (3)$$

$$\text{ESP} = \frac{\text{Exchangeable Na}^{+}}{\text{CEC}} \times 100 \quad (4)$$

$$\text{ESR} = \frac{\text{Exchangeable Na}^{+}}{\text{Exchangeable}\left(\text{Ca}^{2+} + \text{Mg}^{2+} + \text{K}^{+}\right)} \quad (5)$$

The indices used are: total clay (Total clay: TC), the rate of clay dispersed in water (Water Dispersible Clay: WDC), the rate of dispersion of the clay (Clay Dispersible Ratio: CDR), the dispersion rate (Dispersion Ration: DR), the aggregated clay (Clay Aggregation: CA) and the exchangeable Na^+ (Exchangeable Sodium Percentage: ESP and Exchangeable Sodium Ratio: ESR).

4. Results

4.1. Macromorphology

The surface condition of the soils of Gadas is marked by traces of water erosion.

These include the appearance of rills and ravines in cultivated and uncultivated plots, deposits of sandy sediments at the bottom of the slope and in the Mayo, and the outcrops of rocks, cuirasses and lateritic shells. These erosion marks reflect the loss of soil in the cultivated plots. According to [10], erosion presents short-term risks for soils, it leads to an imbalance between pedogenesis and morphogenesis in favor of the latter. According to this toposequence, the slope of the massif is steep. Six successive profiles GF1, GF2, GF3, GF4, GF5, GF6 were made from the foot of the granite massif to Mayo Zapili (**Figure 3**).

4.1.1. Lithosols

In Gadas, the profile of the lithosols is reduced to a humus horizon surmounting the granitic arena. The humus horizon is gray and pink in places, coarse gravelly and clayey sand; grainy structure; tubular porosity. The granitic arena is gray and pink in color, very gravelly sandy and not very clayey. The lithosols of Gadas occupy the high areas of the landscape at an altitude above 420 m.

4.1.2. Colluvial Soils

The GF1 profile has a thickness of 84 cm, this soil pit is located on the SW flank of the granite massif (Mount Gadas 650 m above sea level) (**Figure 3**). Cotton is grown there and the agricultural yield is very significant. This profile presents four horizons. The abbreviation GF stands for Gadas Fouinsilé. From top to bottom, we have:

0 to 22.5 (cm). Horizon A. Dark gray (2.5Y 4/1) dry; sandy clay; polyhedral structure; presence of more or less buried plant debris; presence of fine roots in abundance; quartz and feldspar gravels (orthoclase which gives a pink color to the ground); porous; crumbly when wet and brittle when dry; sharp transition with the underlying horizon.

