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Contribution of GIS to Soil Landscape Mapping by Multi-Criteria Analysis Using Weighting: The Case of the Square Degrees of M'Bahiakro (Centre) and Daloa (Centre-West) in Ivory Coast

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Abstract

As part of the drive to improve coffee and cocoa production in Ivory Coast, studies are carried out to identify soils that are favourable for these crops. It is therefore necessary to orientate soil investigations based on reliable criteria that best discriminate soil cover. With this in mind, this study is being carried out to help improve survey methods by mapping soil landscapes. It uses GIS and weighted multicriteria analysis. To do this, satellite images were processed and the geological map of the square degrees of M'Bahiakro and Daloa was reclassified. The results show that relief is the main factor in soil landscape differentiation, with respective weights of 0.58 and 0.67 for the forest and pre-forest zones. In contrast, the weight of geological formation in soil landscape differentiation remains low (0.05 for the forest zone and 0.07 for the pre-forest zone). The criteria used on the base of aggregation sum methods have made it possible to formulate soil landscape mapping prediction functions according to agro-ecological environments in the humid intertropical zone. This is essential for the orientation of soil survey work. Nevertheless, other comparative methods, such as the coding mapping method, could provide elements for discussion to validate the models.

Keywords

GIS, Multi-Criteria Analysis, Soil Landscapes, M'Bahiakro, Daloa, Ivory Coast

1. Introduction

Despite major efforts to diversify, Ivory Coast's economy is still heavily dependent on coffee and cocoa. Unfortunately, the sustainability of these two crops and the level of exports are compromised by the ageing of the orchards, accentuated by the combined action of biotic, climatic and soil hazards, which considerably reduce the economic lifespan of the orchards. This situation is leading farmers to abandon degraded and/or unproductive plantations in favour of new plantations on other forest clearings in order to stabilise production levels. Soil is therefore essential to the success of farming activities and must be used sustainably [1]. Several studies of Ivorian soils have been carried out [2] [3] [4] [5]. Sectoral studies have also been carried out in the context of agricultural development by institutes such as the National Agricultural Research Centre (CNRA) and the National Bureau for Technical Studies and Development (BNETD). In this agricultural context, soil mapping is a method of inventorying natural resources [6] and always begins by using available documents that can provide information on the climate, vegetation, geology, hydrographic network and land use. After a documentation phase, the soil scientist undertakes a field survey. Before the 1970s, these surveys were carried out in the traditional way (boreholes, profiles) and were based on the layout of parallel and/or perpendicular tracks [7]. However, the analyses highlight numerous shortcomings and constraints that will pose serious threats to the sustainability of these two major pillars of the national economy. Local knowledge of soil resources is a need that must be better met.

Over the past few decades, the coffee and cocoa sector has contributed to funding coffee and cocoa research in Côte d'Ivoire through its "2QC" programme, which aims to improve productivity (Quantity = Q), quality (Quality = Q) and incomes, leading to the generation of wealth (Growth = C), as part of the FIRCA/Plan Contract/Technology Generation—2QC project piloted by the CNRA. The ultimate aim of the research carried out is to develop regionally adapted technical itineraries. To achieve this, it is necessary to improve coffee and cocoa production processes. To this end, the identification of suitable soils by agroclimatic zone in the production regions would be an undeniable area of research. This will involve soil surveys in production areas, according to their distribution on the square degree maps of Côte d'Ivoire, in particular the forest and pre-forest regions.

Given the importance of soils for agricultural populations and the need to quantify them accurately, soil survey methods are increasingly incorporating digital tools [8]. The new (digital) methods use image processing techniques and combinations of readily available data. Digital soil mapping consists of predicting soil classes or soil properties using, on the one hand, the soil data available on the area to be studied and, on the other hand, spatial data representing landscape features in relation (causally or otherwise) with the soil [9]. In order to give an account of the three dimensional coverage of the soil, the soil mapmaker has patiently specified the different possible levels of representation of his object [10]. Four (04) major structuring levels are currently in force: horizons, soil typology units, soil mapping units and soil landscape units. The results of semi-automated processes for the delineation of soil mapping units and soil landscape units are viewed as "pre-zonings", intended to guide the soil scientist in his fieldwork and sampling strategy [10].

The overall aim of this study is to help improve soil survey tools by identifying soil landscape units. The cartographic divisions concerned by this study are located in pre-forest zones (M'Bahiakro square degree) and forest zones (Daloa square degree). The approach used consists of setting up Geographic Information Systems (GIS) based on multi-criteria analyses to identify soil landscapes using the weighting method.

