

1. Carbon sequestration: an assessment method based on allometric equations and a generalized coefficient

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Abstract

Forests have been at the centre of climate change negotiations for a number of years because of their potential to absorb carbon dioxide, which is heavily responsible for climate change. Indeed, deforestation and forest degradation accounts for about 20% of greenhouse gas emissions. In this chapter, we adapt on a large scale a method developed to assess the quantity of carbon stored by marginal vegetation formations in the Congo watershed. To achieve this, the adopted approach is based on the closed-vegetation formations of the Ngaoundere plateau in Adamaoua-Cameroon. The approach in question uses an indirect technique based on allometric equations and a generalized coefficient. Floristic surveys were first carried out on 90 plots of 400 m² each.

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Robert Christian Anaba Banimb, Narcisse Talla Tankam, Pierre Marie Mapongmetsem and Michel Tchotsoua, 'Carbon sequestration: an assessment method based on allometric equations and a generalized coefficient' in: *Carbon Sequestration in African Forests* (Pelagic Publishing, 2026): 10.53061/HWR13333

This step was followed by assessment of their aboveground biomass through Brown's allometric equation, as adapted by Anderson and Ingram and taken up by Ana-Helena. Subsequently, the carbon assessment is based on the assumption that the carbon contained in a tree is 50% of the value of its dry biomass. The results obtained at plot level are then generalized to all the closed-forest areas in the region by means of an expansion factor. According to this method, it appears that these formations in their state in 2015, the year of acquisition of the images, sequestered about 10 million tons of carbon. This figure shows the importance of these marginal closed-vegetation formations in the Congo watershed. The international and national bodies in charge of the REDD+ mechanism must also take this into account.

Key words: Biomass, carbon sequestration, closed vegetation formation, allometric equation, aboveground biomass, Congo watershed

1.1 Introduction

The increase in the concentration of greenhouse gases (GHGs) in the atmosphere, mainly carbon dioxide (CO₂) and methane (CH₄), is recognised as one of the causes of current climate change. This increase in GHGs in the atmosphere is one of the most studied issues today. This is why a great deal of interest has developed around forests, with their capacity to sequester carbon in their biomass via photosynthesis. Their destruction and combustion cause the release of stored carbon, thus leading to an increase in this chemical element in the atmosphere. According to Ana-Helena (op. cit.) and the IPCC (2007), carbon dioxide emissions linked to land-use change are the second major cause of the increase in atmospheric carbon dioxide concentration after emissions linked to fossil fuel combustion. In Cameroon, forests cover 41.3% of the national territory and represent 10% of the Congo Basin forests (EDF 2010). According to MINEF (1994) cited by IUCN (2015), greenhouse gas emissions in Cameroon in 1994 were estimated at 43,988 Gg of CARBON DIOXIDE equivalent with 50.44%, 37.83%, 7.36% caused respectively by land-use change, agriculture and energy.

In order to limit the increase of greenhouse gases in the atmosphere (methane, CARBON DIOXIDE and so on) strategies such as the Clean Development Mechanism (CDM), REDD and REDD+ have been developed. The REDD mechanism, a concept introduced at the Bali Conference in 2007, aims to provide technical support and financial incentives to countries in the south that have the capacity to reduce greenhouse gas emissions from the forestry sector. According to Kersenty (2009), the aim is to remunerate developing countries that reduce deforestation and forest degradation over a given period.

In order to benefit from the financial or technological revenues linked to these mechanisms, it is essential, even imperative, to know the quantity of carbon stored in the forests. However, little data on biomass or carbon stock in Cameroon is available to date and most of the studies that have been carried out there have been conducted in the dense forests of the greater south of Cameroon (Tayo-Gamo 2014; Dmapo Wembo 2011; Vincke 2011).

The state of the literature on the issue in the Sudano-Guinean savannahs of Adamaoua reveals a need for knowledge on quantification methods but also on carbon stocks in this ecosystem and mainly on closed-canopy areas. The studies carried out by Tchobsala (2010), Aoudou (2010), Kouedjou (2015), Kalda (2015) constitute references in the Sudano-Guinean savannahs of Adamaoua. In this article, the authors, based on the spatialization

and phytogeographic characterization of closed vegetation formations in this geographical area, develop a method for quantifying hypogenous carbon stocks stored in the said formations.

1.2 Site of study

Located between 12° and 15° east longitude and 6° and 8° north latitude, the Division of Vina (Figure 1.1), the capital of the Adamaoua region. It was created by decree n° 72/349 of 24 June 1972. It has eight subdivisions, including Belel, Mbe, Nganha, Ngaoundéré I, Ngaoundéré II, Ngaoundéré III, Nyambaka and Martap. Orographically, the relief of Vina Division is a plateau with gentle slopes, which become steep towards the north. 30 km north of N'Gaoundéré, there is an escarpment that separates the district of Mbé from the rest of the districts of the Division. As regards the soil aspect, this Administrative Division is essentially characterised by ferralitic soils, rough mineral soils and hydromorphic soils



Figure 1.1 Location of the study area

(MINEPAT 2000). The hydrographic network in the area is quite dense. There are several rivers, the Vina and the Bini being the main ones, as well as numerous lakes such as Lake Tyson, Lake Wakwa, Lake Dibi, which characterises the area.

Landsat satellite imagery was chosen in our study because it provides sufficient details to identify land cover features while offering more or less complete coverage of the study area. The spatial resolution of the images used is 30 m.

1.3 Methodology

1.3.1 Field surveys

Before the first mission on the field for data collection, we need to conceive and realize a certain number of surveys. This is done in several phases, namely:

Selection of training sites

This first stage was of utmost importance. It consisted first of all of using Google Earth software to visualize the study area in order to identify the most representative sites in terms of plant cover and above all in terms of accessibility, which could be used to create the plots.² Once the sites have been visualized and identified, their geographical coordinates are recorded and inserted into the GPS.

In order to have a maximum representativeness of the species in the study area, nine sampling sites were selected. They were chosen according to their accessibility, the rate of cover and certain parameters that could influence the specific richness of the formations. These parameters include hydromorphic, lakes and proximity to urban centre.

Plot delineation

Once in the previously identified area, we activate the 'Go to' option on the GPS to orient ourselves towards the site whose points have been recorded. Once at the site, we compare the satellite imagery with the reality on the ground. The aim is to see if the sites previously identified on Google Earth satellite images are really woodland formations that could be exploited. If the site is exploitable, we locate a homogeneous surface with a view to establishing our plots with a surface area of 400 m², i.e., 20 m*20 m.

After identifying this area, we select a tree (A₁) on which we mark a red sign. This tree serves as one of the 04 ends of the plot (Photo 1). The second step is to unroll the tape measure over a distance of 20 m with the help of the four cardinal points indicated by the GPS and then we mark this point with a red sign. If this point A2 corresponds to a tree, we will use it, otherwise we use a stake to mark the second end of the plot. We will proceed in this way for points A3 and A4 until we have a square (Figure 1.2). A total of 90 plots were marked out in the field in gallery forests and forest groves. After delimiting the plot, we proceeded to take a partial picture of the formation and to record the coordinates of the four corners of the plot.

² A plot is an area of 400 m² within a tract of vegetation in which the inventory takes place.



Picture 1.1 Marking a corner of a plot ($6^{\circ}54'57.5''\text{N}$ / $14^{\circ}26'69.9''\text{E}$)

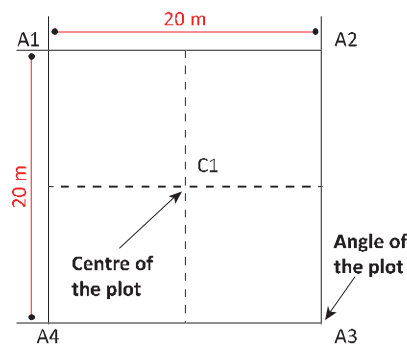


Figure 1.2 Simplified diagram of a plot

Characterization of the plot

This allows the study of stationary factors of the area and the ecological environment where the species develop. Knowledge of these factors will undoubtedly provide elements of an answer that will make it possible to explain the distribution of species in the different ecological environments of the plateau. This characterization allows us to answer the question why we find 'X' species here and not elsewhere?

This stage consists of filling in the plot sheet previously established data, taking care to fill in the following information carefully the plot code, the geographical coordinates of the plot, the mission date, the vegetation type (grove or gallery forest), the morphology

(plateau or massif), its position (lowland, depression, etc.), its exposure, the state at the time of observation (pruned foot, trace of herds), its slope, its hydromorphic (drained or not), the presence or absence of outcrops, surface accumulation (clay, sand, etc.), the bioturbation (soil, water, etc.), the soil type, the soil texture and structure, the characterization of the dry biomass (dead leaves, dead wood), the decomposition of dry biomass (slow or advanced) and finally the identification of the plot corresponding photos.

Carrying out the inventory

This stage is undoubtedly the most crucial part of the fieldwork, as it allows the collection of data on the biomass of the trees, which is necessary for estimating the quantity of carbon stored.

The floristic inventory consists of identifying all the trees in the plot with a circumference equal to or greater than 31.5 cm and a height of at least 5 m. Individuals not meeting these criteria were purely counted but not measured. On each of the individuals fulfilling the above-mentioned conditions, the following operations were carried out:

1. Determination of the scientific name.
2. Taking of coordinates.
3. Measurement of the circumference.
4. Taking of the photograph for the calculation of the height.
5. Measurement of the distance to the plot centre.

All information was recorded on the species record sheets provided for this purpose.

Determination of scientific names

The identification of the plants was done in situ. The team consisted of a botanist and a geographer, who had a good knowledge of the plants, and a guide who gave the vernacular names of the plants. In addition, we made use of the reference document by Arbonnier (2000), 'Ligneux du sahel'. For unidentified species, specimens were collected for determination at the national herbarium of Cameroon.

Circumference measurement

The circumference of a tree is the most widely measured and used dendrometry characteristic (Vincke 2011 and Toung 2010.). This measurement was made with a tape measure at 1.30 m above the ground. If the tree has branches less than 1.30 m above the ground, each branching stem is considered as a separate stem and is measured. Because we work in the forest, some trees had buttresses at 1.30 m. To remedy this, we measured the circumference beyond the buttress as suggested by Walker et al. (2014).

Measuring heights

The height of a tree is the second most important dendrometry value after the circumference. To determine the height of the trees, we used a photograph of the tree taken beforehand and then used the software 'Mesurim' to determine the value.