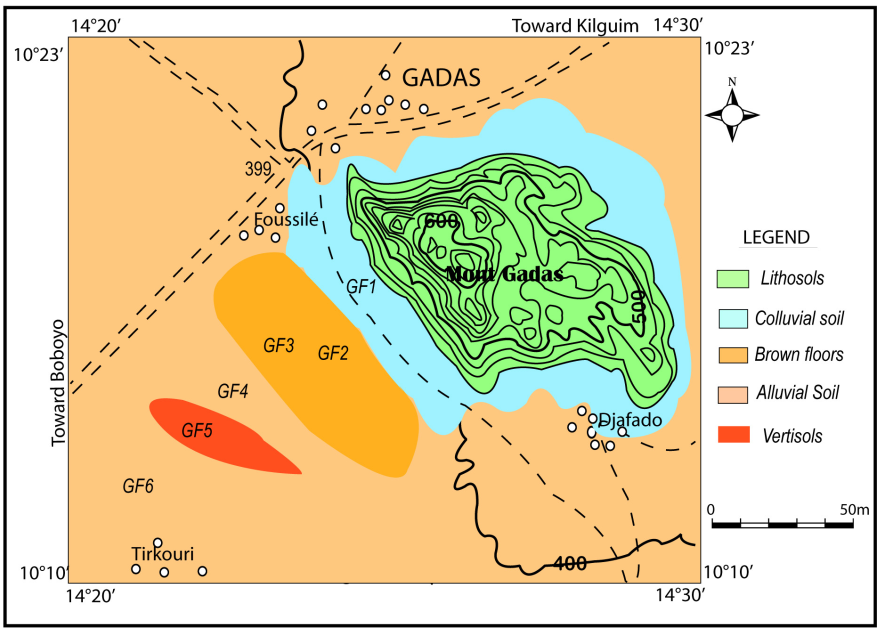

Figure 3. Soil distribution map of Gadas.

22.5 to 41 cm. Horizon B1. Brown (10YR 4/3) dry; sandy; particulate to gritty structure; few fine roots; presence of orthoclase and quartz gravels; porous; crumbly and brittle when dry; abrupt contact with the underlying horizon.

41 to 75 cm. Horizon B2. Yellowish brown (10YR 5/4) dry; sandy clay; particle structure; presence of quartz gravels and feldspar no roots; porous; crumbly and fragile; sharp transition with the underlying horizon.

75 to 84 cm. Horizon B3. Very light brown (10YR 7/3) dry; alteritic horizon; whitish-pink in appearance; polyhedral structure; presence of quartz and feldspar gravels; presence of traces of biotite weathering; gradual contact with the pink granite.

In short, this profile is made up of four distinct horizons: a dark gray, sandy-clayey horizon, 22.5 cm thick; a brown, sandy horizon, 18.5 cm thick; a yellowish brown, sandy-clayey horizon, 34 cm thick and a very pale brown alteritic horizon, whitish pink in appearance, 9 cm thick. This profile is made up of colluvial materials resting on granite. It is colluvial soil (regosol).

4.1.3. Brown Soils Formed on Granite

The GF2 profile has a thickness of 50 cm and is located about 500 m from the granite massif (Mount Gadas) (**Figure 3**). It has no cultivation because we note the outcrop of boulders. This profile presents three horizons. From top to bottom, we have:

0 to 3 cm. Horizon A. Light brown (10YR 6/3) dry; sandy; particle structure; presence of fine and medium sand in abundance; abrupt contact with the underlying horizon.

3 to 10 cm. Horizon B1. Gray (10YR 5/1) dry; clayey-sandy; polyhedral structure; very porous and crumbly; presence of fine roots and residues; presence of quartz grains; direct contact with the underlying horizon.

10 to 25 cm. Horizon B2. Brownish gray (10YR 5/2); sandy clay; nuciform to particulate structure; presence of fine, medium and coarse sand; sudden contact with an alteritic horizon.

25 to 50 cm. Horizon B3. Pale brown (10YR 6/3) dry; alteritic horizon; poorly preserved structure; minerals are recognizable (quartz, feldspar, biotite); gradual contact with the granitic bedrock.

This profile presents four horizons: a pale brown, sandy horizon, 3 cm thick; a gray horizon, argilo-sandy 7 cm thick; a brownish-grey, sandy-clayey horizon, 15 cm thick and a pale brown alteritic horizon, 25 cm thick. The clear limit between the first three horizons shows that these identified horizons result from successive contributions. These three horizons rest on an alteritic horizon. It is an alterite on which rests successive deposits having no connection with each other. It is a brown soil formed on granite.

The GF3 profile has a thickness of 150 cm, this soil pit is located about 1100 m from the granite massif (Mount Gadas). Peanuts are grown there and the yield is appreciable. This profile presents three horizons. From top to bottom, we have:

0 to 24 cm. Horizon A. Greyish brown (2.5Y 5/2) dry; clayey-sandy; polyhe-

dral structure; crumbly; abundant fine roots; quartz and feldspar grains; abrupt contact with the underlying horizon.

24 to 41 cm. Horizon B. Light olive brown 2.5Y 5/3) dry; sandy clay; polyhedral structure; crumbly; grains of quartz in abundance; very little feldspar; a few white spots; abrupt contact with the underlying horizon.

