New Approach for the Evaluation of Carbon Sequestration Capacity: Case of Closed Plant Formations and Gallery Forests

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Abstract. Many techniques for the assessment of Carbone sequestration are developed for classic forests. But less researchers are interested in the evaluation of the Carbone sequestration capacity of marginal forests. In this paper, we propose an innovative technique of evaluating the capacity of Carbon sequestration of marginal forests, based on a new allometric equation and a new technique of colored and multiband image classification.

Based on a series of 151 plots identified and characterized in 15 training representative sites, we identify the various species present on the site of study and we customize the Brown allometric equation. The obtained equation is successfully used to assess the capacity of Carbone sequestration of marginal forests in Adamawa Cameroon. Finally, we obtain that the gallery forests of Mayo Paro sequestered 194.22 t/ha while closed plant formations of Vina sequestered 108.85 t/ha. These results are validated through a verification mission on the site of study.

Keywords: Colored image classification · Vina closed plant formations · Gallery forest · Allometric equation · Carbone sequestration · Marginal forest

1 Introduction

The increase in greenhouse gases (GHGs) concentration in the atmosphere, mainly carbon dioxide (CO2) and methane (CH4), is recognized as one of the causes of current climate change. This increase in GHGs in the atmosphere is, nowadays, one of the most studied issues. Thus, a great scientific interest has developed around forests with their ability to sequester carbon in their biomass via photosynthesis. This stored carbon is lost and abandoned in the nature when the forest is destroyed and combusted, inducing the increase of the proportion of this chemical element in the atmosphere. According to [1] and [2], CO2 emissions from land-use change is the second leading cause of increased atmospheric CO2 concentration, after emissions from fossil fuel combustion.

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In Cameroon, forests cover 41.3% of the national territory and represent 10% of Congo watershed forests [3]. According to [4], greenhouse gas emissions in Cameroon in 1994 were estimated at 43 988 Gg of CO2, equivalent with 50.44%, 37.83% and 7.36% caused respectively by land use change, agriculture and energy.

In order to limit the increase of CO2 in the atmosphere, strategies such as the Clean Development Mechanism (CDM) and REDD have been developed to reduce GHG emissions such as methane and CO2. The REDD mechanism, introduced at the Bali Conference in 2007, is to compensate developing countries that reduce deforestation and forest degradation over a period of time. In order to benefit from the financial or technological revenues linked to these mechanisms, it is essential, if not imperative, to know the amount of carbon stored in forests. However, few data on biomass or carbon stock in sub-Saharan Africa, notably in Cameroon, are available to date and most of the studies that have been conducted there have been conducted in the dense forests of greater South-Cameroon, part of the Congo watershed [5–7]. The state of the literature on the issue in the Sudano-Guinean savannahs of Adamawa reveals a need for knowledge on the quantification of the carbon stock in this ecosystem and mainly on closed plant formations. The studies carried out by [8] and [9] constitute reference frames in the Sudano-Guinean savannahs of Adamawa. To evaluate the carbon stock in the ecosystem, the authors used the classical allometric equation [10] as if the site of study were in the dense forest of Congo watershed.

In this study, based on the spatialization and quantification of Gallery forests and closed plant formations, we propose a new methodology of sequestered hypogeous carbon stock evaluation. The proposed approach, thank to an inventory of various species present in the site of study, customizes the classical allometric equation for sequestered carbon estimation and describes an accurate methodology of carbon stock evaluation, based on a new technique of colored image classification, adapted for marginal forests.

The remaining paper is organized as follows: we first present, in the next section, the site of study, then in the 3rd section, we present the materials, data and methods. In the 4 section before the conclusion, we present and discuss some relevant results obtained.