2. Materials and Methods

2.1. Study Area

The study area covers two square degrees (Daloa and M'Bahiakro) according to the cartographic division of Ivory Coast (**Figure 1(A)** and **Figure 1(B)**).

The M'Bahiakro square degree is located in central-eastern Côte d'Ivoire, between 7˚ and 8˚ north latitude and 5˚ and 4˚ west longitude, and covers around 12,000 km^2. It has a humid tropical climate (of the Baoulean type) with a marked dry season and light winds [11]. The topography is generally flat, with a maximum altitude of 200 m. The temperature in the study area fluctuates between 14˚C and 33˚C, with humidity varying between 40% and 70% [12]. The geology of the area is a complex of igneous, metamorphic and volcano-sedimentary rocks [13]. The flora is dominated in the pre-forest zone by shrubs interspersed with groves and patches of forest. The Daloa square degree, with a surface area of around 12,000 km^2, is located in central-western Ivory Coast between 6˚ and 7˚ north latitude and 6˚ and 7˚ west longitude. The topography is characterised by a drop in altitude (from 200 to 300 m) in a NE-SW direction, with rounded or tabular interfluves. The plains and low plateaux dominate the landscape, with a tropical climate and an average temperature of 25.6˚C. Average rainfall is 1317 mm/year [14], with average monthly temperatures fluctuating between 24˚C and 28˚C. The geological substratum of the Daloa square degree is characterised by Middle Precambrian formations, dominated by granitic, migmatitic and schistose rocks.

2.2. Data Used

The data used in this study includes satellite images (Landsat OLI 8 and SRTM)

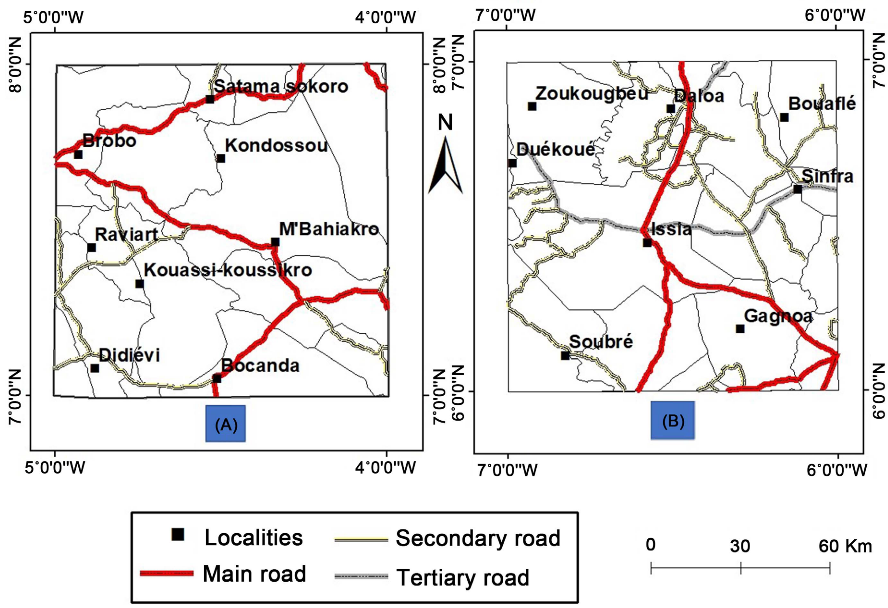

Figure 1. Presentation of the square degrees of M'Bahiakro (A) and Daloa (B) according to the square degree map of Côte d'Ivoire.

and geological maps of the areas concerned. The Landsat images were used to map land use, while the SRTM images were used to map slopes and altitudes. Geological maps were used to understand the geological formations of the areas studied. It should be noted that radiometric and atmospheric processing were used to enhance the quality of the Landsat images.

2.3. Study Methods

The methodology adopted in this study is based on multi-criteria analysis methods for drawing up soil landscape maps. The soil landscape unit is described as a pattern of spatial organisation of several soil typological units (**Figure 2**), themselves defined by one or more representative profiles [10].

2.3.1. Identification of Criteria

According to [15], the identification of criteria is a decisive and delicate phase which conditions the quality of the information generated for decision-making. Thus, with reference to the work of [16] [17], a number of criteria are identified, selected and evaluated in order to define soil landscapes. The hypothesis underlying the choice of data is that there is a close relationship between the distribution of soils and the physiognomy of the land. This physiognomy is expressed in terms of original material (deposition mode, thickness, granulometry, mineralogy, stratigraphy, etc.), topographical models, slopes, water regimes, exposure and land use. Soil landscapes (relatively homogeneous areas in terms of soil content, taking into account the morphology of the land, geological formations and soil cover) were delineated by combining several pseudo-images derived from the processing of satellite images and the geological map.