41 to 150 cm. Weather horizon C. Light gray (5Y 7/1) dry; alteritis; presence of brown spot; weathered feldspar; unaltered quartz crystals; the minerals are recognizable; gradual contact with the granitic bedrock.

In short, this profile has three horizons from top to bottom, one: grayish brown, clayey-sandy, 24 cm thick; a light olive brown, sandy-clayey horizon, 17 cm thick and a light gray alteritic horizon, 105 cm thick. This profile is an alterite surmounted by input materials, these input materials have no pedogenetic link between them.

4.1.4. Alluvial Soils

The GF4 profile has a thickness of 100 cm, this soil pit is located about 1600 m from the granite massif (Mount Gadas). Red millet is grown there (sorghum for the rainy seasons), the yield is very significant (**Figure 3**). This profile presents three horizons. From top to bottom, we have:

0 to 8 cm. Horizon A. Dark gray (2.5Y 4/1) dry; clayey-sandy; polyhedral structure; porous; non-friable when dry; grains of quartz and feldspar; some fine and medium roots; sharp transition with the underlying horizon.

8 to 45 cm. Horizon B1. Brown (10YR 5/3) dry; sandy; nuciform to particulate structure; presence of fine, medium and coarse grains of sand (quartz and feldspar); abrupt contact with the underlying horizon.

45 to 100 cm. Horizon B2. Light grayish brown (10YR 4/2) dry; clayey-sandy; porous; slightly crumbly when dry; presence of quartz and feldspar; brutal contact with the granitic bedrock.

This profile is made up of three horizons: a grey, clayey-sandy horizon, 4 cm thick; a brown, sandy horizon, 37 cm thick and a grey, clayey-sandy horizon, 55 cm thick. This profile is an alluvial soil (fluvisol) which presents successive deposits with no pedogenetic link between them.

The GF6 profile has a thickness of 270 cm, this soil pit is located about 2600 m from the granite massif (Mount Gadas). Onions and vegetables are grown there after the rainy season (garden). The agricultural yield is very appreciable. This profile presents seven horizons. From top to bottom, we have:

0 to 40 cm. Horizon A. Very light brown (10YR 7/3) dry; sandy; particle structure; presence of fine to very fine sand; abundant fine and medium roots; crumbly and brittle when dry; abrupt transition with the underlying horizon.

40 to 85 cm. Horizon B. Very light brown (10YR 7/3) dry; sandy; particle structure; presence of very fine sand; few fine and medium roots; abrupt contact with the underlying horizon.

85 to 118 cm. Light yellowish brown (10YR 6/4) dry; sandy clay; polyhedral structure; porous; crumbly; presence of fine sand; direct contact with the under-

lying horizon.

118 to 146 cm. Light yellowish brown (10YR 6/4) dry; sandy; particle structure; crumbly; presence of fine sand; direct contact with the underlying horizon.

146 to 204 cm. Pale brown (10YR 6/3) dry; sandy clay; polyhedral structure; crumbly in places; presence of fine sand.

204 to 240 cm. Light yellowish brown (10YR 6/4) dry; sandy clay; polyhedral structure; crumbly; porous; presence of fine sand; presence of abundant rust (brown) stain; sharp transition with the underlying horizon.

240 to 270 cm. Very light brown (10YR 7/4) dry; sandy; particle structure; fine, medium and coarse sand; presence of ferruginous nodules; direct contact with groundwater.

In summary, this profile is an alluvial soil (fluvisol) given its topographic position, it is formed of seven horizons with no pedogenetic link between them.