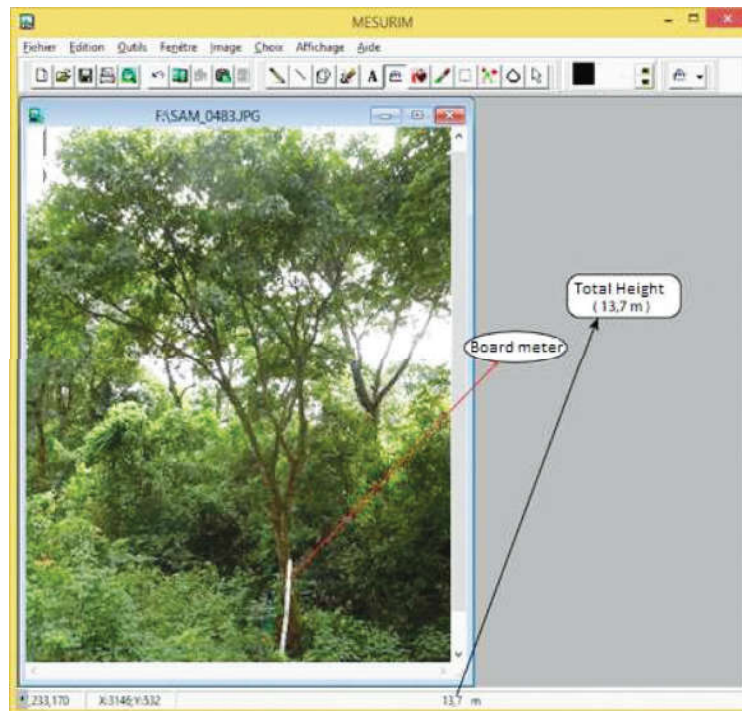


Figure 1.3 Tree height display

1.3.2 Biomass and carbon assessment

In order to determine the quantity of carbon stored at the individual level and given the diversity of species, the use of an allometric equation for each species would be ideal because of the diversity of forms (Ketterings 2001). But considering this diversity, the lack of means forces us to use the same equation for all species. Thus, the estimation of the carbon stock of these closed vegetation formations is based on the determination of the dry above-ground biomass.

Concerning protection measures to which the forests are subject, the traditional methods of estimating the biomass, which involve the clear-cutting of a large number of representative individuals of the stand with a view to drying and weighing them, appeared unsuitable for such a study. It was therefore necessary to opt for a method based on non-destructive sampling. The non-destructive method consists of determining the biomass of trees from allometric equations. An allometric equation is an equation that allows the estimation of data that is difficult to measure on all trees (volume, total mass, biomass) from simple characteristics such as diameter, height (Picard et al. 2012). This is a proportionality equation between biomass and mensuration increments.

Choice of an allometric equation

Many authors recommend developing regression equations for the species most commonly found in sites (Dmapo Wembo 2012; IPCC 2003) as was the case for Thiams et al. (2014) for *Acacia Senegal* in Senegal. In this study, equations generated in other research conducted under similar biophysical conditions were used. Among the existing equations for

estimating biomass, the one of Brown et al. (1989), adapted by Anderson and Ingram (1993) and taken up by Ana-Helena et al. (op. cit.), was chosen. It was developed under climatic conditions where the average annual rainfall varies from 1,500 to 4,000 mm, including that of Adamaoua (1,200–2,000 mm), the coefficient of determination between tree biomass and their two parameters (DBH and height) is highly significant ($R^2 = 0.987$). In addition, this formula takes into account the dendrometry factors from the inventory carried out. The equation is as follows:

$$B = \exp -3,1441 + 0,9719 * \ln (DHP^2 * H)$$

B: biomass; DBH: diameter at breast height; H: total height

R: 0.97 robustness or strength factor; $3.14 = \pi$

Note however that the Pan Tropical equation of Chave et al. (2005) update in 2014 appeared unsuitable for our study because we did not have the data on species density.

Determination of biomass at the formation scale

To date, several methods for estimating the biomass of a region are known. Of these, two are particularly used (Bombelli et al. 2009) cited by Molto (2010).

Naïve methods: the plots inventoried must be representative of the area or region. The biomass of the region is equal to the average of the biomass inventories carried out there.

Co-variable methods: the inventoried plots are described by the variables that will serve as predictors in the non-inventoried areas. This method uses spatial remote sensing to determine the total area covered by the formation.

In the present study, we will use the Co-variable method using remote sensing. First, the total area covered by the vegetation formations will be determined from satellite imagery. This will then be multiplied by an expansion factor.

1.3.3 Carbon assessment

The estimate of carbon contained in a tree is 50% the value of its dry biomass. (IPPC 2003; Brow and Lugo 1992). This relationship has been modelled by the following equation:

$$\text{Stored carbon (C)} = \text{Biomass} * 0.5$$

Estimating the carbon stored in a plot

The amount of carbon sequestered at the plot level is obtained either by multiplying the total above-ground biomass of the plot by the conversion factor (0.5) or by summing the carbon value of all trees in the plot.

Generalization to the formation scale

The carbon stock values found at the scale of the individual plots will be extrapolated to the whole formation using an expansion factor (EF).

$$EF = \frac{\text{Expansion factor}}{\sum_{i=1}^n n_i}$$

With EF: expansion factor: area of a plot

The carbon stock at the scale of the formations will be equal to:

$$\left(\sum_i^n n_i \times 0,5 \right) \times EF$$

With EF: expansion factor: Biomass of a plot

1.3.4 Image processing

Classification method

The land cover classification in our study is based on the FAO Land Cover Classification System (LCCS). It is a comprehensive standardized a priori classification system designed for mapping purposes and is not dependent on the scale or the mapping method used. The classification is based on a set of independent criteria, through which it is possible to correlate with other classifications and associated legends. (OSS³ 2013; Anaba 2010).

Class definition

The classification process starts with the development of the predefined land-use classes, using the LCCS system which will allow the identification of the various thematic classes on the field and the specification of each of them. After the field trip, eleven (11) significant thematic classes have been identified on the site of study. These thematic classes are reported on Table 1.1.

Table 1.1 Selected thematic classes

Waterbody	Bare ground
Shrubby savannah	Wooded savannah to woodland
Burnt land	Closed vegetation formations
Building	Open forest
Grassy savannah	Cloud
	Fields

Choice of the classification method

Classification is a process of sorting and grouping pixels of an image, which allows a moment from satellite images to land cover maps. In the present study, we used the directed classification whose principle is to provide the software with samples of pixels representing the reference region and whose nature of the training sites (classes) is known. We opted for the 'maximum likelihood' classification method because of its widespread use in remote sensing. This method is based on probabilistic methods. It consists of calculating the probability of a pixel belonging to one class rather than another. At the end of this operation, each pixel of the image is attached to one of the land cover classes listed above.

Creation of the geodatabase, import of the shapefiles and calculation of the areas of the thematic classes

After the supervised classification, a geodatabase is created with ArcGIS 9.3. Then, the raster files resulting from the classification are converted into shapefiles and integrated into the geodatabase with the ArcCatalog module of ArcGIS software. In each associated attribute table, an 'Area' attribute is added, which will contain the area of each polygon.

Evaluation of the classification

To evaluate our classification, we opted for the calculation of the Kappa index, which is commonly used in remote sensing and which makes it possible to estimate the accuracy of a classification. It measures the accuracy and expresses the proportional reduction of the error obtained by a classification, compared to the error obtained by a completely random classification (Anaba 2010).

1.4 Results

1.4.1 Floristic composition of the sampled plant formation

In the sampled closed-canopy areas, 1,124 individuals were recorded. They are divided into 82 species with 11 undetermined species for a total of 55 genera and 29 families. *Syzygium guineense* var. *guineense*, *Vitex doniana* and *Breonadia salicina* present the highest frequencies – respectively 276, 94 and 80 out of the 1,124 individuals counted.

Table 1.2 Distribution of biomass and stored carbon by species in the sampled plant formations

species	B (Kg)	Stored carbon (Kg)
<i>Acacia seyal</i>	3,383.39	1,691.7
<i>Acacia sieberiana</i>	176.26	88.13
<i>Albizia adianthifolia</i>	3388.53	1694.26
<i>Albizia coriaria</i>	3386.28	1693.14
<i>Albizia glaberrima</i>	1828.85	914.43
<i>Albizia lebbeck</i>	6810.02	3405.01
<i>Albizia zygia</i>	7508.99	3754.49
<i>Anogeissus leiocarpus</i>	953.36	476.68
<i>Azadirachta indica</i>	349.3	174.65
<i>Bombax costatum</i>	465.44	232.72
<i>Breonadia salicina</i>	54014.86	27,007.43
<i>Bridelia ferruginea</i>	255.76	127.88
<i>Bridelia micrantha</i>	586.77	293.38
<i>Bridelia scleroneura</i>	111.85	55.92
<i>Combretum adenogonium</i>	2207.46	1103.73
<i>Combretum collinum</i>	1299.63	649.81

species	B (Kg)	Stored carbon (Kg)
<i>Combretum molle</i>	2715.42	1357.71
<i>Combretum nigricans</i>	2605.32	1302.66
<i>Cordia africana</i>	339.76	169.88
<i>Cordia myxa</i>	150.86	75.43
<i>Croton gratissimus</i>	2284.64	1142.32
<i>Croton macrostachyus</i>	33275.13	16637.57
<i>Cussonia barteri</i>	1154.18	577.09
<i>Daniellia oliveri</i>	781.01	390.5
<i>Dialium guineense</i>	5584.83	2792.42
<i>Diospyros mespiliformis</i>	35864.33	17932.16
<i>Ekebergia senegalensis</i>	1241.5	620.75
<i>Entada abyssinica</i>	504.02	252.01
<i>Erythrophleum suaveolens</i>	833.83	416.92
<i>Fagara lepreuri</i>	1680.09	840.04
<i>Fagara senegalensis</i>	6064.71	3032.36
<i>Ficus binosa</i>	1821.16	910.58
<i>Ficus dicranostyla</i>	1341.24	670.62
<i>Ficus exasperata</i>	192.33	96.17
<i>Ficus glumosa</i>	1390.17	695.08
<i>Ficus natalensis</i>	388.25	194.12
<i>Ficus platyphylla</i>	12022.52	6011.26
<i>Ficus sur</i>	39.28	19.64
<i>Ficus sycomorus</i>	10509.51	5254.76
<i>Ficus thonningii</i>	2199.17	1099.59
<i>Flacourtia indica</i>	59.84	29.92
<i>Garcinia ovalifolia</i>	615.53	307.77
<i>Gliricidia sepium</i>	40.87	20.44
<i>Gmelina arborea</i>	275788.81	137.9
<i>Holarrhena floribunda</i>	12726.26	6363.13
<i>Hymenocardia acida</i>	39.28	19.64
<i>Khaya senegalensis</i>	125.06	62.53
<i>Lannea acida</i>	2504.35	1252.18
<i>Lannea microcarpa</i>	3954.39	1977.2
<i>Lonchocarpus sericeus</i>	661.38	330.69
<i>Malacantha alnifolia</i>	605.68	302.84

Continued

Table 1.2 Distribution of biomass and stored carbon by species in the sampled plant formations *Continued*

species	B (Kg)	Stored carbon (Kg)
<i>Margaritaria discoidea</i>	1473.42	736.71
<i>Mitragyna inermis</i>	319.27	159.63
<i>Monotes kerstingii</i>	1532.14	766.07
<i>Morelia senegalensis</i>	760.97	380.49
<i>Ochna schweinfurthiana</i>	3007.86	1503.93
<i>Pavetta corymbosa</i>	57.99	28.99
<i>Pericopsis laxiflora</i>	6947.57	3473.78
<i>Persea americana</i>	30.42	15.21
<i>Phoenix reclinata</i>	430.71	215.35
<i>Polyscias fulva</i>	1099.11	549.55
<i>Prosopis africana</i>	202.63	101.32
<i>Pseudocedrela kotschy</i>	1214.43	607.21
<i>Psidium guajava</i>	450.6	225.3
<i>Psychotria psychotrioides</i>	1424.74	712.37
<i>Pterocarpus santalinoides</i>	2878.27	1439.14
<i>Rhus natalensis</i>	535.87	267.94
<i>Sapium ellipticum</i>	2657.84	1328.92
<i>Spondianthus preussii</i>	1428.36	714.18
<i>Sterculia setigera</i>	534.1	267.05
<i>Syzygium guineense</i> var. <i>guineense</i>	154,522.66	77261.33
<i>Syzygium guineense</i> var. <i>macrocarpum</i>	1776.13	888.06
<i>Tectona grandis</i>	5139.45	2569.72
<i>Terminalia albida</i>	81.37	40.69
<i>Terminalia macroptera</i>	741.56	370.78
<i>Terminalia mollis</i>	136.22	68.11
<i>Terminalia schimperiana</i>	174.81	87.4
<i>Uapaca togoensis</i>	32411.38	16205.69
<i>Vitellaria paradoxa</i>	939.13	469.56
<i>Vitex doniana</i>	40999.76	20499.88
<i>Vitex madiensis</i>	1990.15	995.08
<i>Voacanga africana</i>	5714.34	2857.17
Unspecified / Indeterminate	3249.44	1624.72
Total number of individuals	1199	
Total biomass (Kg)	783694.2	
Total carbon (Kg)	253952.68	

1.4.2 Specific diversity

This was assessed by Simpson's index, Pielou's equitability and the Shannon diversity index, the values of which are given in Table 1.3.