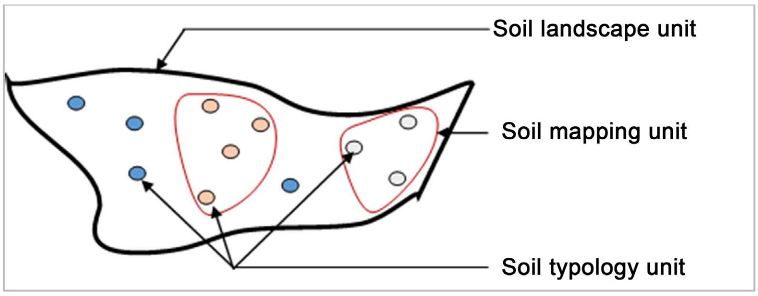

Figure 2. Different levels of interlocking soil cover.

The main factors taken into account in modelling the soil landscape maps of the areas studied are: 1) land use, 2) slopes, 3) elevation and 4) geological formations.

2.3.2. Criteria Classification and Standardisation

The aim of these methods is to determine the level of influence of each of the criteria on the soil landscape. Classification consists of combining the values of each criteria into a number of classes (ranks). The boundaries chosen for these classes are not necessarily equidistant, but depend on the objectives set and the general context of the study [18] [19]. These limits are set according to the data available and are not fixed. Therefore, whether the impact is significant or not, this degree of impact must be classified according to the relative importance and contribution made by this particular criteria, with a view to achieving the objective set. In this work, several subclasses were identified based on the data available to us. These criteria were classified according to a rank and in several subclasses according to a code going from 0 to 10. As for the standardisations of the various criteria, they are expressed in different units and for a good multi-criteria analysis, standardisation is necessary. A common range of 1 to 10 is used for this operation. A score of 10 is assigned to the "very weak" or "very strong" classes, based on whether they contribute to the excellent achievement of the indicator in question. In the contrary case, a score of 1 is assigned to these classes. Following the same logic, intermediate values are assigned to intermediate classes according to a linear distribution. A number of criteria are used to develop each indicator (**Table 1** and **Table 2**).

2.3.3. Drawing up the Comparison Matrix

A matrix of pairs of comparisons for each criterion is drawn up, taking into account their importance in the creation of the map. Scores are allocated to the decision criteria according to their degree of importance. When one factor is more important than others are, the first factor is given a score of between 3 and 9, depending on its importance. In the contrary case, it is given a score of between 1/3 and 1/9 (*i.e.* the inverse of the first score). The sum of the weighting coefficients developed by Saaty is equal to 1. The advantage of Saaty's method lies in its ability to verify the coherence of the judgement made when comparing more than two criteria, thanks to the coherence index it calculates. Thus, a reasoning

Table 1. Reclassification of soil landscape criteria by weighting (M'Bahiakro).

Criteria	Rank	Code	Subclasses	Value
Geology	1	10	Acid rock	-
	2	4	Mafic rock	-
Altitude	1	10	Valley	95 - 177 m
	2	8	Watershed	177 - 254 m
	3	5	Middle slope	254 - 374 m
	4	1	Summit	374 - 467 m
Solpe	1	10	Low	0% - 5%
	2	8	Medium	5% - 10%
	3	5	High	10% - 15%
	4	1	Very high	>15%
Land use	1	10	Degraded forest-forest	-
	2	8	Crop/fallow	-
	3	5	Savannah	-
	4	3	Habitat/bare soil	-
	5	1	Water	-

Table 2. Reclassification of soil landscape criteria by weighting (Daloa).

Criteria	Rank	Code	Subclasses	Value
Geology	1	10	Mafic rock	-
	2	8	Sedimentary rock	-
	3	5	Intermediate rock	-
	4	11	Acid rock	-
Altitude	1	10	Valley	146 - 200 m
	2	8	Watershed	200 - 250 m
	3	5	Middle slope	250 - 300 m
	4	11	Summit/Platform	300 - 393 m
Slope	1	10	Low	0% - 5%
	2	5	Medium	5% - 10%
	3	3	High	10% - 15%
	4	11	Very high	>15%
Land use	1	10	Degraded forest	-
	2	8	Crop/fallow	-
	3	5	Savannah	-
	4	3	Habitat/bare soil	-
	5	11	Water	-

is said to be coherent when its coherence index remains less than or equal to 10% [19].