2 Site of Study

The site of study is located in the Cameroonian Adamawa region (Fig. 1), between 12° and 15° East Longitude and between 6° and 8° North Latitude. The Mayo Paro watershed is located in the district of Tignère, the capital of the Division of Faro-et-Déo, Adamawa Region. It is located between latitudes 6°60′ and 7°24′ North and longitudes 12°30′ and 12°42′ East. Limited in the West by the Galim-Tignère sub-division, it shares its northern borders with the Mayo Lolti watershed, in the South with the Mayo Poutghou watershed and in the East with the Mayo Tignère watershed. The catchment area covers an area of approximately 56 118.7134 ha, occupied by 12 villages: Loungtoung, Walkossam, Mayo-Toloré, Laura, Sadeck, Mayo rounkongo 1 and 2, Paro lewel 1 and 2, Gassanguel, Carrefour Galim, and Paro Ndjidda. The climate is equilibrated by a rainy season and a dry season. The temperature varies from 12^{o} to 34^{o}. The main activity in the study site is breeding.

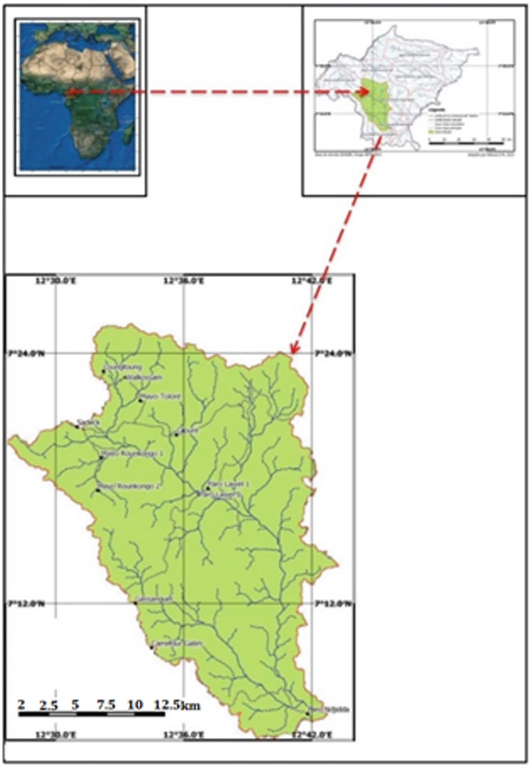

Fig. 1. Localization of the site of study.

3 Materials, Data and Methods

3.1 Materials and Data

To carry out the inventory, we used: a GPS (Global Positioning System) terminal for the acquisition of geographic coordinates of eligible trees in selected plots; a tape measure to measure the circumference of individuals (eligible trees); a digital camera for taking pictures of trees to determine their height; inventory sheets to copy auxiliary data; machetes to facilitate progression in the forest and to bark trees and a meter board to calibrate the height of individuals for the height evaluation process.

As data, we used Landsat images taken on May 2014, with 30 m spatial resolution, for the extraction of information related to the areas of the closed plant formations of the site of study. We also used Google EarthView images to locate the site of study.

3.2 Methods

Following is the flowchart of the proposed approach (Fig. 2).

3.2.1 Preliminary Work

The preliminary work consists of the first five actions of the flowchart.

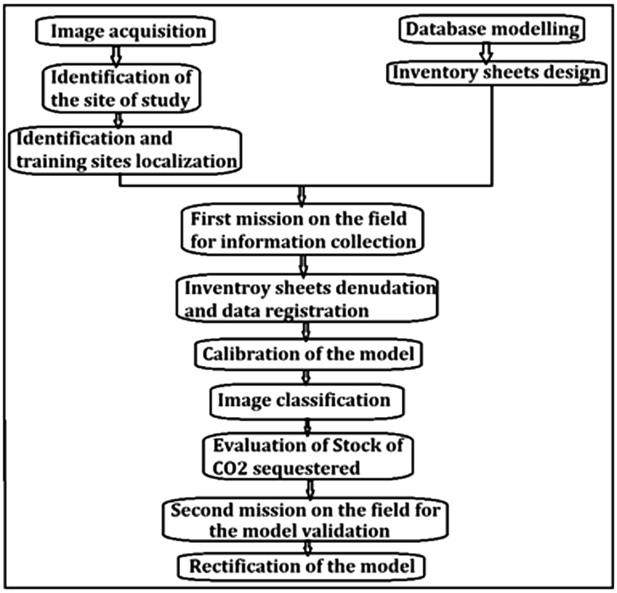

Fig. 2. The flowchart of the proposed approach.