Table 1.3 Index types comparison

index	Value
Shannon	5,441
Pielou	0,802
Simpson	0,040

Source: Analysis of field data

The Shannon and Pielou equitability indices are very high in these plant formations, in contrast to Simpson's index.

Pielou's equitability index is an index that tends towards zero (0) when there is dominance and towards one (1) when a maximum number of species participate in the cover. In the context of our work, this index tends towards one (1), which reflects the presence of several species participating in the stand's cover. This high value of the Shannon diversity index reveals great diversity, i.e. the co-dominance of several species and the fact that individuals belong to different species. The low value of Simpson's index indicates high specific diversity, which is consistent with all the calculated indices.

1.4.3 Determination of the biomass of the sampled area

Biomass is the dry woody plant mass per unit area and is the basis for calculating the carbon stored by the forests. For the entire sampled area, its value is 507,905.37 kg (507.905 t) with an average of 141.08 t/ha. Table 1.4 shows the distribution of this biomass according to the sampling sites. It also reveals that sites F1 (*Falaise 1*) and Wak1 (*Wakwa 1*) have the highest biomass concentrations.

Table 1.4 Distribution of biomass and stored carbon by species in the sampled plant formations

Site	Biomass (kg)
Baw1	8029.39
BIN1	8257.35
F1	103055.075
F2	49489.91
F3	68089.05
T1	67740.21
T2	24792.026
WAK1	143819.31
WAK2	34633.01
Total (kg)	507 905.37

Table 1.5 presents the distribution of biomass by species in the sampled plant formations. It can be observed that the species with a high biomass are respectively *Syzygium guineense* var. *guineense*, *Breonadia salicina* and *Vitex doniana*, while *Persea americana*, *Hymenocardia acida* and *Terminalia albida* contain very little.

Table 1.5 Distribution of biomass by species in the sampled plant formations

Species	Biomass (Kg)
<i>Persea americana</i>	30.42
<i>Ficus sur</i>	39.28
<i>Hymenocardia acida</i>	39.28
<i>Gliricidia sepium</i>	40.87
<i>Pavetta corymbosa</i>	57.99
<i>Flacourtia indica</i>	59.84
<i>Terminalia albida</i>	81.37
<i>Bridelia scleroneura</i>	111.85
<i>Khaya senegalensis</i>	125.06
<i>Terminalia mollis</i>	136.22
<i>Cordia myxa</i>	150.86
<i>Terminalia schimperiana</i>	174.81
<i>Acacia sieberiana</i>	176.26
<i>Ficus Exasperata</i>	192.33
<i>Prosopis africana</i>	202.63
<i>Bridelia ferruginea</i>	255.76
<i>Mitragyna inermis</i>	319.27
<i>Cordia Africana</i>	339.76
<i>Azadiratcha indica</i>	349.30
<i>Ficus natalensis</i>	388.25
<i>Phoenix reclinata</i>	430.71
<i>Psidium guajava</i>	450.60
<i>Bombax costatum</i>	465.44
<i>Entada abyssinica</i>	504.02
<i>Sterculia setigera</i>	534.10
<i>Rhus natalensis</i>	535.87
<i>Bridelia micrantha</i>	586.77
<i>Malacantha alnifolia</i>	605.68
<i>Garcinia ovalifolia</i>	615.53
<i>Lonchocarpus sericeus</i>	661.38
<i>Terminalia macroptera</i>	741.56
<i>Morelia senegalensis</i>	760.97

Species	Biomass (Kg)
<i>Daniellia oliveri</i>	781.01
<i>Erythrophleum suaveolens</i>	833.83
<i>Vitellaria paradoxa</i>	939.13
<i>Anogeissus leiocarpus</i>	953.36
<i>Polyscias fulva</i>	1099.11
<i>Cussonia barteri</i>	1154.18
<i>Pseudocedrela kotschy</i>	1214.43
<i>Ekebergia senegalensis</i>	1241.50
<i>Combretum collinum</i>	1299.63
<i>Ficus dicranostyla</i>	1341.24
<i>Ficus glumosa</i>	1390.17
<i>Psychotria psychotrioides</i>	1424.74
<i>Spondianthus preussii</i>	1428.36
<i>Margaritaria discoidea</i>	1473.42
<i>Monotes kerstingii</i>	1532.14
<i>Fagara leprieuri</i>	1680.09
<i>Syzygium guineense</i> var. <i>macrocarpum</i>	1776.13
<i>Ficus binosa</i>	1821.16
<i>Albizia glaberrima</i>	1828.85
<i>Vitex madiensis</i>	1990.15
<i>Ficus thonningii</i>	2199.17
<i>Combretum adenogonium</i>	2207.46
<i>Croton gratissimus</i>	2284.64
<i>Lannea acida</i>	2504.35
<i>Combretum nigricans</i>	2605.32
<i>Sapium ellipticum</i>	2657.84
<i>Combretum molle</i>	2715.42
<i>Pterocarpus santalinoides</i>	2878.27
<i>Ochna schweinfurthiana</i>	3007.86
Indeterminate	3249.44
<i>Acacia seyal</i>	3383.39
<i>Albizia coriaria</i>	3386.28
<i>Albizia adianthifolia</i>	3388.53
<i>Lannea microcarpa</i>	3954.39
<i>Tectona grandis</i>	5139.45
<i>Dialium guineense</i>	5584.83
<i>Voacanga africana</i>	5714.34

Continued

Table 1.5 Distribution of biomass by species in the sampled plant formations *Continued*

Species	Biomass (Kg)
<i>Fagara senegalensis</i>	6064.71
<i>Albizia lebbbeck</i>	6810.02
<i>Pericopsis laxiflora</i>	6947.57
<i>Albizia zygia</i>	7508.99
<i>Ficus sycomorus</i>	10509.51
<i>Ficus platyphylla</i>	12022.52
<i>Holarrhena floribunda</i>	12726.26
<i>Uapaca togoensis</i>	32411.38
<i>Croton macrostachyus</i>	33275.13
<i>Diospyros mespiliformis</i>	35864.33
<i>Vitex doniana</i>	40999.76
<i>Breonadia salicina</i>	54014.86
<i>Syzygium guineense</i> var. <i>guineense</i>	154522.66
Overall total	507905.37

Source: Field surveys

1.4.4 Determination of stored carbon in sampled plant formations

The determination of the carbon stored in these sampled formations is tributary to their previously calculated biomass. Thus, based on the adopted methodology, we quantified the carbon sequestered by the plant species constituting these formations (Figure 1.4). From this figure, the species that sequester the most carbon are *Syzygium guineense* var. *guineense*, *Breonadia salicina* and *vitex doniana*.

In sum, the sampling carried out stores approximately 253,952.685 kg over an area of 3.6 ha. From this data, we generalize to all the sites of study. We need then to determine the area of the surface covered by these formations. This operation is made easy because of the cartography of the site of study based on remote sensing images.

Determination of the total area of closed vegetation formations

In order to determine the total aboveground biomass of the closed vegetation formations in the Administrative Division of “La Vina”, we used the method based on co-variables in remote sensing. The aim is to determine the total area covered by these vegetation formations from image processing. Thus, in the following lines, the mapping of the said vegetation formations and their determined surface areas will be carried out.

Evaluation of the directed classification

The average value of the Kappa index obtained in our classification is 97.25%. According to Pontius (Anaba, op. cit.), in a land cover study, when the Kappa index evaluated is

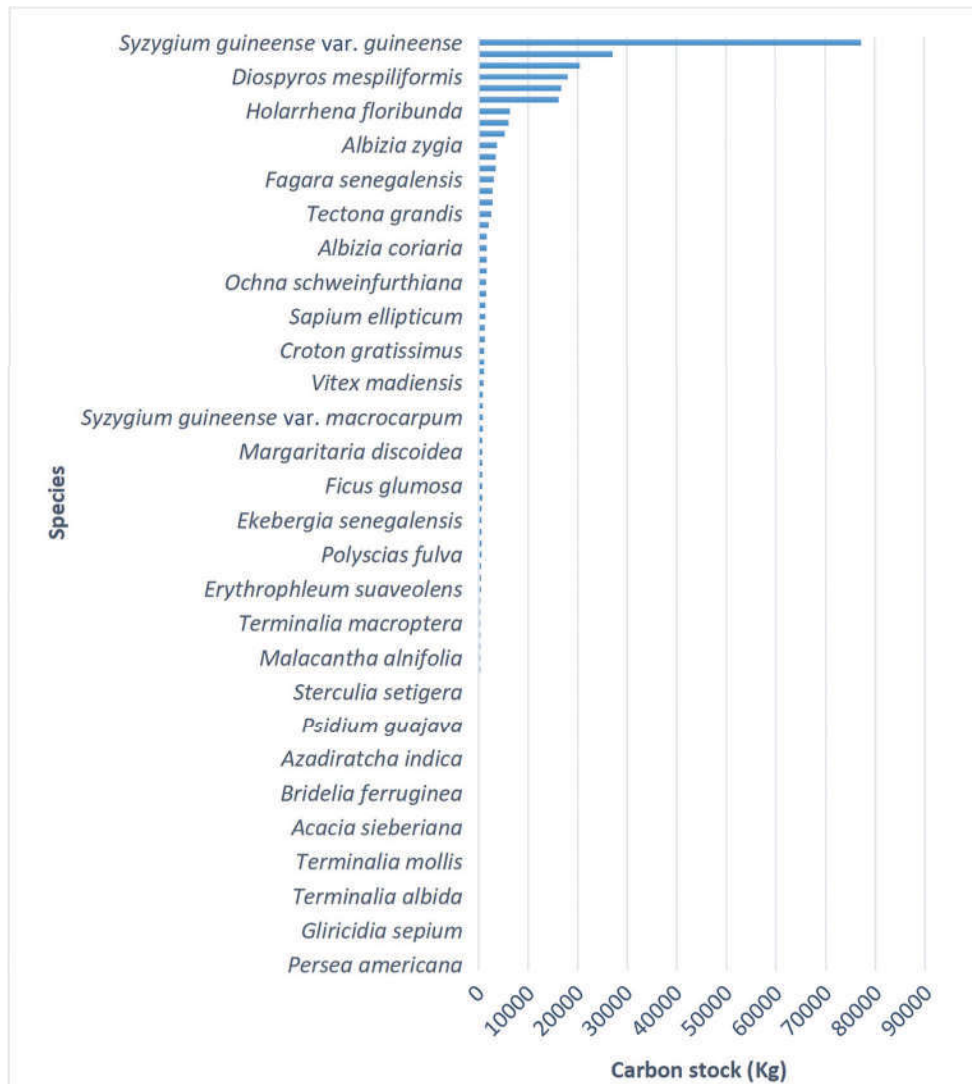


Figure 1.4 Carbon stock by plant species

between 50 and 75%, the classification adopted can be qualified as valid. On the other hand, when it is higher than 75% as in the case, it is very good.