Using the matrix generated by the pairwise comparison of values, eigenvectors are obtained by calculating their geometric mean per line according to Equation (1).

$$Vp = \sqrt[n]{\prod_{i}^{n} gi} \quad (1)$$

Vp: eigenvector; *n*: number of criteria; *gi*: score for criteria *i* and *i* indicates the note criteria for geology, relief or land use.

Table 3 shows the qualitative and numerical expressions of the comparative weight of a factor according to El morjani (2002) [20].

Lastly, pairwise comparison matrices were established for M'Bahiakro (**Table 4**) and Daloa (**Table 5**) in order to compare the most critical parameters for soil landscape identification.

2.3.4. Aggregation of Criteria

Several aggregation methods exist. However, we have chosen the method of complete aggregation by weighting used by some authors as Jourda (2005), El morjani (2002) and Saley (2003) [18] [21] [22]. This method consists of summing the standardised and weighted values of each criteria involved in the development of the specific indicator [22]. It can be summarised by Equation (2) below:

$$S = Wi \times Xi \quad (2)$$

with S: the result, *Wi*: weight of criteria *i*, *Xi*: standardised value of criteria *i* and *i* indicates the criteria for geology, relief or land use.

3. Result

3.1. Spatial Distribution and Analysis of Major Factors Taken into Account in Modelling

3.1.1. Geology Mapping

The first factor considered for soil landscape mapping using weighted multicriteria analysis is geology (**Figure 3**).

The geological map (reclassified from the map of geological units) highlights four types of geological formation: acid, mafic, sedimentary and intermediate rocks. Groups of "sedimentary or schistose rocks with mineral fragments, shell fragments", with poorly identified properties due to the accumulation of materials from which they are derived, are classified as intermediate. Sedimentary and intermediate formations occupy 31.60% and 7.8% of the square degree of Daloa respectively, but are not present in M'Bahiakro.

The mafic rocks consist of basic to intermediate volcanic rocks and pegmatite gabbro. They are more common in Daloa (55.4%) than in M'Bahiakro (24.4%). Acidic rocks cover almost the entire area of M'Bahiakro (75.6%) and are very poorly represented in Daloa (5.2%).

Table 3. Qualitative and numerical expression of the comparative weight of a factor.

Expression of one criteria in relation to another	Note
Same importance	1
Moderately important	3
Highly important	5
Very important	7
Extremely important	9
Moderately less important	1/3
Less important	1/5
Significantly less important	1/7
Extremely less important	1/9

Table 4. Pairwise comparison matrix (M'Bahiakro square degree).

Criteria	Geology	Slope	Altitude	Land use
Geology	1	1/3	1/7	1/3
Altitude	7	5	1	3
Slope	3	1	1/7	3
Land use	3	1/3	1/3	1

Table 5. Pairwise comparison matrix (Daloa square degree).

Criteria	Géologie	Altitude	Pente	Os
Geology	1	1/3	1	1/7
Altitude	7	1	9	7
Slope	1	1/9	1	1/7
Land use	7	1/7	7	1

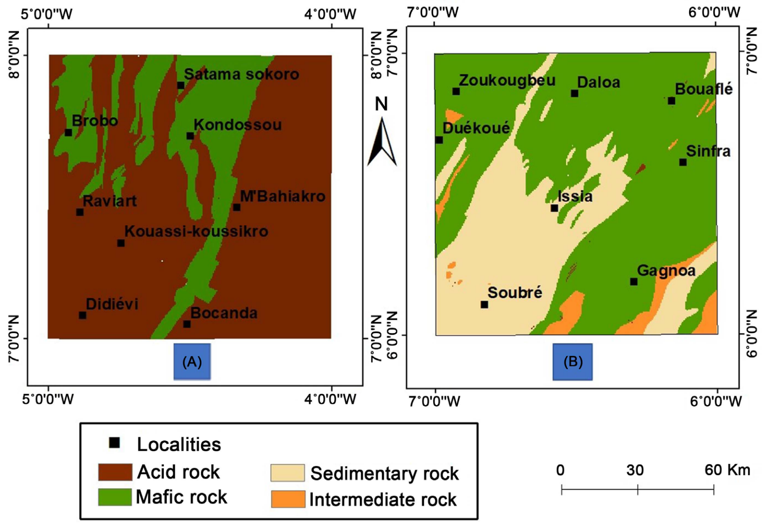

Figure 3. Geological cover of the square degrees of M'Bahiakro (A) and Daloa (B).

3.1.2. Topography Mapping

The second factor considered for soil landscape mapping using weighted multi-criteria analysis is land elevation (Figure 4).