From the laboratory, on the one hand, the conceptual model of data is built and the relational model is derived for the inventory sheets building. On the other hand, from the Landsat image acquired, the site of study is identified and extracted. From the site of study, the various training sites are localized and their geographical coordinates extracted.

3.2.2 Field Missions

Once the preliminary work is done in the laboratory, the first mission is organized on the field. Within this first mission; in the first site of study (closed plant formations), 90 plots of 400 m^2 each are carried out in 09 representative sampling sites. In the second site of study, 61 plots of 400 m^2 each are carried out in 6 sampling sites. The sampling sites were chosen accordingly to the accessibility and representativeness of the plant formation.

The floristic inventory consisted of identifying and characterising, for each plot, all trees of at least 31.5 cm circumference and at least 5 m height within the plot. Individuals that did not meet these criteria were simply identified and registered in the database, without being menstruated. On each of the individuals fulfilling the above conditions, the determination of scientific names was done *in situ*, thanks to the "Ligneux du sahel" [11] book. For unidentified species, specimens were collected for identification at the Cameroon National Herbarium. The circumference was measured in order to deduce the Diameter at Breast Height (DBH). In the forest, some trees had foothills at 1.30 m (DBH). For this category, we measured the circumference beyond the buttress as suggested in [12]. To determine the height of the trees, we used the photograph of the tree calibrated with a meter board, and we determined the height thanks to the software "Mesurim" [13].

3.2.3 Determination of Biomass and Carbon

In order to determine the amount of carbon stored at the individual level and considering the diversity of species, the use of allometric equations for each species would be ideal because of the diversity of forms [14]. But considering this diversity, lack of resources forced many researchers to use the same methodology for all species.

Many authors use regression equations for the most commonly encountered species in sites [15] and [16]. Among the existing equations for estimating biomass, that of Brown et al. [10] was retained because it has been developed under climatic conditions similar to our site of study, with an average annual rainfall varying from 1500 to 4000 mm, including that of Adamawa (1200–2000 mm) and the coefficient of determination between the biomass of the trees and their two parameters (DBH and height) is highly significant ($R^2 = 0.987$). In addition, this formula takes into account the dendrometric factors from our inventory. For a given specie *i*, this biomass equation is given by:

$$B_i = e^{-\alpha_i + \beta_i * \ln(DBH_i^2 * h_i)} \tag{1}$$

h_i being the total height of the tree of specie *i*.

For the Berlinia grandiflora specie for example, the coefficients are given by:

$$\alpha_i = -3.1441; \ \beta_i = +0.9719 \tag{2}$$

It is known that the estimation of the carbon contained in a tree is the half of the value of its dry biomass [10]. This relationship has been modeled by the following equation:

$$\text{Stored carbon } (\mathrm{C_i}) = \frac{1}{2}\mathrm{B_i} \tag{3}$$

The amount of carbon sequestered in a plot j is then obtained by the following equation,

$$SC_j = \frac{1}{2}\sum\nolimits_i \left(e^{-\alpha_i + \beta_i * \ln(DBH_i^2 * h_i)}\right)_j \tag{4}$$

Since the size of a plot is P = 20 m × 20m = 400 m^2, the quantity of sequestered carbon per unit of 1 m^2 in the whole site of study, made of Ns plots, is given by the following equation:

$$SC_u = \frac{1}{2P}\sum_{j=1}^{Ns}\sum_i \left(e^{-\alpha_i + \beta_i * \ln(DBH_i^2 * h_i)}\right)_j \tag{5}$$

Once the quantity of Carbone sequestered per 1 m^2 is known, we classify the image, using a supervised image classification approach and we calculate the total area of the marginal forest. Then the Total quantity of sequestered Carbone is given by the following equation:

$$SC_t = \frac{A}{2P}\sum_{j=1}^{Ns}\sum_i \left(e^{-\alpha_i + \beta_i * \ln(DBH_i^2 * h_i)}\right)_j \tag{6}$$

A being the total area of the marginal forest in the area of study, expressed in m^2.