Analysis of land-use types

Figure 1.5 shows the mapping of land-use types in the Vina district. It shows that natural vegetation formations are distributed throughout the study area. These vegetation formations constitute the relics of forests whose progressive disappearance would have been caused by the increase in agricultural areas.

These vegetation formations are mainly concentrated in the north of the map and in its western part. They are almost non-existent near the urban centre in Ngaoundéré, probably

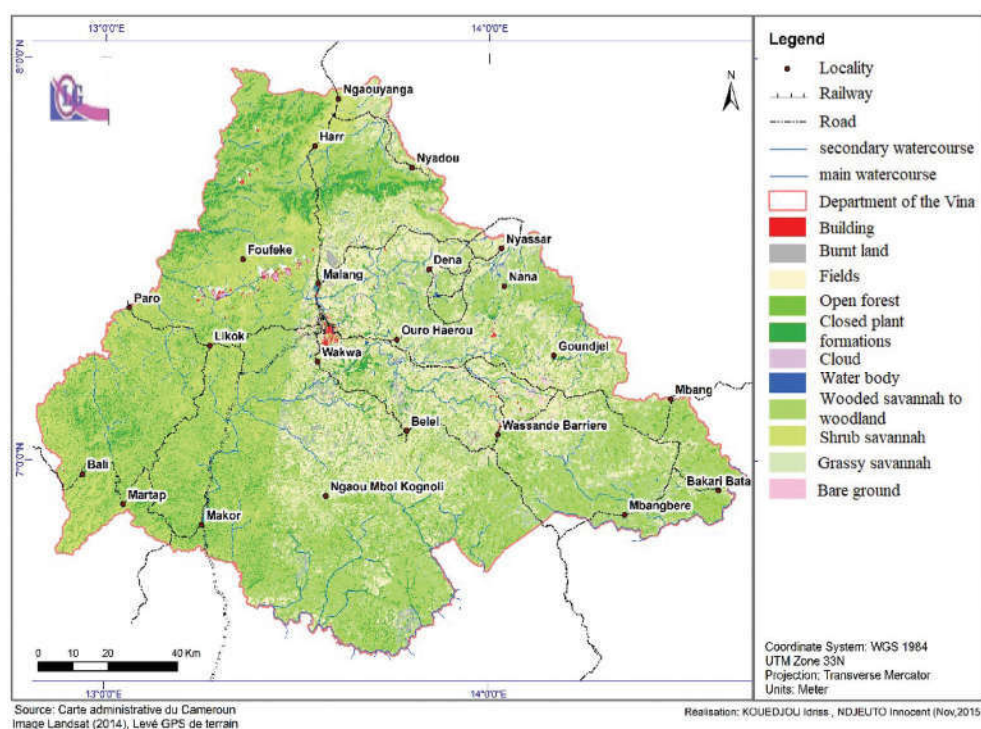


Figure 1.5 Land-use types

due to their over-exploitation due to their proximity. Table 1.6 presents the different areas used for a better characterization of land-use types in the study area. The post-classification treatments made it possible to identify the different types of land use as well as their respective surface areas in hectares.

Based on Table 1.6, the closed vegetation formations in the Division cover an area of 145,678 ha and represent 1/8 th of the total area of the Administrative Division of Vina.

Figure 1.6 shows the spatial distribution of closed vegetation formations in the Vina Division. It can be seen that these formations are distributed over the whole area but are more concentrated at the northern and south-western ends of the study area. This situation is probably the result of clearing by the local population with a view to developing agricultural areas. This class is characterised by species such as *Syzygium guineense* var. *guineense*, *Vitex doniana*, *Phoenix reclinata*, *Ficus platyphylla*, *Voacanga africana*, *Uapaca togoensis*, *Fagara*, *Albizia Zygia*, *Albizia coriara* and *Afzelia africana*.

Estimation of the Biomass and the quantity of carbon stored at the scale of the Administrative Division

The estimation of the biomass contained in all the closed vegetation formations of the Vina Division was based on an extrapolation from an expansion factor (40,466.11), which was determined using the biomass value of the sampled area.

Table 1.6 Area of the different land-use types

Types of land use	Area (ha)	Percentage (%)
Buildings	4,775	0.28
Fields	335,815	19.57
Open forest	42,555	2.48
Closed vegetation formations	145,678	8.49
Burnt land	47,354	2.76
Waterbody	2,890	0.17
Wooded savannah	848,626	49.45
Shrubby savannah	247,165	14.40
Grassy savannah	25,943	1.51
Bare ground	15,264	0.89
Cloud	1	0.00006
Total	1,716,065	100

**Figure 1.6** Spatial distribution of closed vegetation formations

The value of the carbon stored by all the closed vegetation formations in the study area is therefore equal to:

$$AL: EF* \sum_{1}^n CVP \quad (1.1)$$

With EF: expansion factor; CVP: carbon value of a plot

The value of the total biomass contained in the closed vegetation formations of the Vina Division is approximately 31,712,885.75 t. The amount of carbon stored by these closed vegetation formations is estimated at 10 15 856 442.88 t C. It should be noted that these results are highly dependent on the method used and the period of the field surveys.

1.5 Discussion

The use of Landsat imagery for land cover mapping is the main limitation of this study. Indeed, with a precision of 30 m, it is difficult, if not impossible, to identify the different boundaries of land cover types clearly enough. Despite this constraint, maximum effort was made to obtain a representation as close to reality as possible. The perfect knowledge of the terrain coupled with the information from Google Earth was decisive. This is illustrated by the statistically acceptable classification rate (Kappa index = 97%).

Another limitation is the relatively small size of the sampled closed vegetation formations. Working on a much larger sample would certainly improve the results.

The average amount of carbon stored per hectare by the closed vegetation formations of the Vina Division is 107.50 t/ha. Our results are higher than those of Ana-Helena et al. (op. cit.) who found 29.348 t C /ha in the wooded savannas of the Nhecolandia-Pantanal in Brazil. Our results are also superior to those of Tchobsala (2010) who found a value between 13.61 and 19.28 t C/ha in the savannas of Ngaoundéré. In this respect, in Sudanese-Guinean environments, closed-canopy areas are better carbon reservoirs than open plant formations. They therefore deserve to be better conserved and preserved.

Our results are also higher than those found in the Sudano-Guinean savannahs of Mali, which report 100 t C/ha (AEDR 2013). This difference can be explained by the choice of method adopted for the evaluation of epigenetic carbon. However, this value of carbon obtained per hectare (107.50 t/ha) in the Vina Division combined with the area covered by the closed vegetation formations of the said Division (145,678 ha) shows the extent to which the marginal forests of the Congo Basin and particularly that of our study area, are an integral part of the response to climate change, through their role in reducing the quantity of carbon present in the atmosphere.

1.6 Conclusion

The aim of this work was to adopt an adequate method for estimating hypogeous carbon stocks of marginal closed vegetation formations in the Congo Basin based on the Vina vegetation formations. It also aimed at providing data on the biomass and quantity of carbon contained in the closed vegetation formations of the Vina Division as well as their spatialization. To achieve this, the authors adopted the following allometric equation. The result obtained was then multiplied by 0.5, representing the conversion coefficient of

biomass to stored carbon according to the literature. The generation to the whole forest area was possible through the use of an expansion factor determined as follows

$$A = \left(\sum_{i=1}^n n_i \times 0,5 \right) \times EF \quad (1.2)$$

This expansion factor was calculated thanks to the following equation 1.3

$$EF = \frac{\text{total area}}{\sum_{i=1}^n n_i} \quad (1.3)$$

Thus, at the end of this study, the Vina Division covers a total area of 1,716,065 ha. Closed vegetation formations occupy an area of 145,678 ha. Based on the methodology adopted for the study, taking into consideration the period of collection of phytogeographical data, these vegetation formations sequester approximately 15,856,442.88 t of carbon.

Despite the methodological limitations outlined above, this study can thus serve as a benchmark for future research. It also makes a significant contribution to the understanding of climate dynamics in the Cameroonian Sudano-Guinean savannahs. Climate change is the environmental challenge of the century and sustainable forest management, which is a component of REDD+, is one of the main ways to effectively combat this threat. This management requires basic, reliable information on the state of the forests, their evolution and their carbon storage potential. This study goes some way to meet these expectations.

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2. A novel technique for carbon sequestration assessment applied to marginal forests

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Abstract

Many techniques for the assessment of carbon sequestration are developed for classic forests. But very few researchers are interested in evaluation of the carbon sequestration capacity of marginal forests. In this chapter, we propose an innovative technique of evaluating the capacity of carbon sequestration of marginal forests, based on a new allometric equation and a novel technique of colored and multiband image classification. Based on a series of 151 plots identified and characterized in 15 representative sites, we identify the various tree species present on the site of study and then we customize the Brown allometric equation. The obtained equation is successfully used to assess the

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capacity of carbon sequestration of marginal forests in Adamawa Cameroon. Finally, we ascertain that the gallery forests of Mayo Paro sequestered 194.22 t/ha while closed-canopy areas of Vina sequestered 108.85 t/ha. These results are validated through a verification mission at the site of study.

Key words: Image classification, closed-canopy area, gallery forest, allometric equation, carbon sequestration, biomass assessment

2.1 Introduction

The increase in greenhouse gases (GHGs) concentration in the atmosphere, mainly carbon dioxide (CARBON DIOXIDE) 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 deal of scientific interest has developed around forests with their ability to sequester carbon in their biomass via photosynthesis. This stored carbon is lost when forest is destroyed and burnt, inducing an increase of the proportion of this chemical element in the atmosphere. According to (Ana-Helena et al. 2012) and (Pachauri and Reisinger 2007), carbon dioxide emissions from land-use change is the second leading cause of increased atmospheric carbon dioxide concentration, after emissions from fossil fuel combustion. In Cameroon, forests cover 41.3% of the national territory and represent 10% of Congo watershed forests (Wasseige et al. 2012). According to (IUCN Cameroon, Forest Conservation Programme 2013), greenhouse gas emissions in Cameroon in 1994 were estimated at 43 988 Gg of carbon dioxide, 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 carbon dioxide in the atmosphere, strategies such as the Clean Development Mechanism (CDM) and REDD have been developed to reduce GHG emissions such as methane and carbon dioxide. 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 (Tayo Gamo 2014), (Dmapo Wambo 2012), (CIRAD 2014). 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-canopy areas. The studies carried out by (Tchobsala 2010) and (Aoudou Doua 2010) 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 (Brown et al. 1989) 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-canopy areas, we propose a new methodology of sequestered hypogenous carbon stock evaluation. The proposed approach, thanks 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 rest of this chapter is organized as follows: we first present, in the next section, a general overview of carbon sequestration, followed by a comparative study of some techniques of Carbon sequestration assessment. A fourth section presents the proposed approach for carbon sequestration assessment. The fifth section before the conclusion then presents some main results.