4.1.5. Topomorphic Vertisols

The GF5 profile has a thickness of 433 cm, this soil pit is located about 2100 m from the granite massif (Mount Gadas) (**Figure 3**). The rainy season sorghum is also grown here. This profile includes five horizons with pedogenetic links between them. From top to bottom, we have:

0 to 50 cm. Horizon A. Gray (2.5Y 5/1) dry; clayey; massive to slightly blocky structure; shrinkage slots exhibiting a well-developed prismatic macrostructure; compact; sticky when wet; porous; non-friable when dry; observes a few rare grains of quartz and feldspar; traces of earthworm activity; gradual contact with the underlying horizon.

50 to 110 cm. Horizon B. Pale brown (2.5Y 8/2) dry; massive structure; clayey to clayey-sandy; shrinkage slots exhibiting a slightly developed prismatic macrostructure; compact; sticky when wet; non-friable when dry; white and black spots; grains of quartz and feldspar; gradual contact with the underlying horizon.

110 to 172 cm. Horizon Bca1. Pale brown (2.5Y 8/3) dry; massive structure; clayey to clayey-sandy; fine removal slots; non-friable; non-porous; compact; sticky when wet; fine to very fine elements; white and brown spot; gradual contact with the underlying horizon.

172 to 319 cm. Horizon Bca2. Pale brown (2.5Y 8/4) dry; sandy clay; polyhedral structure; non-friable; increasingly fine withdrawal slits; compact and sticky when wet; grains of quartz and feldspar; gradual contact with the underlying horizon.

319 to 433 cm. Horizon Bca3. Pale brown (2.5Y 8/4) dry; sandy clay; massive structure; non-friable; compact; sticky when wet, abundant quartz grains; contact with water.

In short, this profile is made up of five horizons, from top to bottom, we can distinguish: a dark gray horizon, clayey, 50 cm thick; a pale brown, clayey to clayey-sandy horizon, 60 cm thick; a pale brown, clayey to clayey-sandy horizon, 62 cm thick; a pale brown, sandy-clayey horizon, 147 cm thick and a pale brown, sandy-clayey horizon, 114 cm thick. We observe a gradual passage between the different horizons, reflecting the existence of a filiation between the different horizons. The well-marked shrinkage cracks and prismatic macrostructure are the main morphological characteristics of these soils. This profile is a vertisol and given its topographic position, it is a topomorphic vertisol.

The macromorphological data made it possible to identify the types of soils formed at Gadas. We have:

- The lithosols which occupy the high zones of the landscape, at an altitude of over 420 m, and whose profile is reduced to a humus-bearing horizon surmounting the granitic arena;
- Colluvial soils (regosols) which are located on the foothills (410 m altitude), of sandy texture and comprising three horizons;
- Brown soils formed on granite, sandy-clayey, located between colluvial soils and alluvial soils;
- Lithomorphic vertisols (vertisols) are located between two alluvial soils, of sandy texture and have three horizons with a genetic link between them;
- The alluvial soils (fluvisols) located at the bottom of the slope are the most extensive, of sandy texture, and comprising four to eight horizons. Thus, this toposequence is marked by the great extension of alluvial and colluvial soils.

4.2. Physico-Chemistry

The physico-chemical analysis (**Table 1**) of the soils of Gadas shows that: the colluvial soils are weakly acidic, sandy-clayey, saturated and characterized by average proportions of exchangeable bases and organic matter; the brown soils formed on granites are weakly acidic, sandy-clayey to sandy-clayey, saturated, low in total nitrogen and have a low proportion of exchangeable bases and organic matter; topomorphic vertisols are acidic, clayey-loamy, saturated, low in total nitrogen and have high proportions of exchangeable bases; the alluvial soils are acid, clayey-sandy and characterized by medium proportions of exchangeable bases. These soils are saturated, poor in organic matter and nitrogen.

4.3. Soil Erodibility

Soil erodibility is defined as the vulnerability or susceptibility of that soil to erosion [16]. The erodibility of a soil can also be defined as the evaluation of the susceptibility of the soil to the detachment of its particles and their transport by the agents of erosion [18].