It is then compulsory to estimate the total area of the closed plant formations and gallery forests present in the site of study. For this purpose, we proceed by image classification.

3.2.4 Colored Image Classification

The classification process begins with the development of the predefined classes of land occupation. Eleven (11) thematic classes have been defined: River, Tree savannah, Burns, Grassy savannah, Built, Wooded savannah, Closed plant formations, Clear forest, Cultivated field and Gallery forest.

We opted for the "maximum likelihood" in a supervised classification method because of its fairly widespread use in remote sensing. It is a method based on probabilistic approaches. It consists in calculating the probability of one pixel to belong to one class rather than another. At the end of this operation, each pixel of the image is attached to one of the previously listed land occupation classes.

For this purpose, the first action was the separation of various bands (R, G, B) of the image. Indeed, the remote sensing colored image is a combination of at least three image bands, each being a grey scale image that can be treated separately. On each band, a series of 20 textural parameters is tested and the correlated ones eliminated. At the end of this process, the following textural parameters [Haralick, 1973] were adopted:

(1) The Energy parameter. This textural parameter measures the uniformity of the texture. Its expression, for a given band R, is given by the following equation.

$$ENE_R = \sum_{i=0}^{MaxGS}\sum_{j=0}^{MaxGS}\left(P_{t_R}(i,j)\right)^2. \tag{7a}$$

Where *MaxGS* is the maximum grey scale in the R image band, t_R is the translation vector *t*, linking the pixel of grey scale *j* to the pixel of grey scale *i* in band R and $P_{t_R}(i,j)$ is the probability of occurrence of a couple (i, j) linked by this vector t_R in the image. Similarly, the energy parameter for the two other bands is given by respectively by the following equations.

$$ENE_G = \sum_{i=0}^{MaxGS} \sum_{j=0}^{MaxGS} \left(P_{t_G}(i,j)\right)^2; \; B_{ENE} = \sum_{i=0}^{MaxGS} \sum_{j=0}^{MaxGS} \left(P_{t_B}(i,j)\right)^2. \quad (7b)$$

From Eqs. 7a and 7b, Considering that B1 = Red image band; B2 = Green image band and B3 = Blue image band, we define the equation of the energy textural parameter for the coloured image as follows:

$$ENE = \frac{1}{3}\left(ENE_{B1} + ENE_{B2} + ENE_{B3}\right) = \frac{1}{3}\sum_{k=1}^{3} \sum_{i=0}^{MaxGS} \sum_{j=0}^{MaxGS} \left(P_{t_{Bk}}(i,j)\right)^2. \quad (8)$$

(2) The entropy parameter. In contrary to the Energy, this textural parameter measures the untidiness observed in the image. For a given image band Bk (k = 1, 2, 3), its expression is given by the following equation:

$$ENT_{Bk} = \sum_{i=0}^{MaxGS} \sum_{j=0}^{MaxGS} \left[Log\left(P_{t_{Bk}}(i,j)\right) \times P_{t_{Bk}}(i,j)\right]. \quad (9)$$

According to Eq. 9 and similarly to Eq. 8, the value of the parameter Entropy for the image is given by:

$$ENT = \frac{1}{3}\sum_{k=1}^{3} \sum_{i=0}^{MaxGS} \sum_{j=0}^{MaxGS} \left[Log\left(P_{t_{Bk}}(i,j)\right) \times P_{t_{Bk}}(i,j)\right]. \quad (10)$$