In the areas studied, variations in altitudes are dependent on the landform. The relief (M'Bahiakro and Daloa) is made up of vast, monotonous peneplains with little unevenness throughout the study areas. Altitude varies between 50 and 649 metres. The valleys are moderately abundant in the M'Bahiakro areas and marked by low altitudes that extend to the Centre with altitudes of between 95 m and 200 m. The lower slopes cover almost all of the two zones studied, with relatively average altitudes of 177 metres to 250 metres. On the other hand, altitudes are high in the mid-slopes (between 250 metres and 300 metres). They are concentrated to the north and north-east of the square degrees. Finally, the plateaux are very poorly represented, with altitudes ranging from 300 metres to 467 metres.

3.1.3. Slope Mapping

The third factor considered for soil landscape mapping using weighted multicriteria analysis is slope (Figure 5).

The two square degrees covered by the study are dominated by gentle slopes (0% - 5%). Medium slopes (5% - 10%) are more noticeable in the M'Bahiakro square degree. However, they are more pronounced to the south and east of this square degree. The class of steep slopes (10% - 15%) is poorly represented in all the study areas, while the class of very steep slopes (>15%) is only found in places in the landscape, concentrated in part in the south and centre of the territories.

3.1.4. Land Use Mapping

The last factor considered for soil landscape mapping using weighted multicriteria analysis is land use (Figure 6).

Figure 6 shows the land cover maps in five (5) classes. Savannah and degraded forest dominate all zones, with proportions of over 50%. They are more concentrated in the south and south-east. In addition, the total square degree is moderately covered by cultivated areas in the North and Centre, with more than 20% of the surface area under cultivation. Bare ground and habitats cover only 4.86% of the area, compared with 1.36% covered by water.

3.2. Mapping of Soil Landscapes by Weighting

In this study, the coherence index (CI) of the pairwise comparison matrices calculated is equal to 0.067 and 0.093. Since these values are less than 10%, the matrices are coherent. Consequently, the weighting coefficients obtained can be used as weights for drawing up the weighting maps (Table 6 and Table 7).

The sum of the weighted values (Geology + Altitude + Slope + OS) of each criteria involved in the development of the soil landscapes has resulted in the maps below (Figure 7 and Figure 8).

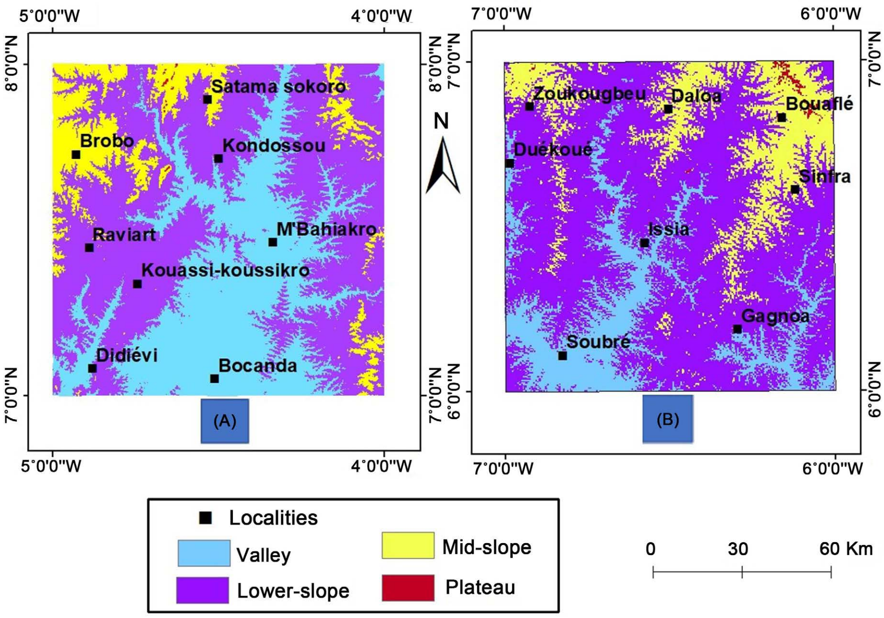

Figure 4. Reliefs of the square degrees of M'Bahiakro (A) and Daloa (B).