The total clay (Total Clay, TC) of the soils of this transect varies from 42.4% for the alluvial soils to 50.2% for the topomorphic vertisols (**Table 2**). Alluvial soils are less clayey while topomorphic vertisols are the most clayey of the soils of this toposequence.

Water dispersible clay or WDC ranges from 40.2% for alluvial soils to 43.4% for brown soils formed on granite (**Table 2**). Water dispersible clay has high values for the GF21 profile and lower values for other soils.

Table 1. Physico-chemical characteristics of the surface horizons of the NE-SW transect of Gadas.

Soil type	Particle size with dispersant (%)			Particle size without dispersant (%) pH			pH		ΔpH
	Clay	Silt	Sand	Clay	Silt	Sand	H_2O	KCl	
Colluv soil GF11	44.2	11.4	45.3	42.2	14.8	42.6	6.20	5.60	0.6
Soil on granite GF21	45.0	2.3	53.4	42.6	2.2	54.8	6.40	5.80	0.6
Soil on granite GF31	44.5	12.3	43.1	43.4	7.8	48.2	6.40	5.40	1.0
Alluv Soil GF41	42.6	16.2	40.2	40.2	18.8	40.1	6.30	5.30	1.0
Topo vert GF51	50.2	36.6	13.0	42.4	40.8	16.1	6.30	5.80	0.5
Alluv soil GF61	42.4	4.1	54.3	40.8	3.8	54.8	6.50	5.80	0.7

Soil type	Organic matter (%)				Exchangeable cations (meq/100g) (%)						
	OM	OC	NT	C/N	Ca^{2+}	Mg^{2+}	K^+	Na^+	S	CEC	S/T
Colluv soil GF11	9.25	5.36	0.18	29.7	12.88	0.56	0.23	0.09	13.76	19.20	**72**
Soil on granite	3.79	2.20	0.17	12.9	6.08	0.40	0.45	0.09	7.03	20.00	**35**
Soil on granite	6.61	3.83	0.12	31.9	13.05	0.60	0.53	0.09	14.27	18.20	**78**
Alluv soil GF41	5.37	3.12	0.13	24	15.68	0.80	0.68	0.09	17.25	19.80	**87**
Topo vert GF51	8.01	4.65	0.16	29	21.28	0.72	0.60	0.09	22.70	28.80	**79**
Alluv soil GF61	**1.85**	**1.07**	**0.16**	**6.7**	**11.60**	**1.04**	**0.23**	**0.09**	**12.96**	**35.20**	**37**

Colluvial soil: colluv soil, Alluvial soil: alluv soil, Topomorphic vertisol: topo vert, Soil on granite: brown soil formed on granite, OM: organic matter, OC: organic carbon, NT: total nitrogen.

Table 2. Erodibility indices of surface soil horizons.

Soil type	WDC (%)	TC (%)	CDR (%)	DR	CFI	CA	ESR	ESP
Colluv soil GF11	42.2	44.2	0.95	**1.02**	43.24	2.0	0.006	**0.47**
Soil on granite GF21	42.6	45.0	0.94	0 .95	44.05	2.4	**0.013**	**0.45**
Soil on granite GF31	**43.4**	44.5	**0.97**	**0.90**	43.52	1.1	0.006	**0.49**
Alluvial soil GF41	**40.2**	42.6	0.94	1.00	41.65	2.4	0.005	**0.45**
Topo vert GF51	42.4	**50.2**	**0.84**	0.96	**49.35**	**7.8**	**0.004**	**0.31**
Alluvial soil GF61	**40.8**	**42.4**	**0.96**	**0.95**	**41.34**	**1.6**	**0.007**	**0.25**

[16] and [19] show that soils with a high WDC value erode more easily than those with a low WDC value. It therefore appears that brown soils formed on

granite GF31 are more susceptible to erosion while alluvial soils are less susceptible to erosion. By applying this WDC method, the different soils studied can be classified according to their decreasing degree of erodibility: brown soil formed on granite < colluvial soil < topomorphic vertisol < alluvial soil.