(3) The correlation parameter. This textural parameter measures the linear dependence (related to the translation vector *t*) of grey levels in the image. It is neither in correlation with the energy nor the entropy parameters. For a given image band Bk (k = 1, 2, 3), its expression is given by the following equation:

$$COR_{Bk} = \sum_{i=0}^{MaxGS} \sum_{j=0}^{MaxGS} \left[\frac{(i-\mu)(j-\mu)}{\sigma^2} P_{t_{Bk}}(i,j)\right]. \quad (11)$$

According to Eq. 11 and similarly to Eq. 8, the value of the parameter Entropy for the image is given by:

$$COR = \frac{1}{3}\sum_{k=1}^{3} \sum_{i=0}^{MaxGS} \sum_{j=0}^{MaxGS} \left[\frac{(i-\mu)(j-\mu)}{\sigma^2} P_{t_{Bk}}(i,j)\right]. \quad (12)$$

Where μ and σ represent respectively the mean and the standard deviation related to the structural operator.

(4) The contrast parameter. This textural parameter, the last among the selected parameters, deals with the passage of higher to lower grey levels consecutively in the image. Its expression, for a given image band Bk, is given by the following equation:

$$CST_{Bk} = \sum_{i=0}^{MaxGS} \sum_{j=0}^{MaxGS} \left[(i-j)^2 P_{t_{Bk}}(i,j)\right]. \quad (13)$$

According to Eq. 13 and similarly to Eq. 8, the value of the parameter Contrast for the image is given by:

$$COR = \frac{1}{3}\sum_{k=1}^{3}\sum_{i=0}^{MaxGS}\sum_{j=0}^{MaxGS}\left[\frac{(i-\mu)(j-\mu)}{\sigma^2}P_{t_{Bk}}(i,j)\right]. \quad (14)$$

The value of $P_{t_{Bk}}(i,j)$ is given by the following equation

$$P_{t_{Bk}}(i,j) = \frac{|\{(r,s),(r,s)+t \in Bk/Bk(r,s) = i \; and \; Bk((r,s)+t) = j\}|}{|(r,s)/(r,s) \in Bk \; and \; (r,s)+t \in Bk|}. \quad (15)$$

Where |X| is the cardinal number of the set X.

Centred on each identified plot in the various sites of study, an image window of size 9 × 9 is extracted. This size was adopted after a series of empirical tests of image window sizes, from 3 × 3 to 15 × 15. For each image window W_i, the four adopted textural parameters are calculated to form a textural vector

$$V_{W_i} = (ENE_{W_i}, ENT_{W_i}, COR_{W_i}, CST_{W_i}). \quad (16)$$

For the Np plots identified on the training site as dominated by a certain information class C, the characteristic textural vector CV_C of the information class C is given by the following equation.

$$CV_C = \frac{1}{N_p}\left(\sum_{i=1}^{N_p} ENE_{W_i}, \sum_{i=1}^{N_p} ENT_{W_i}, \sum_{i=1}^{N_p} COR_{W_i}, \sum_{i=1}^{N_p} CST_{W_i}\right). \quad (17)$$

Nine information classes have been identified on the training site: Built, Cultivated field, Clear forest, Closed plant formations, Burns, Tree savannah, Wooded savannah, Grassy savannah and Gallery forest.

For each pixel of the image, a 9 × 9 size image window is extracted and the characteristic vector calculated. The pixel is assigned to the information class that minimises the distance between the characteristic vector of the pixel and its proper characteristic vector. The symmetric border filling method is adopted for the management of border pixels.

4 Results

4.1 Land Cover Analysis

Figure 3 shows the mapping of land cover types in the Vina Division. It shows that natural plant formations are distributed over the entire area. The linear form of construction is located mainly along the roads, which reflects the fact that the roads are development factors. The strong concentration of the Mount in the center of the map, is justified by the fact that, it is the place of junction of the various road axes, materializing the principal city (Ngaoundéré) of the region. Fields and burns are more concentrated around the city. This situation reflects the fact that the populations do not have enough space around their compounds for the practice of agro-pastoral activities.