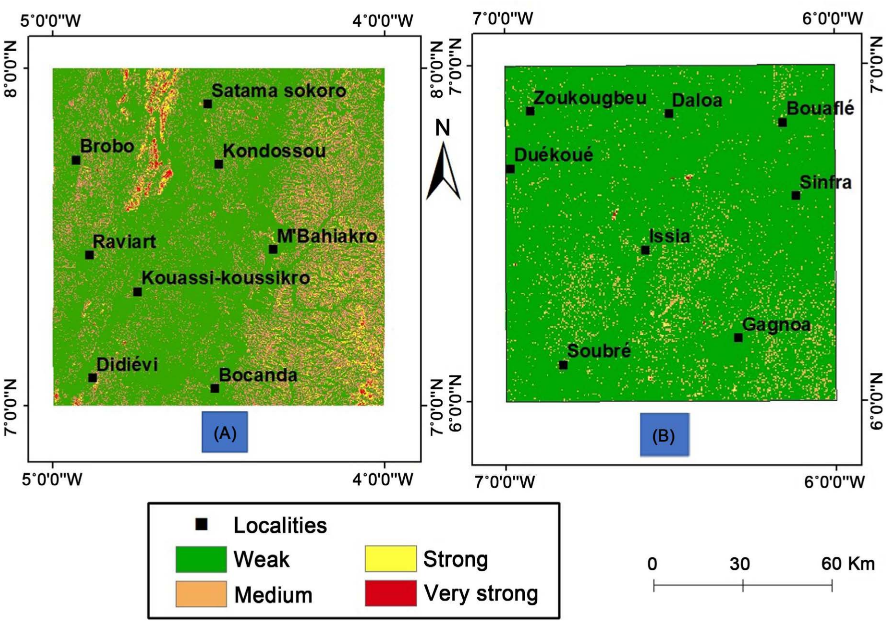

Figure 5. Obliquity of square degrees of M'Bahiakro (A) and Daloa (B).

Figure 7 and Figure 8 show the spatial distributions of the soil landscapes developed using the weighting method. Each map shows five soil landscapes on either side of the square degrees. In the M'Bahiakro square degree, there is a predominance of acid rock (94.94%) on a moderate relief under savannah and fallow crops. However, the Daloa square degree has a high proportion of mafic rock (84.27%) on a moderate relief under degraded forest, crops and fallow land.

The criteria aggregation sum method can therefore be used to establish a prediction function for mapping soil landscapes according to the agro-ecological

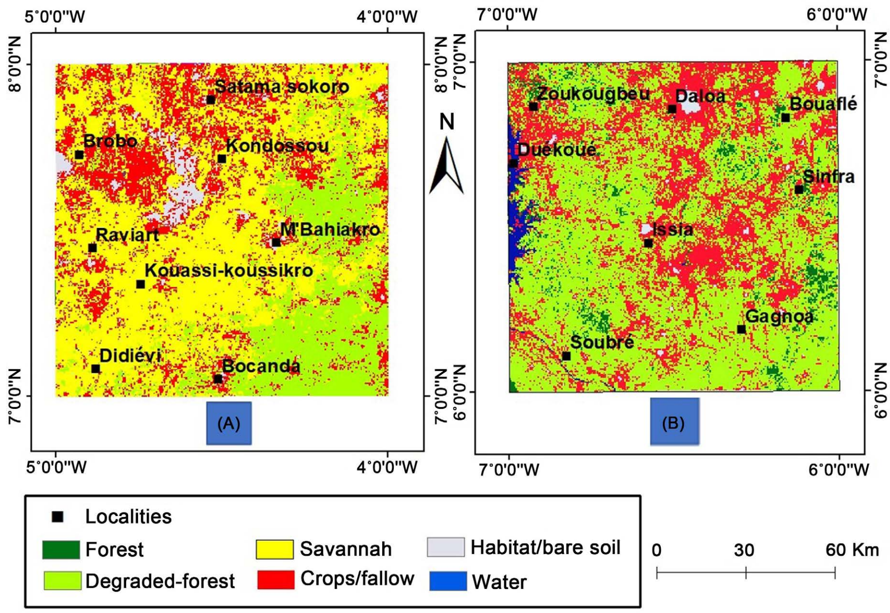

Figure 6. Land use of square degrees of M'Bahiakro (A) et de Daloa (B).

Table 6. Weighting coefficients (Degré carré M'Bahiakro).

Criteria	Geology	Slope	Altitude	Land use	Vp	Cp
Geology	1	1/3	1/7	1/3	0.354	0.07
Slope	3	1	1/7	3	1.158	0.21
Altitude	7	5	1	3	3.201	0.58
Land use	3	1/3	1/3	1	0.759	0.14
	IC = 0.093				**5.472**	**1**

Table 7. Weighting coefficients (Degré carré M'Bahiakro).