The DR or degree of dispersion varies between 0.90 for brown soils formed on granite and 1.02 for colluvial soils (**Table 2**). Some authors [11] [13] [16] [19] have shown that the higher the DR value, the more the soil has the potential to erode. The DR values obtained indicate that colluvial soils have a higher rate of dispersion than brown soils formed on granite. Based on the DR values, the soils of Gadas Fouinsilé can be classified, ranging from soils with the greatest potential to erode to soils with the least potential to erode: colluvial soil < brown soil formed on granite < topomorphic vertisol < alluvial soil.

The Clay Dispersion Ratio (CDR) or clay dispersion rate has proportions between 0.84% for GF51 topomorphic vertisols and 0.97% for brown soils formed on GF31 granite (**Table 2**). According to [17], soils with a high CDR indicate severe dispersal, while those with low CDR reveal weak dispersal. It appears from the CDR values that the brown soils formed on granite are more dispersed while the topomorphic vertisols are less dispersed. Using the CDR values, we can classify the soils according to their degree of dispersion, we have the following order going from the most dispersed soils to the least dispersed soils: brown soil formed on granite < colluvial soil < alluvial soil < topomorphic vertisol.

The CA indicates the stability class of the soil. Soils that are richer in aggregates erode more slowly than soils that are poor in aggregates [16]. The aggregate clay rate for the different soils studied varies between 1.1 for brown soils formed on granite and 7.8 for topomorphic vertisols (**Table 2**). The studied soils have CA values between 1 and 8. As a result, topomorphic vertisols are more aggregated than all other soils. As a result, the topomorphic vertisols are the most stable and therefore the least vulnerable, and the alluvial soils and brown soils formed on granite are the most unstable and the most susceptible to erosion. At the end of this study, we find that alluvial soils and brown soils formed on granite are the most susceptible to erosion.

The flocculation index of clays varies from 41.34 for alluvial soil to 49.35 for topomorphic vertisol (**Table 2**).

The values of the exchangeable sodium rate or the Exchangeable Sodium Ratio (ESR) are generally moderate for all the soils studied. They range between 0.013 for brown soils formed on granite and 0.004 for topomorphic vertisols (**Table 2**).

The exchangeable sodium percentage (ESP) values are between 0.25 (alluvial soils) and 0.49 (brown soils formed on granite). ESP values are low for the GF61 profile [20].

In short, according to this toposequence (**Figure 4**), vertisols are more stable while brown soils formed on granite and alluvial soils are the most unstable and the most susceptible to erosion.

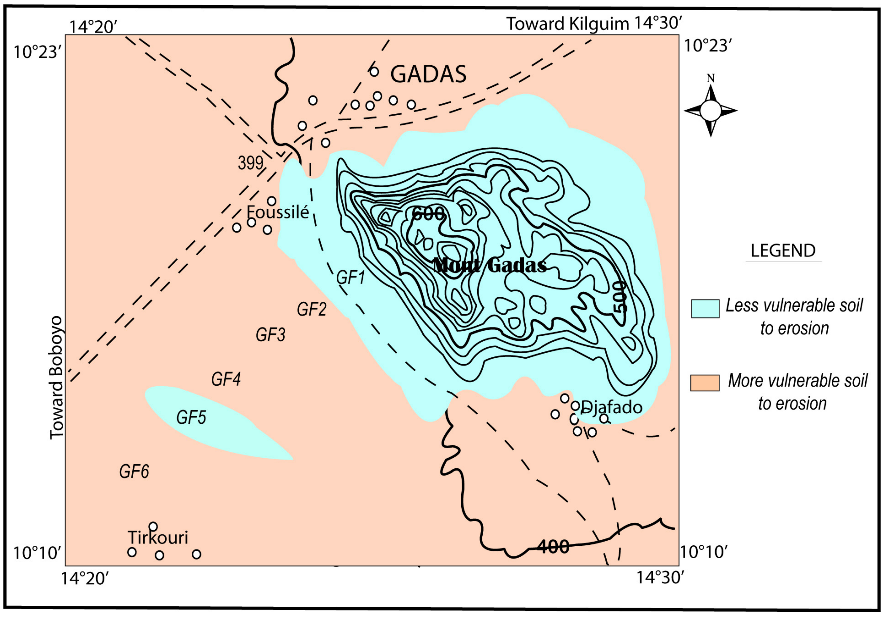

Figure 4. Gadas soil erodibility map.