2.2 Carbon sequestration

Carbon is one of the most abundant chemical elements on Earth. It is present in all living things. It is also a naturally occurring component of Earth's atmosphere. Carbon in large quantities is found in the leaves, branches, stems and trees roots. In addition to being made up of 50% water, the biomass of a live tree contains approximately 25% carbon. If all the water contained in a live tree were removed, the proportion of the remaining dry biomass that consists of carbon would increase from 25% to 50%. Therefore, carbon makes up roughly half of the total Above Ground Biomass (AGB) of a tree. For example, if a tree has an AGB of 2.4 metric tons, then the carbon found in that tree has a weight of 1.2 metric tons. Denoted by the symbol C, carbon is found in the chemical compounds carbon dioxide (carbon dioxide) and methane (CH₄), two greenhouse gases that occur naturally in the atmosphere but are also produced in large quantities through human activities, namely the burning of fossil fuels such as coal and oil. Greenhouse gases act like a blanket above the Earth, trapping heat near the surface, keeping the temperature of the planet warm enough to support life (Walker et al. 2011). It is well known that carbon dioxide is the greenhouse gas, harmful for human beings and most commonly produced in the world. Carbon sequestration can be defined as the process of capturing and storing atmospheric carbon dioxide. It is one method of reducing the amount of carbon dioxide in the atmosphere with the goal of reducing global climate change (U.S. Department of the Interior 2022).

One distinguishes two major types of Carbon dioxide gas: geologic and biologic. Geologic carbon sequestration is the process of storing carbon dioxide (CO₂) in underground geologic formations. The carbon dioxide is usually pressurized until it becomes a liquid and then it is injected into porous rock formations in geologic basins. This method of carbon storage is also sometimes a part of enhanced oil recovery, otherwise known as tertiary recovery, because it is typically used later in the life of a producing oil well. In enhanced oil recovery, the liquid carbon dioxide is injected into the oil-bearing formation in order to reduce the viscosity of the oil and allow it to flow more easily to the oil well. The main question that arises with this method is how to identify the best area for the geological sequestration of geological carbon? This method also requires advanced technologies and an important budget. This is why this method cannot be implemented in developing countries.

On the other hand, biological carbon sequestration is the natural ability of life and ecosystems to store carbon. Forests, peat marshes and coastal wetlands are particularly good as storing carbon. Carbon can be stored in plant tissue, such as long-lived tree bark or in extensive root systems. In other words, biologic carbon sequestration is a natural method that refers to storage of atmospheric carbon in vegetation, soils, woody products and aquatic environments. For example, by encouraging the growth of plants, particularly larger plants like trees, advocates of biologic sequestration hope to help remove carbon dioxide from the atmosphere (U.S. Department of the Interior 2022). One question of

interests of administrations and researchers: How to estimate the carbon sequestration capacity of a given forest? Indeed, countries are interested in estimating the amount of carbon they can store by biologic carbon sequestration.

Much research is being conducted all over the world on how to estimate the carbon sequestration capacity of natural forests, principal absorbers of atmospheric carbon dioxide gas. In (Chabi et al. 2019), authors highlight the relevance of using the in-situ carbon and nitrogen content of the main tree species for estimating aboveground carbon and nitrogen stocks in the Sudan Savannah environment. They combine satellite images with in situ carbon and nitrogen content in dry matter of stem woods, together with locally derived and published allometric models to estimate above ground. Their results provided crucial information for carbon accounting programs related to the implementation of the REDD + initiatives in developing countries. Indeed, the estimated mean carbon content per tree species varied from $44.28 \pm 0.21\%$ to $49.43 \pm 0.27\%$. The overall mean carbon content in dry matter for the 277 wood samples of the 18 main tree species of the region was $47.01 \pm 0.28\%$, which is close to the Tier 1 coefficient of 47% default value suggested by the Intergovernmental Panel on Climate Change (IPCC). In order to provide key knowledge on vegetation structure, root biomass distribution and soil carbon stock of savannah agrosystems in Sudano-Sahelian zone of Cameroon, authors used the transect method to carry out their investigations (Awé Djongmo et al. 2019). For soil and roots sampling, they used the excavation method. As experimental device, they used the split plot. Their results showed that the highest densities were recorded in *Anogeissus leiocarpus* stands (408 ± 11.12 stems/ha).

As principal results, higher values of basal area (11.56 ± 0.57 m²/ha), biovolume (116.78 ± 16.57 m³/ha) and eco-volume (157.82 ± 22.12 m³/ha) were recorded in *Khaya senegalensis* stands. The highest total large roots biomass (65.81 ± 5.37 tC/ha) and fine roots biomass (11.42 ± 0.67 tC/ha) were recorded in *Khaya senegalensis* stands. The highest total medium root biomass was recorded in *Burkea Africana* stands (23.21 ± 1.15 TC/ha). The soil carbon stock was higher in *Khaya senegalensis* stands (132.16 ± 16.34 tC/ha). They finally concluded that savannah agrosystems in Sudano-Sahelian zone of Cameroon can be considered as carbon sinks. In (Awé Djongmo et al. 2020) authors developed an approach to assess the carbon storage in cashew plantations in the Sudano-Sahelian zone of Cameroon. In order to quantify the stock of biomass and carbon dioxide contained in agroforestry systems, the authors identified three cashew plantations selected according to age classes (0–10 years; 10–20 years and over 20 years). They undertook a 100×20 m transect method in a complete random Fisher block with five repetitions to conduct their studies. They used allometric equations to assess carbon stock in biomass and they noticed that the cashew plantation is actively sequestering carbon, showing the potentiality to mitigate global climate change. Finally, they concluded that the obtained results were an important economic, ecological and dynamic informative value to serve as a basis for guiding any program of action aiming at the conservation and sustainable management of the studied species.

2.3 Comparative study of some techniques of carbon sequestration assessment

Many techniques have been developed for carbon sequestration assessment, among which is Simple Allometry to estimate the aboveground tree biomass (Chhetri, Subberi and Katel 2021) and the famous allometric equation of Sandra Brown et al. (Brown et al. 1989)

2.3.1 Simple allometry to estimate aboveground tree biomass (Chhetri, Subberi and Katel 2021)

In this approach, tree biomass allometric equations are considered fundamental to determine the carbon sequestration potential of different species. Five broadleaved tree species – *Quercus lamellosa*, *Beilschmiedia sikkimensis*, *Castanopsis hystrix*, *Persea clarkiana* and *Symplocos sumintia* – are destructively sampled using a Randomized Branch Sampling technique (RBS) to develop allometry for AGB estimation in cool broadleaved forests in Bhutan. A total of 159 sample trees with a minimum of 32 trees from each species under different diameter class (5 cm < 90 cm), height class (4 m < 46 m) from four physiographic zones are sampled. The observed total aboveground dry biomass of the trees ranges between 4.12 and 5,579.31 kg for *Quercus lamellosa*; 3.62 < 3,464.51 kg for *Beilschmiedia sikkimensis*; 5.99 < 3,600.52 for *Castanopsis hystrix*; 8.89 < 3,689.82 kg for *Persea clarkiana* and 7.08 < 2,993.22 kg for *Symplocos sumintia*. Linear regression is attributed to *heteroscedasticity* with unequal distribution of the residual errors, while linearized regression with transformed variables exhibits the best fit line for biomass estimation. Significant prediction of aboveground tree biomass is then observed with natural log base transformed linearized power function of DBH -tree height relationships ($t(29) = 11.91, 1.63, p \leq 0.001$) $R^2 = 0.98$) followed by the transformed model of DBH as independent variable ($t(30) = 34.31, p \leq 0.001$) $R^2 = 0.97$). Therefore, the study concludes that, linearized power function with antilog bias correction factor seems better in predicting aboveground tree biomass of cool broadleaved species in Bhutan.

Concerning sample size and sample collection, authors collected sample trees of the five above species from the four physiographic zones (western, west central, eastern and east central) representative of the population. They selected the tree species based on the dominance, common timber species and those species having existing volume equation of the country. The selected samples represented range of diameter classes (Diameter class of 5–10; 10.1–20; 20.1–30; 30.1–40; 40.1–50; 50.1–60; 60.1–70 and 70.1–100) with diameter range of 5 cm – 90 cm.

2.3.2 Allometric equation of Sandra Brown et al.

In this paper, authors developed a strategy for estimating the total aboveground biomass (AGB) of tropical forests. Their approach is based on four steps:

1. they developed and tested a set of regression equations to estimate total aboveground biomass (TAGB, kg) of individual trees as a function of life zone group, diameter at breast height (D, cm), total height (H, cm) and wood density or specific gravity (S, mg/m³) and to estimate H as a function of D and life zone for use in double sampling estimates of biomass;
2. they applied the developed regressions to some 5,300 trees from 43 independent sample plots to yield estimates of TAGB per unit area by forest type. Hence, they estimate expansion factors, defined as the ratio of TAGB to commercial (stem) biomass. Commercial biomass being calculated as the product of commercial volume (as reported by the data sources) and species woods density;
3. They also applied the developed regression equations to independent stand tables from large-scale forest inventories in four countries, yielding additional TAGB estimates;
4. they combined the stock tables from the same inventories with wood density data to obtain commercial biomass, allowing additional estimates of expansion factors. Finally, they reconcile the biomass estimates reported by Brown and Lugo (S. a.-A. Brown 1984)

2.3.3 Development of biomass regression equations

Authors derived the biomass regression equation from nine datasets. They followed by evaluating several linear and transformed non-linear equations for each of the three forest types, notably wet and rain, moist and dry forest life zones. The regression equation was developed as a function of the diameter at the breast height (DBH), the total height (H), the wood density (S) and the Holdridge life zone (Holdridge 1967) to estimate the AGB of individual trees. They selected 53 independent sample plots from which they identified some 5,300 and 101 tables from large-scale forest inventories in four countries, on which the regressions were applied to estimate commercial and total AGB per unit area by forest type and to estimate expansion factors defined as the ratio of AGB to commercial biomass. They noticed that the quadratic stand diameter (QSD, i.e., the diameter of a tree average basal area) in a given forest stand influences the magnitude of the expansion factor. Their study revealed that Stands of small trees have large expansion factors (up to 6.4) and as QSD increases, the expansion factor decreases to a constant value around 1.75. For undisturbed forests in moist, moist transition to dry and dry life zones respectively, authors obtained respectively 1.54, 1.95 and 1.57 as expansion factors for total AGB. For undisturbed, logged and non-productive forest categories used by the FAO to report global commercial wood volume data, they obtained respectively 1.75, 1.90 and 2.00 as estimated expansion factors. They concluded that, applying these factors to FAO data results in a 28 to 47% increase in previous volume-derived estimates of tropical forest biomass. However, estimates of tropical forest biomass based on small destructive samples continue to be high relative to estimates based on volume data.