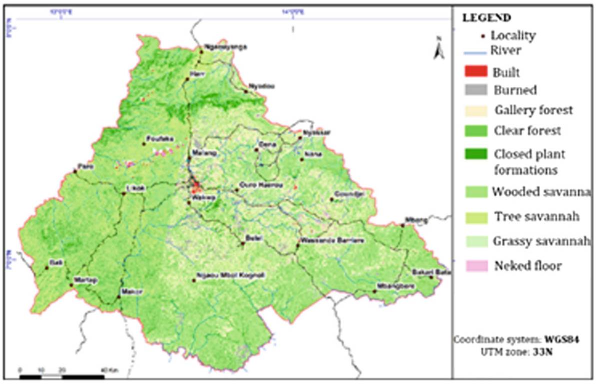

Fig. 3. Land cover types

Figure 3 shows the spatial distribution of closed plant formations in the Vina Division. It appears that these formations are distributed over the whole area but are more concentrated at the northern end of the study area.

The classification quality can be evaluated by the Overall accuracy (OA) statistic parameter, which designates the percentage of correctly classified pixels. In addition to OA, the classification can be evaluated by the use of confusion matrix in term of the designated target C (information class). In this case, the probability detection for a given thematic class C (tree savannah for example) is assimilated to the precision of C signatures detection which corresponds to the pixels correctly classified. Therefore, the probability of false alarms reported in normal site of study becomes equivalent to the commission error to detect the absence of selected thematic class in the studied area [17]. For the present study, the Kappa index was used to evaluate our classification accuracy. It measures accuracy and expresses the proportional reduction of the error obtained by a classification method, compared to the error obtained by a completely random classification technique. The average value of the Kappa Index obtained as part of our classification is 97.25%.

The post-classification treatments made it possible to highlight the areas (in hectares) of the different types of land use (Table 1). Thus, the closed plant formations of the Division of Vina cover an area of 145 678 ha and represent eighth of the total area of this Division.

Table 1. Area of different types of land use

Land cover type	Area (ha)	Percentage (%)	Land cover type	Area (ha)	Percentage (%)
Built	4775	0.28	Tree savannah	848 626	49.45
Culture field	335 815	19.57	Wooded savannah	247 165	14.40
Clear forest	42 555	2.48	Grassy savannah	25 943	1.51
Closed plant formations	145 678	8.49	Gallery forest	10 000	0.6
Burns	47 354	2.76	Unclassified	7 856	0,46

4.2 Floristic Composition and Carbone Stock Per Specie

In the closed plant formations sampled, 1 199 individuals were identified. They are divided into 27 families, 55 genera, 92 species with 11 indeterminate species (Table 2). Syzygium guineense, Vitex doniana, Breonadia salicina, have the highest frequencies respectively 276, 94 and 80 individuals out of the 1 199 individuals identified. The estimated amount of biomass is 783.69 tones for all the plant formations sampled with an average of 217.7 t/ha. The approximate value of the total amount of carbon stored by these sampled formations is 391.845 tones of Carbon with an average of 108.85 t/ha.

Table 2. Distribution of biomass and stored Carbone by family

Species	Quantities	Biomass (Kg)	Stocked Carbone (t)
Myrtaceae	284	156749.39	78.37
Euphorbiaceae	172	73056.79	36.53
Rubiaceae	98	56577.83	28.29
Verbenaceae	187	323918.17	24.06
Ebenaceae	67	35864.33	17.93
Moraceae	57	29903.63	14.95
Mimosaceae	51	27188.97	13.59
Total	916	703259,11	213,72

Species with less than 2 tones of Carbone sequestered are ignored in the table.