Criteria	Geology	Slope	Altitude	Land use	Vp	Cp
Geology	1	1/3	1	1/7	0.37	0.05
Slope	7	1	9	7	4.58	0.67
Altitude	1	1/9	1	1/7	0.35	0.05
Land use	7	1/7	7	1	1.62	0.23
	IC = 0.067				**6.92**	**1**

Vp = eigenvalue; Cp = weighting coefficient; Ic = coherence index.

environment in the humid intertropical zone. In the forest zone, this function is equal to:

$$S = 0.58R + 0.21S + 0.14L + 0.07G + \varepsilon \quad (3)$$

In pre-forest zones, it can be written as follows:

$$S = 0.67R + 0.23L + 0.05S + 0.05G + \varepsilon \quad (4)$$

S = Soil landscape, R = Relief, S = Slop, L = Land use, G = Géology and ε = estimated errors (kappa index, geological map digitization scale, etc.)

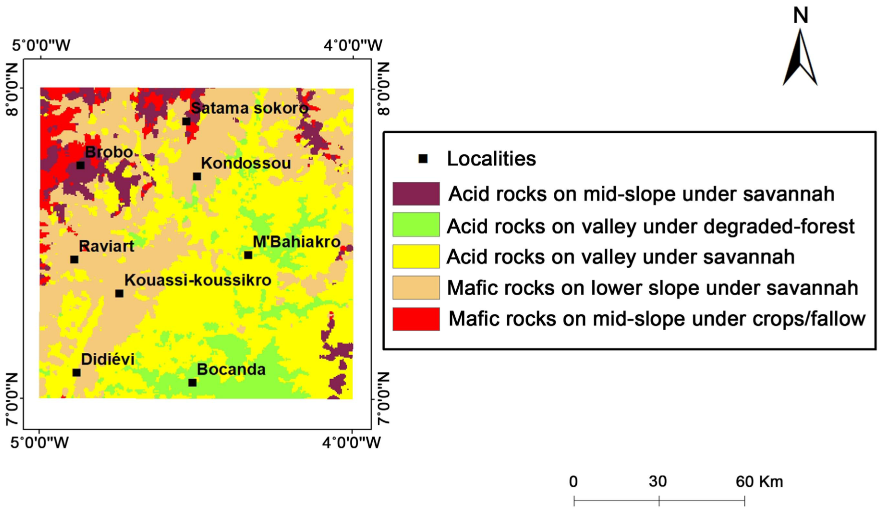

Figure 7. Soil landscape map of the M'Bahiakro square degree.

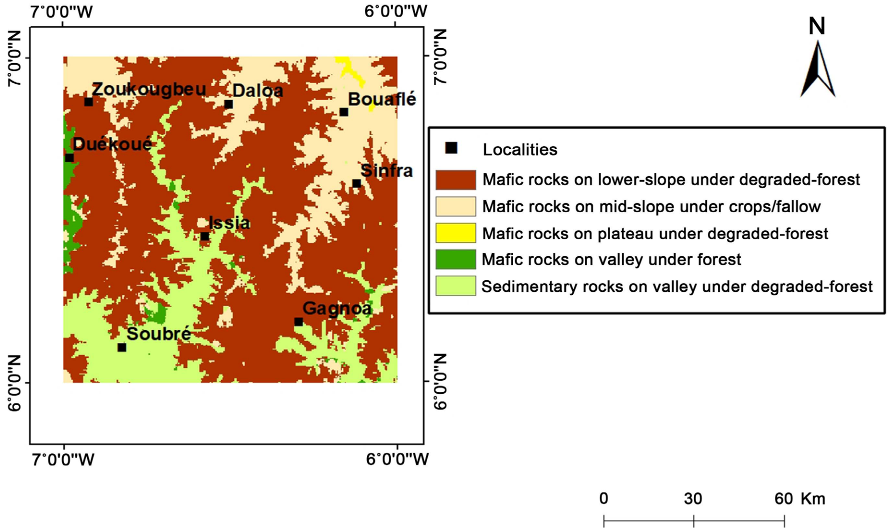

Figure 8. Soil landscape map of the Daloa square degree.