To obtain these results, they first developed and tested a set of regression equations to estimate the total AGB of individual trees as a function of life zone group, DBH, total height wood or specific gravity. Then they applied these regressions to some 5,300 trees selected from 43 independent sample plots to yield estimates of total AGB per unit area by forest type, followed by the estimation of the expansion factors and the calculation of commercial biomass. After, they applied the regression equations to independent stand tables from large-scale forest inventories in four countries, yielding additional total AGB estimates. Finally, they estimated the biomass reported by Brown and Lugo (Brown and Lugo 1982) (S. a.-A. Brown 1984).

To construct the biomass regression, they started by a non-linear model in the form $Y = \beta_1 X^{\beta_2}$. Taking the natural log this equation is written in the following form:

$$\ln(Y) = \ln(\beta_1) + \beta_2 \ln(X) = \alpha_1 + \alpha_2 \ln(X) \quad (2.1)$$

Based on the equation (2.1) model, considering D as the diameter at breast height, H as the total height of the tree and S as the specific gravity, the authors derived the following six models:

Linear (weighted):

$$\hat{Y} = \beta_1 + \beta_2 D + \beta_3 D^2 \quad (2.2)$$

$$\hat{Y} = \beta_1 + \beta_2 (D^2 H) \quad (2.3)$$

$$\hat{Y} = \beta_1 + \beta_2 (D^2 HS) \quad (2.4)$$

Transformed non-linear:

$$\widehat{\ln(Y)} = \beta_1 + \beta_2 \ln(D) \quad (2.5)$$

$$\widehat{\ln(Y)} = \beta_1 + \beta_2 \ln(D^2 H) \quad (2.6)$$

$$\widehat{\ln(Y)} = \beta_1 + \beta_2 \ln(D^2 HS) \quad (2.7)$$

The authors finally came out with the regression equations reported in the following Table 2.1.

Table 2.1 Regression equations for the estimated TAGB (Y, kg/tree) and total height (H, m) in tropical forests by life zone group

N°	Life zone	Equation	n	R ² (Adj)	MSE
1	Dry	$\hat{Y} = 34.4703 - 8.0671(D) + 0.6589(D^2)$	32	0.67	0.02208
2	Moist	$\hat{Y} = 38.4908 - 11.7883(D) + 1.1926(D^2)$	168	0.78	0.06181
		$\hat{Y} = e^{-3.1141 - 0.9719 \ln(D^2 H)}$	168	0.97	0.1161
		$\hat{Y} = e^{-2.4090 + 0.9522 \ln(D^2 HS)}$	94	0.99	0.06079
		$\hat{H} = e^{(1.0710 + 0.5677 \ln(D))}$	3824	0.61	0.07495
3	Wet	$\hat{Y} = 13.2579 - 4.8945(D) + 0.6713(D^2)$	69	0.90	0.02247
		$\hat{Y} = e^{-3.3012 + 0.9439 \ln(D^2 H)}$	69	0.90	0.02110
		$\hat{H} = e^{1.2017 + 0.5627 \ln(D)}$	69	0.74	0.4299

2.3.4 Application of the regression equations

Equations of Table 2.1 were applied to individual trees from moist, moist-transition-to-dry and dry life zone plots to estimate the TAGB/ha. Authors also applied regressions for the moist forest to plot data from moist-transition-to-dry forest. The minimum tree diameter included in sample plots ranged from 5 to 25 cm.

2.3.5 Results

Authors concluded that the moist life zone has the most biomass per unit area, followed by moist-dry and dry life zones.

2.4 A new approach of carbon sequestration assessment

A biomass equation considering both diameter at the breast height D and the total height H should yield better estimates than an equation using D only, because of the additional information imported by the knowledge of H (S. a.-A. Brown 1984). In contrast

to closed-plan formation, most large-scale tropical forest inventories do not measure H , due to time and cost constraints

2.4.1 Site of study

The site of study is located in the Adamawa region of Cameroon (Figure 2.1), 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-Déou, Adamawa Region. It is located between latitudes $6^{\circ}60'$ and $7^{\circ}24'$ north and longitudes $12^{\circ}30'$ and $12^{\circ}42'$ 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 covers an area of approximately 56,118.7134 ha, occupied by 12 villages: Loungtoug, Walkossam, Mayo-Toloré, Laura, Sadeck, Mayo rounkongo 1 and 2, Paro lewel 1 and 2, Gassanguel, Carrefour Galim and Paro Ndjidda. The climate is balanced between wet and dry seasons. The temperature varies from 12° to 34° . The main activity in the region is farming.



Figure 2.1 Location of the site of study

2.4.2 Materials and data

To carry out the inventory, four of us went to the field. We used: four GPS (Global Positioning System) terminals for the acquisition of geographic coordinates of eligible trees in selected plots; four tape measures 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; four machetes to facilitate progress through the forest and to de-bark trees, and a four-meter board to calibrate the height of individuals for the total height-evaluation process.

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

2.4.3 Methods

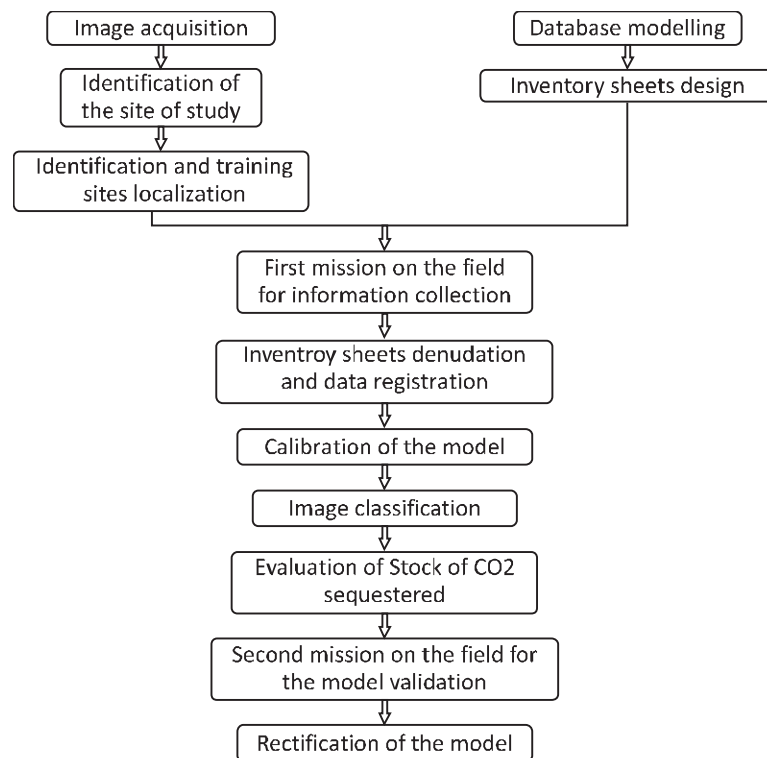


Figure 2.2 Flowchart of the proposed approach

Image acquisition and identification of site of study

We used Google earth to identify the area of study and to extract the geographic coordinates of its boundaries. These geographic coordinates were used to download images from Landsat archives on the one hand and the Sentinel images on the other hand. We downloaded two scenes that we merged in order to obtain a single image that covers

the entire site of study. The result of this phase is detailed in section 2.4.1 above. We were familiar with the study site, because we had conducted many other projects on the same site, notably the framework of students' dissertations.

Identification of training sites

After some geometric and radio corrections made on the obtained image, we were able to identify a total of 21 training sites. The main criteria of selection were the homogeneity of the area and the texture color. For each training site, the geographic coordinates of the center point were extracted for verification purposes in the field.

Database modelling

This is a laboratory work that first consists in identifying and characterizing the various classes of entities, followed by the establishment and characterization of classes of relations and the insertion of cardinalities. We came out with the following Conceptual Model of Data.

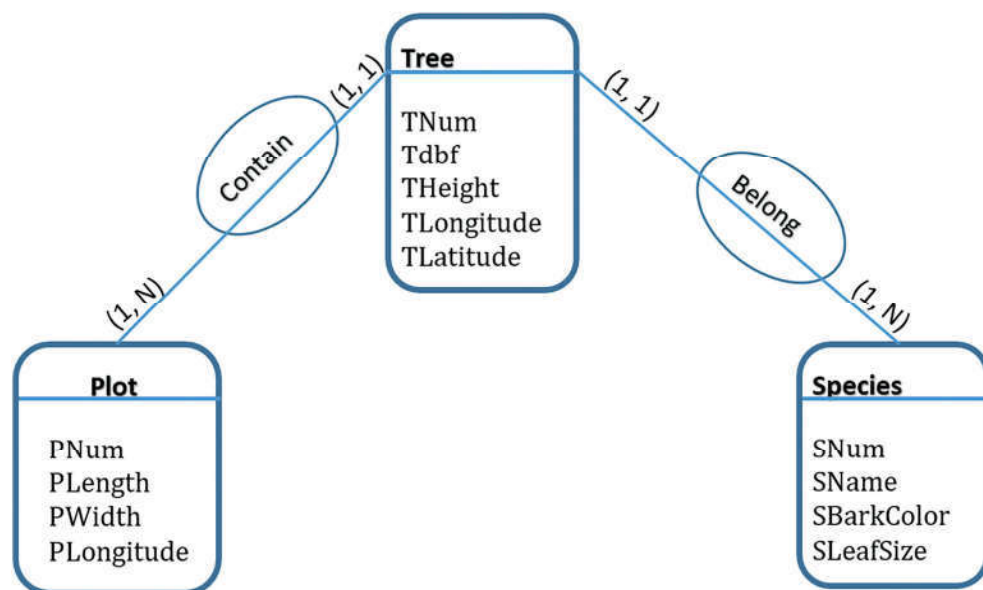


Figure 2.3 Conceptual model of data

Inventory sheet design

From the conceptual model of Figure 2.3, the following Logical Model of Data (relational model) is derived.

Plot (**Pnum**, Plength, Pwidth, Plongitude, Platitude)
 Tree (**Tnum**, Plotnum*, Speciesnum*, Tdbf, Theight, Tlongitude, Tlatitude)
 Species (**Snum**, Sname, Sbarkcolor, Sleafsize, Sserfcolor)

Where Plotnum and Speciesnum are foreign keys identifying the plot and the species respectively. From these relations, three forms (inventory sheets) are built for field data collection.

Data collection

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-canopy areas), 90 plots of 400 m² (20 m size square) each are carried out in 09 representative sampling sites. In the second site of study, 61 plots of 400 m² each are carried out in 6 sampling sites. The sampling sites were chosen according to the accessibility and representativeness of the plant formation. A total of 151 plots were then identified and characterized on the site of study.

The floristic inventory consisted of identifying and characterizing, for each plot, all trees of at least 31.5cm circumference and at least 5m height within the plot. Individuals that did not meet these criteria were simply identified and registered in the database, without being measured. On each of the individuals fulfilling the above conditions, the determination of scientific names was done *in situ*, thanks to the “Ligneux du sahel” (BONNET, ARBONNIER et GRARD 2008) 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 1.30m (DBH). For this category, we measured the circumference beyond the buttress as suggested in (Walker et al. 2011). 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’ (IFE - Institut français de l’éducation 2018).

Inventory sheet denudation and data registration

Before the data collection, all the tables (relational model) are created in the QGIS environment. Since the sheets are designed in conformity with the relational model of the data base, it is very easy to register the collected data in the system.