5. Discussion and Test of Interpretation

5.1. Gadas Soil Morphology

In Gadas, there are five types of soils: lithosols, colluvial soils, alluvial soils, topomorphic vertisols, brown soils formed on granite. Lithosols are characterized by a dull color predominantly gray [9]. These soils are very gravelly and would be very sensitive to erosion. They were not analyzed in this study. The colluvial soils of Gadas are poorly structured, brown to dark brown, sandy, and have many quartz and feldspar gravels. They are in a piedmont situation and benefit from the supply of materials transported along the slopes [21]. Gadas vertisols are gray in color with a clayey to clayey-sandy texture. Indeed, it is recognized that the vertisols have a dark gray to black color and are clayey to clayey-sandy [22], the vertisols of our study area clearly present the characteristics of a vertisol. The vertisols of Gadas, located in the alluvial plain, are recognized by their shrinkage cracks and a prismatic macrostructure. According to [9] and [10], the prismatic macrostructure and the well-marked shrinkage cracks are the main morphological characteristics of these soils. Alluvial soils are recent deposits of valleys, they are located in the major bed of rivers [21]. They have a predominantly brown to pale brown, sandy color, they have a blocky structure and good permeability. The soils encountered are similar to those described by [1] [2] [9] [10].

5.2. Physico-Chemical Characteristics of the Soils of Gadas

The physico-chemical analysis focused on four types of soils, namely colluvial soils, topomorphic vertisols, alluvial soils and brown soils formed on granite. The colluvial soils found in Gadas are acidic to weakly acidic, sandy, poor in total nitrogen and have a low proportion of exchangeable bases and organic matter

(**Table 1**). According to [9] [21], colluvial soils are characterized by a variable grain size but always predominantly sandy (around 40% to 60%), the pH is weakly acidic and oscillates between 5.5 and 6.5, the organic matter is around 0.8% to 1.3%, the cation exchange capacity varies between 3 and 15 meq/100g of soil, but the saturation rate is high (between 60% and 90%). The colluvial soils encountered at Gadas present the same characteristics as those described by these authors.

The alluvial soils found in Gadas are neutral, sandy, rich in exchangeable bases and have an average organic matter content. In general, alluvial soils are characterized by a sandy to sandy-clayey texture (10% to 20% clay), the cation exchange capacity is between 8 and 12 meq/100, and is saturated between 60% and 80%, the pH is acidic (5.5 to 6.5), the organic matter content is average (1.1% to 1.6%) and the C/N ratio between 9 and 12 indicates good soil biological activity [9]. These characteristics are quite similar to those of the soils of Gadas. It is important to emphasize that basic cations (Ca^{2+}, Mg^{2+}, K^+) play a role in the study of the absorbing complex and in the phenomena of cation exchange [11]. They not only act as nutrients but play an essential role in neutralizing acidity, maintaining biological activity and structuring the soil.

According to [9] [22], topomorphic vertisols are characterized by a clayey to clayey-sandy texture, the pH is between 7 and 8 only surface samples can have a pH less than 7, the organic matter content is average (0.8% to 1.5%), the C/N ratio is between 10 and 14, the cation exchange capacity is always high (25 to 35 meq/100) and is more than 80% or even 100% saturated, calcareous nodules are generally present throughout the profile. These characteristics are quite similar to those of the vertisols of Gadas.