4.3 Biomass and Stocked Carbone Quantity Estimation

The estimate of the biomass contained in all the closed plant formations of the site of study was based on the previous data summarized in the following Table 3.

Table 3. Summaries of data used to estimate the global Carbon stock.

Data	Values
Closed plan formations	145 678 ha
Sampled area	3.6 ha
Expansion factor	40 466
Total quantity of stocked Carbone par sample	783 694.16 kg
Total quantity of stocked Carbone par sample	253.95 kg C

The estimate of the biomass contained in all the closed plant formations of the site of study was based on an extrapolation, from an expansion factor (40 466).

Thus, the value of the total biomass contained in the closed plant formations of the zone of study is approximately 20 552 681.4 t. The amount of carbon stored by these closed vegetation formations is estimated at 10 276 340.7 t C.

Knowing that one tone of CO2 reduction is equivalent to one tone of carbon credit [18], one can estimate the amount of total credit of Carbone generated by marginal forests of Adamaoua Cameroon.

4.4 Carbon Credit

There are several carbon estimation programs and methodologies, and carbon credit nomenclature may vary depending on the programs under which the credits in question were recorded:

- Verified Emissions Reduction (VER) are the carbon units generated according to ISO 14 064-2
- The Climate Reserve Tonne (CRT) is the carbon unit recorded by the Climate Action Reserve (CAR), a California registry.

The Verified Carbon Standard (VCS) program names the Verified Carbon Unit (VCU) carbon credits using various methodologies other than the VCS methodology; for example, the Clean Development Mechanism (CDM) methodology and the Climate Action Reserve (CAR) methodology (except for the Forest and Urban Forest methodology). Our approach falls within this program. The vintage of the carbon credit and the methodology used for quantification are some of the factors that influence the price of carbon credit. The vintage is a term for the year of production of the carbon credit, which is the year the GHG reduction occurred [18].

To obtain carbon credits that can be sold on the market, three stages are required:

- The first step is to **quantify its emissions**, that is, the quantification of the reduction according to a protocol or methodology.
- The second step is to validate and/or to verify, by a third party. It is a question of validating the initial hypotheses and the calculation methodology. Verification is always mandatory. An auditor certifies that the protocol and the data used for calculation and mathematical reasoning are accurate.

- Finally, the third step is the registration of carbon credits on a recognized register. This registration creates a unique and traceable serial number. It is this serial number that is sold on the carbon market.

The present project contributes at the first stage.

4.5 Discussion

The plant formations involved in this study are still not continuous in space and hermetically closed. Despite this constraint, a maximum of effort has been made to obtain a representation as close to reality. The good knowledge of the field, coupled with information extracted from Google Earth tool were decisive. The illustration is also given by the statistically acceptable classification rate (Kappa index = 97%).

However, this value of carbon obtained per hectare (108.85 t/ha) in the Division of Vina, combined with the area covered by the closed plant formations of this Division (145 678 ha) show how marginal the forests of the Congo watershed, and particularly that of our site of study, are an integral part of the response to climate change, through its role in reducing the amount of carbon present in the atmosphere.

5 Conclusion

The purpose of this work was to provide an accurate method of estimating the biomass and quantity of Carbon sequestered in the closed plant formations. The Vina Division, located in cameroonian Adamaoua region has been selected as site of study. Taking into account the collection period of the phytogeographic data, these plant formations sequestered about 10 276 340,7 tones of Carbone (tC) in May 2014 (year of image acquisition and month of field mission). The species ensuring the largest carbon stocks are Syzygium guineense (77 tC), Breonadia salicina (27tC), Vitex doniana (20 tC). This study can serve as a reference for future research. This research can be extended by integrating stocks of hypogeous carbon.

Climate change, representing the environmental challenge of the century, including sustainable forest management as a component of REDD+ is an effective way to address this threat. This management requires basic, reliable information on the state of the forest, their evolution and carbon storage potential. This is a major contribution for this issue.

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