Calibration of the model of biomass and carbon estimation

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 (Ketterings et al. 2001). But considering this diversity, lack of resources forced many researchers to use the same methodology for all species. This is why many authors use regression equations for the most commonly encountered species in sites (Penman et al. 2003) and (Thiams et al. 2014). Among the existing equations for estimating biomass, that of Brown et al. (1989) was retained because it has been developed under climatic conditions almost similar to our site of study, with an average annual rainfall varying from 1,500 to 4,000 mm, including that of Adamawa (1,200–2,000 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 dendrometry factors from our inventory. For a given tree species i , this biomass equation is given by the following equation 2.8.

$$B_i = e^{-\alpha_i + \beta_i \ln(DBH_i^2 * h_i)} \quad (2.8)$$

h_i being the total height of the tree of species i .

For *Berlinia grandiflora*, for example, the coefficients are given by the following equation 2.9.

$$\alpha_i = -3.1441; \beta_i = +0.9719 \quad (2.9)$$

It is known that the estimation of the carbon contained in a tree is half of the value of its dry biomass. This relationship has been modeled by the following equation 2.10.

$$\text{Stored carbon } (C_i) = \frac{1}{2} B_i \quad (2.10)$$

The quantity of carbon sequestered in a plot j ($1 \leq j \leq N_s$) is then obtained by the following equation 2.11. N_s being the total number of plots in the site.

$$SC_j^i = \frac{1}{2} \sum_i \left(e^{-\alpha_i + \beta_i \ln(DBH_i^2 * h_i)} \right)_j \quad (2.11)$$

The total quantity of sequestered carbon for the N_s plots is given by the following equation 2.12.

$$SC_t^i = \frac{1}{2} \sum_{j=1}^{N_s} \left[\sum_i \left(e^{-\alpha_i + \beta_i \ln(DBH_i^2 * h_i)} \right)_j \right] \quad (2.12)$$

Knowing that plots are of size $P = 20 \times 20 \text{ m} = 400 \text{ m}^2$, we can calculate the quantity of carbon sequestered per surface unit (1 m^2) by a given tree species “ i ”. This quantity is the average of the quantities of carbon sequestered by this tree species in the N_s plots divided by the size P of a plot. The formula is given by the following equation 2.13.

$$SC_u^i = \frac{1}{PN_s} SC_t = \frac{1}{2PN_s} \sum_{j=1}^{N_s} \left[\sum_i \left(e^{-\alpha_i + \beta_i \ln(DBH_i^2 * h_i)} \right)_j \right] \quad (2.13)$$

Once the quantity of Carbon sequestered per surface unit (1 m^2) by a given tree species “ i ” is known, we classify the image. Using a supervised image classification approach and we calculate the total area Ω of the marginal forest. Then the Total quantity of Carbon sequestered by the species “ i ” is given by the following equation 2.14.

$$SC_t^i = \frac{\Omega}{2PN_s} \sum_{j=1}^{N_s} \left[\sum_i \left(e^{-\alpha_i + \beta_i \ln(DBH_i^2 * h_i)} \right)_j \right] \quad (2.14)$$

N_T being the number of tree species identified in the plot.

To generalize this formula on the whole site of study, we use the results acquired on the various experimental plots to assess the proportion of each tree species per surface unit.

Estimation of the proportion of a tree species in the site of study

The probability of occurrence of a given tree species in a plot depends on the type of forest in which the plot has been delimited. We study separately the plots delimited in the Closed-canopy areas and those delimited in Gallery forests. Experimentally, 90 plots were delimited in the Close-canopy area and 61 in the Gallery Forest.

Let H_x and D_x be respectively the total height and the DBH (about 1,30m from the grown) of a tree of species “x” found in a plot.

For each plot “j” delimited in the Gallery Forest thematic class, we calculate the proportion P_{s_j} of the tree species “s” contained in the plot j, using the following formula.

$$P_{s_j} = \left(\frac{\sum_i (H_i * D_i)_{i=s}}{\sum_i (H_i * D_i)} \right)_j \quad (2.15)$$

Where the parameter i represents the identifier of a tree found in the plot. The condition $i=s$ verifies if the i^{th} tree (tree of identifier i) identified in the plot is of species s. The proportion P_{s_G} of the tree species “s” present in the site of study and identified as belonging to the gallery forest thematic class is then defined by the following formula:

$$P_{s_G} = \frac{1}{N_G} \sum_{j=1}^{j=N_G} P_{s_j} = \frac{1}{N_G} \sum_{j=1}^{j=N_G} \left(\frac{\sum_i (H_i * D_i)_{i=s}}{\sum_i (H_i * D_i)} \right)_j \quad (2.16)$$

N_G being the total number of plots delimited in the gallery forest. For the present study, $N_G = 61$.

Similarly, considering N_p as the total number of plots delimited in the closed plan formation, the proportion P_{s_p} of the tree species “s” present on the site of study and identified as belonging to the closed-canopy area thematic class is given by the following formula.

$$P_{s_C} = \frac{1}{N_C} \sum_{j=1}^{j=N_C} P_{s_j} = \frac{1}{N_C} \sum_{j=1}^{j=N_C} \left(\frac{\sum_i (H_i * D_i)_{i=s}}{\sum_i (H_i * D_i)} \right)_j \quad (2.17)$$

For the present study, $N_C = 90$.

Knowing the proportion of each tree species in each of the two types of forest (gallery forest and closed-canopy area), we need to know the total area of each of them. From this total area, we can estimate the total quantity of each tree species in the site of study. From this total quantity, we assess the total above ground biomass (TAGB) on the site of study. For this purpose, we need to classify the image acquired on the site of study. This image is a Sentinel coloured image.

2.4.4 Colored image classification

The classification process begins with the identification and development of a certain number of predefined important thematic classes or land uses. Nine (9) thematic classes have been identified on the site of study. These classes are the following: tree savannah,

burned areas, grassy savannah, built-up areas, wooded savannah, closed-canopy areas, clear-cut forest, cultivated fields and gallery forest. Among all the nine thematic classes, only two – gallery forest and closed-canopy areas – contain trees in a considerable proportion. This is why we are particularly interested in these two categories. But for accuracy purposes, we classify the image, taking into consideration all the thematic classes because indeed, each pixel must be assigned to the nearest thematic class during the classification process.

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 assigned to one of the previously listed land use or thematic 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. The application is done on a Sentinel-2 image made-up of thirteen bands. From the thirteen bands, the Red, Green and Blue (band 2, 3 and 4) ones are extracted. On each band, a series of 20 textural parameters are tested and the correlated ones eliminated. The following are the aforementioned textural parameters:

Contrast:

$$Cst = \frac{1}{N} \sum_{i=0}^{MaxGS} \sum_{j=0}^{MaxGS} (i-j)^2 P_{ij}$$

Correlation:

$$Cor = \frac{1}{N} \sum_{i=0}^{MaxGS} \sum_{j=0}^{MaxGS} \frac{(i-\mu_x)(j-\mu_y)}{\sigma_x \sigma_y} P_{ij}$$

Covariance:

$$Cov = \frac{1}{N} \sum_{i=0}^{MaxGS} \sum_{j=0}^{MaxGS} (i-\mu_x)(j-\mu_y) P_{ij}$$

Inverse difference:

$$InvD = \frac{1}{N} \sum_{i=0}^{MaxGS} \sum_{j=0}^{MaxGS} \frac{1}{1+|i-j|} P_{ij}$$

Dissymmetry:

$$Diss = \frac{1}{N} \sum_{i=0}^{MaxGS} \sum_{j=0}^{MaxGS} |i-j| P_{ij}$$

Standard deviation:

$$StD = \frac{1}{N} \sqrt{\sum_{i=0}^{MaxGS} \sum_{j=0}^{MaxGS} (i-\mu_x)^2 P_{ij}}$$

Cluster shade:

$$CS = \frac{1}{N} \sum_{i=0}^{MaxGS} \sum_{j=0}^{MaxGS} (i+j-2\mu_x)^3 P_{ij}$$

Cluster prominence:

$$CP = \frac{1}{N} \sum_{i=0}^{MaxGS} \sum_{j=0}^{MaxGS} (i+j-2\mu_x)^4 P_{ij}$$

Importance of large numbers:

$$IGN = \frac{1}{N} \sum_{i=0}^{MaxGS} \sum_{j=0}^{MaxGS} (i^2 + j^2) P_{ij}$$

Importance of small numbers:

$$ISN = \frac{1}{N} \sum_{i=0}^{MaxGS} \sum_{j=0}^{MaxGS} \frac{1}{(i^2 + j^2) + \epsilon} P_{ij}$$

Inverse differential moment:

$$IDM = \frac{1}{N} \sqrt{\sum_{i=0}^{MaxGS} \sum_{j=i+1}^{MaxGS} \frac{1}{(i-j)^2 + 1} P_{ij}}$$

Mean:

$$\mu_x = \frac{1}{N} \sum_{i=0}^{MaxGS} \sum_{j=0}^{MaxGS} i P_{ij}$$

Variance:

$$Var = \frac{1}{N} \sum_{i=0}^{MaxGS} \sum_{j=0}^{MaxGS} (i - \mu_x)^2 P_{ij}$$

Entropy:

$$Ent = \frac{1}{N} \sum_{i=0}^{MaxGS} \sum_{j=0}^{MaxGS} P_{ij} \log(P_{ij})$$

Depth importance:

$$DIm = \frac{\sum_{i=0}^{MaxGS} \sum_{j=0}^{MaxGS} (P_{ij})^2}{\sum_{j=0}^{MaxGS} P_{ij}}$$

Maximum probability:

$$MP_r = \max_{0 \leq i, j \leq \text{MaxGS}} \{P_{ij}\}$$

Second angular moment:

$$SAM = \sum_{i=0}^{\text{MaxGS}} \sum_{j=0}^{\text{MaxGS}} (P_{ij})^2$$

Third angular moment:

$$TAM = \sum_{i=0}^{\text{MaxGS}} \sum_{j=0}^{\text{MaxGS}} (P_{ij})^3$$

Square sum of variance:

$$SSV = \frac{1}{N} \sum_{i=0}^{\text{MaxGS}} \sum_{j=0}^{\text{MaxGS}} (i - \mu_x)^4 P_{ij}$$

Energy:

$$Ene = \sum_{i=0}^{\text{MaxGS}} \sum_{j=0}^{\text{MaxGS}} (P_{ij})^2$$

Where P_{ij} is the probability that, in a given image window, a pixel of a gray scale i is followed by a pixel of gray scale j ($0 \leq i, j \leq 255$) and MaxGS is the maximum gray scale in the image window.

At the end of this verification process and elimination of the correlated textural parameters (Haralick, Shanmugam et Dinstein 1973), the following parameters are adopted:

1. The Energy parameter. This textural parameter measures the uniformity of the texture. Its expression, for a given band (selected between red, green and blue bands), is given by the following equation 2.18.

$$Ene_R = \sum_{i=0}^{\text{MaxGS}} \sum_{j=0}^{\text{MaxGS}} (P_{t_R}(i, j))^2 \quad (2.18)$$

Where MaxGS is the maximum grey scale in the red (R) band, t_R is the translation vector t , linking the pixel of grey scale j to the pixel of grey scale i in red band image R and $P_{t_R}(i, j)$ is the probability of occurrence of the couple of grey scales (i, j) linked by the translation vector t_R in the image band R.