5.3. Erodibility Indices in Relation to the Physico-Chemical Characteristics of Soils

In the tropics, the destabilization of the primary minerals of the rocks usually results in a very schematic way, by the elimination of the basic cations and the partial or total evacuation of the silica. The excess non-leached silica, or on the contrary silica imported in solution, combines with the residual aluminum to neoform or transform secondary clay minerals [22].

The erodibility indices (total clay, rate of clay dispersed in water, rate of dispersion, clay aggregation and exchangeable Na^+) calculated can be related to the physico-chemical properties. Indeed, the soils most vulnerable to erosion (brown soils formed on granite and alluvial soils) show more or less low levels of organic matter. It is recognized that organic matter acts as a binder, it can hold together the clay particles subjected to the osmotic pressure induced by the absorbed sodium; it acts on the aggregation and structure of soils and can also make the surfaces of mineral particles hydrophobic; which has the effect of slowing down the wetting rate of the aggregates and therefore reducing the splitting process. In other words, organic matter can control the flocculation and deflocculation of clay particles [17] [18] [23] [24] [25] [26].

Thus, the high erodibility of the brown soils formed on granite and the alluvial soils of Gadas would be due to the low organic matter content; it would be insufficient to maintain the clay particles forming with the latter a stable clay humic complex. [17] showed that a low organic carbon content in the soil causes severe dispersion of clay in water, just as soils with a high proportion of organic carbon show a low dispersion in water. The results obtained show that the soils susceptible to erosion are alluvial soils and brown soils formed on granite, characterized by low organic carbon content; then the topomorphic vertisols less vulnerable to erosion have a high organic carbon content.

Sodium which is a monovalent cation is recognized as a dispersing agent and has the lowest proportion of all cations. Indeed, the presence of Na^+ in the soil causes the dispersion of clay particles. According to [16] [27] [28], the most erodible soils have the highest sodium proportions. The brown soils formed on granite, identified as the most susceptible to erosion, have the highest proportions of sodium. Furthermore, sodium, in oversaturation situations, could act as a flocculant with negative influences on soil structure [16]. The presence of Na^+ in large quantities causes the dispersion of clay particles from the brown soils formed on granite which are the most susceptible to erosion.

Calcium plays a major role in the physical behavior of the soil. Through its flocculating power vis-à-vis clays and its stabilizing role for humic compounds, it strongly contributes to the organization of the soil structure and to the stability of this structure [29]. Calcium serves as a binding cation between clay and humic precursors, thus contributing to the formation of the clay-humic soil complex [30].

6. Conclusions

The objectives of this study were to identify on the macromorphological level the main types of soils existing in the locality of Gadas, to characterize these soils on the physico-chemical levels and to evaluate the erodibility of these soils in relation to the physico-chemical properties. The macromorphological data made it possible to identify six types of soil: the lithosols which occupy the high zones of the landscape and therefore the profile is reduced to a humus horizon surmounting the granitic arena; colluvial soils which are located high on the foothills, sandy texture and comprising three horizons; alluvial soils which are the most extensive and deep, of sandy texture, and include four to eight horizons; the topomorphic vertisols which are located between two alluvial soils, of clayey to clayey-sandy texture and present five horizons having a genetic link between them and the brown soils formed on granite of clayey-sandy to sandy-clayey texture, located between the colluvial soil and alluvial soil.

The physico-chemical characterization of the soils of Gadas shows that: the colluvial soils are weakly acidic to neutral, sandy to sandy-clayey; the topomorphic vertisols are weakly acidic, clayey to clayey-sandy; alluvial soils are acid to neutral, sandy; the brown soils formed on granite are weakly acidic, sandy-clayey to sandy-clayey. All these soils are saturated to undersaturated, poor in nitrogen and organic matter and characterized by average proportions of exchangeable bases.

All the erodibility indices (WDC, CA, CDR and DR) used show that alluvial soils, brown soils formed on granite are the most susceptible to erosion while topomorphic vertisols are the least vulnerable.

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Conflicts of Interest

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

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