4. Discussion

4.1. Discriminating Factors in Soil Identification at Local Level

Using GIS methods and weighting by multi-criteria analysis, this study highlighted the soil landscape units in the study area. The rationale behind the choice of input data is that, on a local scale, the most decisive factors in soil differentiation are geology, terrain morphology (relief, slope and altitude) and land use. The results obtained from the judgment matrices show that relief is the criteria that contributes most to soil landscape modelling. In the Daloa square degree, relief is the most discriminating factor with a weight of 0.58, followed by slope (0.21), land use (0.14) and geology (0.07). However, the M'Bahiakro area has a relief weighting of 0.67 and a land use weighting of 0.23. Slope and geology have the same weight of 0.05. This method is in agreement with that of [23] who used these four soil landscape criteria in the digitisation of medium-scale soil surveys in France. The influence of geology on soil genesis has long been demonstrated [24] [25]. The authors conclude that a pedological study resulting from the alteration of rocks presents great difficulties due to their heterogeneity, which is responsible for the variation in facies. Discussing the factors that differentiate soils, [1] stated that five (5) main groups of factors were responsible for the existence of very different soils on the earth's surface. Three (3) of these (notably the parent material, the period of weathering and the successive climate or climates) are strictly independent of each other. The other groups of factors are linked to the previous ones, in particular topography (which depends on climate, rock and duration) and all the biological factors, whose relationships with the other factors are particularly complex. As the study area is subject to a transitional sub-equatorial climate [26] and soil evolution is a process that can be measured over a relatively long time scale [27], the most decisive factor of the three main groups of factors mentioned above is geology. According to the schematic definitions of pedogenetic processes [28], the mineralogical constituents of rocks, in particular silica and iron, are involved in the processes of soil laterisation or ferruginisation. However, the low weight of geology in the definition of soil landscapes can be explained by the strong influence of the intertropical climate, characterised by high heat and abundant rainfall [26]. According to [29], the presence of soil types is not exclusive to a geological structure because of the intertropical climate, which is responsible for pedogenetic processes that cause soils to evolve from an azon-al character to an analogous character. The relief, morphology of the terrain and types of land use therefore remain essential in the conduct of soil survey activities.

4.2. Towards the Formalisation of Pedological Expertise

The various combinations of thematic maps were used to map the soil landscapes of the different square degrees studied using the weighting method based on multi-criteria analyses. The conceptual equations for mapping soil landscapes in forest and pre-forest areas are respectively $S = 0.58R + 0.21S + 0.14L + 0.07G + \varepsilon$ and $S = 0.67R + 0.23L + 0.05S + 0.05G + \varepsilon$ (S = soil landscape unit, R = relief, S = slope; L = land use, G = Geology and ε = error estimate). The basic principle was the same as that used by [30]. This principle considers soil cover to be the result of the interaction of several environmental factors such as geology, relief and land use. The methods derived from this principle are based on statistical algorithms that make it possible to detect the soil distribution laws implicitly used by the soil cartographer on the basis of the available data and to quantify them on the basis of soil differentiation factors represented in numerical form. Extrapolation of the model to unmapped areas enables soil distribution to be predicted [31]. To this end, a number of multicriteria analysis computer models for soil definition have been developed. The most famous remains the SCORPAN model (S = soil, C = climate, O = living beings, R = relief, P = bed rock, A = time and N = location) [9]. The conceptual equation is written s = f(s, c, o, r, p, a, n) + ξ (ξ = error estimation) and partly takes up Jenny's (1941) so-called CLORPT concept: Soil = f(CLimate, Organisms, Relief, Parent material, Time). The results obtained in this way support the work carried out subsequently by [9] by integrating the parameter "n" into the equation (where n = forest and pre-forest zone in the humid intertropical environment). In this way, the soil landscape mapping method using weighting by multi-criteria analysis is likely to result in savings due to the reduction in field surveys, the extent of which depends on the data available and the degree of uncertainty accepted. The advantages of this mapping are the objectivity of the pedostatistical method, the relative simplicity of implementation, and the speed and reproducibility of the method. However, there are disadvantages in terms of obtaining relevant and reliable covariates and the difficulty of validating model predictions. As stipulated in [32], digital soil mapping is not sufficient on its own; it must be integrated into a complete harmonisation method in which it is essential to involve expert soil scientists and cartographers.

5. Conclusion

This study, using GIS and weighting methods based on multi-criteria analysis, made it possible to map the soil landscapes of the square degrees of M'Bahiakro (pre-forest zone) and Dalao (forest zone). These analyses show that relief is the main factors differentiating soil landscapes, with weights of 0.58 and 0.67 for the forest and pre-forest zones respectively. After relief, slopes (in the forest zone) and land use types (in the pre-forest zone) were the next most important factors in discriminating soil landscapes, with weights of 0.21 and 0.23 respectively. Contrary to this, the weight of geological structure in the differentiation of soil landscapes remains low. The criteria of geology, slope, altitude and land use used on the base of sum-of-aggregations methods have made it possible to formulate prediction functions for mapping soil landscapes according to agroecological environments in the humid intertropical zone. Other comparative methods, such as the codification mapping method, could provide elements for discussion with a view to validating the models. Nevertheless, the results obtained should guide soil investigations according to the soil landscapes identified.

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Conflicts of Interest

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

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