Similarly, the energy parameters for the Green (G) and Blue (B) bands are given respectively by the following equations 2.19 and 2.20.

$$Ene_G = \sum_{i=0}^{\text{MaxGS}} \sum_{j=0}^{\text{MaxGS}} (P_{t_G}(i, j))^2 \quad (2.19)$$

$$Ene_B = \sum_{i=0}^{MaxGS} \sum_{j=0}^{MaxGS} (P_{t_B}(i, j))^2 \quad (2.20)$$

Let consider B_1 , the red image band, B_2 , the green image band and B_3 , the blue image band. Then, from equations 2.18, 2.19 and 2.20, we define the equation of the energy textural parameter for the coloured image as follows:

$$\begin{aligned} Ene &= \frac{1}{3}(ENE_{B1} + ENE_{B2} + ENE_{B3}) \\ &= \frac{1}{3} \sum_{k=1}^3 \sum_{i=0}^{MaxGS} \sum_{j=0}^{MaxGS} (P_{t_{Bk}}(i, j))^2. \end{aligned} \quad (2.21)$$

2. The entropy parameter. Contrary to the Energy, this textural parameter measures the untidiness observed in the image. For a given image band B_k ($k=1,2,3$), its expression is given by the following equation 2.22.

$$Ent_{Bk} = \sum_{i=0}^{MaxGS} \sum_{j=0}^{MaxGS} \left[\text{Log}(P_{t_{Bk}}(i, j)) \times P_{t_{Bk}}(i, j) \right] \quad (2.22)$$

According to equation 2.20 and similarly to equation 2.21, the value of the parameter Entropy for the image is given by the following equation 2.23.

$$Ent = \frac{1}{3} \sum_{k=1}^3 \sum_{i=0}^{MaxGS} \sum_{j=0}^{MaxGS} \left[\text{Log}(P_{t_{Bk}}(i, j)) \times P_{t_{Bk}}(i, j) \right] \quad (2.23)$$

3. The correlation parameter. This textural parameter measures the linear dependence (related to the translation vector t) of grey scales in the image. It is neither in correlation with the energy nor the entropy parameters. For a given image band B_k ($k=1,2,3$), its expression is given by the following equation 2.24.

$$Cor_{Bk} = \sum_{i=0}^{MaxGS} \sum_{j=0}^{MaxGS} \left[\frac{(i-\mu)(j-\mu)}{\sigma^2} P_{t_{Bk}}(i, j) \right] \quad (2.24)$$

According to equation 2.23 and similarly to equation 2.20, the value of the textural parameter Covariance for the image is given by the following equation 2.24.

$$Cov = \frac{1}{3} \sum_{k=1}^3 \sum_{i=0}^{MaxGS} \sum_{j=0}^{MaxGS} \left[\frac{(i-\mu)(j-\mu)}{\sigma^2} P_{t_{Bk}}(i, j) \right] \quad (2.24)$$

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

4. The contrast parameter. This textural parameter, the last among the selected parameters, deals with the passage of higher to lower grey scales consecutively in the image. Its expression, for a given image band B_k ($k=1,2,3$), is given by the following equation 2.25.

$$Cst_{Bk} = \sum_{i=0}^{MaxGS} \sum_{j=0}^{MaxGS} \left[(i-j)^2 P_{t_{Bk}}(i, j) \right] \quad (2.25)$$

According to equation 2.25 and similarly to equation 2.20, the value of the parameter Correlation for the image is given by the following equation 2.26.

$$COR = \frac{1}{3} \sum_{k=1}^3 \sum_{i=0}^{MaxGS} \sum_{j=0}^{MaxGS} \left[\frac{(i-\mu)(j-\mu)}{\sigma^2} P_{t_{Bk}}(i, j) \right] \quad (2.26)$$

The value of $P_{t_{Bk}}(i, j)$ is given by the following equation 2.27.

$$P_{t_{Bk}}(i, j) = \frac{|\{(r, s), (r, s) + t \in Bk / Bk(r, s) = i \text{ and } Bk((r, s) + t) = j\}|}{|(r, s) / (r, s) \in Bk \text{ and } (r, s) + t \in Bk|} \quad (2.27)$$

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, notably 3×3 , 5×5 , 7×7 , 9×9 , 11×11 and 15×15 sizes. This image window represents $8,100 \text{ m}^2$ on the field since we are using a $10 \times 10 \text{ m}$ spatial resolution image. For each image window W_i , the four adopted textural parameters are calculated to form a textural vector given by the following equation 2.28.

$$V_{W_i} = (ENE_{W_i}, ENT_{W_i}, COR_{W_i}, CST_{W_i}) \quad (2.28)$$

For the N_s plots identified on the training site as dominated by a certain information class C representing a specific tree species, the characteristic textural vector CV_C of the information class C is obtained through the formula reported in the following equation 2.29.

$$CV_C = \frac{1}{N_p} \left(\sum_{i=1}^{N_p} ENE_{W_i}, \sum_{i=1}^{N_p} ENT_{W_i}, \sum_{i=1}^{N_p} COR_{W_i}, \sum_{i=1}^{N_p} CST_{W_i} \right) \quad (2.29)$$

All over the 151 plots identified on the site of study, 9 information classes have been identified: Built, cultivated field, Clair Forest, closed-canopy areas, Burns, Tree savannah, Wooded savannah, Grassy savannah and Gallery Forest.

For each thematic or information class T , a series of 15 image windows of size 9×9 each is extracted for the characterization of the thematic class.

For each extracted image window W_i ($1 \leq i \leq 15$), the 4 adopted textural parameters (Energy, Entropy, Correlation and Contrast) are calculated to constitute a textural vector $V_{T_i} = \begin{pmatrix} Ene_i \\ Ent_i \\ Cor_i \\ Cst_i \end{pmatrix}$

The characteristic vector of the thematic class is then given by the following equation 2.30.

$$CV_T = \frac{1}{15} \begin{pmatrix} \sum_{i=1}^{i=15} Ene_i \\ \sum_{i=1}^{i=15} Ent_i \\ \sum_{i=1}^{i=15} Cor_i \\ \sum_{i=1}^{i=15} Cst_i \end{pmatrix} \quad (2.30)$$

The tolerance threshold τ_T is the maximum distance between characteristic vectors of two different windows extracted from the same thematic class T. Its formula is given by the following equation 2.31.

$$\tau_T = \max_{1 \leq i < j \leq 15} \sqrt{\sum_{k=1}^{k=4} (V_{T_i}^k - V_{T_j}^k)^2} \quad (2.31)$$

If the distance between the characteristic vector of an image window and the characteristic vector of a thematic class T is greater than τ_T , then the pixel at the centre of the image window doesn't belong to the thematic class T.

Once all the thematic classes are characterized, the following steps are followed to assign the nearest thematic class to each pixel of the image.

1. Define a specific colour for each thematic class.
2. Open the original image *Img* of size NC column and NL lines.
3. For each pixel *p* of the image *Img* do:

Extract an image window *W* of size 9×9 centred on the pixel *p*;

Construct the texture vector $V_p = \begin{pmatrix} Ene_p \\ Ent_p \\ Cor_p \\ Cst_p \end{pmatrix}$ made of the four textural parameters (Energy, Entropy, Correlation and Contrast) characterising the image window *W*.

Let Γ be the set of thematic classes identified on the site of study. Calculate the distance D_p between V_p and the characteristic vector V_T of each thematic class T of Γ .

Identify the thematic class T_0 ($T_0 \in \Gamma$) that verifies the following equation 2.32.

$$D_p = \text{dist}(V_{T_0}, V_p) = \min_{T \in \Gamma} \sqrt{\sum_{k=1}^{k=4} (V_T^k - V_p^k)^2} \quad (2.32)$$

$dist(V_{T_0}, V_p)$ being the Euclidian distance between V_{T_0} and V_p .

If $D_p \leq \tau_{T_0}$ then assign the colour corresponding to the thematic T_0 to the pixel p . Otherwise, assign the unknown thematic class T_u to the pixel p .

4. Return the classified image $ImgC$.

For the borderline pixels, the symmetric principle method of border filling is adopted because of the continuity of the space. This principle stipulates that, on the one hand, four new lines are added before and after the first and the last line respectively and on the other hand, four new columns are added before and after the first and the last column respectively. These new lines and columns are filled backwards and symmetrically to the first and the last border (line or column) of the image.

Evaluation of the quantity of sequestered carbon

The evaluation of the quantity of sequestered Carbon starts by the assessment of the total area occupied by each thematic class. This process is made possible thanks to image classification.

Since the relief is not very rugged, the area occupied by a given thematic class is the number of pixels containing the species in question, multiplied by the area of a pixel (100 m²). There follow the steps to estimate the area of the space occupied by each thematic class.

Consider Φ the set of all the thematic classes and N_T a Vector $(T_1, T_2, \dots, T_9)$ representing the number of pixels of each of the nine thematic classes $T_1, T_2, \dots, T_9 \in \Phi$.

Initialize N_T to (0,0,0,0,0,0,0,0,0).

Open the classified image $ImgC$.

For each pixel p of $ImgC$, if its colour is the one assigned to a thematic class T_i then increase the entry $N_T(T_i)$.

The area A_i (m²) occupied by the thematic class T_i is given by the following equation 2.33.

$$A_i = S_p * N_T(T_i) \quad (2.33)$$

S_p being the area of a pixel. In the present case, $S_p = 10m * 10m = 100m^2$.

Let A_G and A_C be the areas occupied by the Gallery Forest and the Closed-canopy area thematic classes respectively. $A_G = S_p * N_T(T_G) = 100 * N_T(T_G)$ and $A_C = S_p * N_T(T_C) = 100 * N_T(T_C)$.

Combining equations 2.16 and 2.33, the assessment of the total quantity of Carbon sequestered respectively inside the Gallery Forest and the Closed-canopy area is given by the following equations 2.34 and 2.35.

$$T_G = \frac{1}{400} A_C P_{s_G} = \frac{N_T(T_G)}{4N_G} \sum_{j=1}^{j=N_G} \left(\frac{\sum_i (H_i * D_i)_{i=s}}{\sum_i (H_i * D_i)} \right)_j \quad (2.34)$$

$$T_C = \frac{1}{400} A_C P_{s_C} = \frac{N_T(T_C)}{4N_C} \sum_{j=1}^{j=N_C} \left(\frac{\sum_i (H_i * D_i)_{i=s}}{\sum_i (H_i * D_i)} \right)_j \quad (2.35)$$

Finally, the total quantity of Carbon sequestered in both Gallery Forest and the Closed-canopy area is given by the following equation 2.36.

$$T = \sum_s SC_u^s \left[\frac{N_T(T_C)}{4N_C} \sum_{j=1}^{j=N_C} \left(\frac{\sum_i (H_i * D_i)_{i=C}}{\sum_i (H_i * D_i)} \right)_j + \frac{N_T(T_G)}{4N_G} \sum_{j=1}^{j=N_G} \left(\frac{\sum_i (H_i * D_i)_{i=G}}{\sum_i (H_i * D_i)} \right)_j \right] \quad (2.36)$$

Where SC_u^s is defined in equation 2.13.

2.5 Results

2.5.1 Land cover analysis

Figure 2.4 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 main city (Ngaoundere) 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.

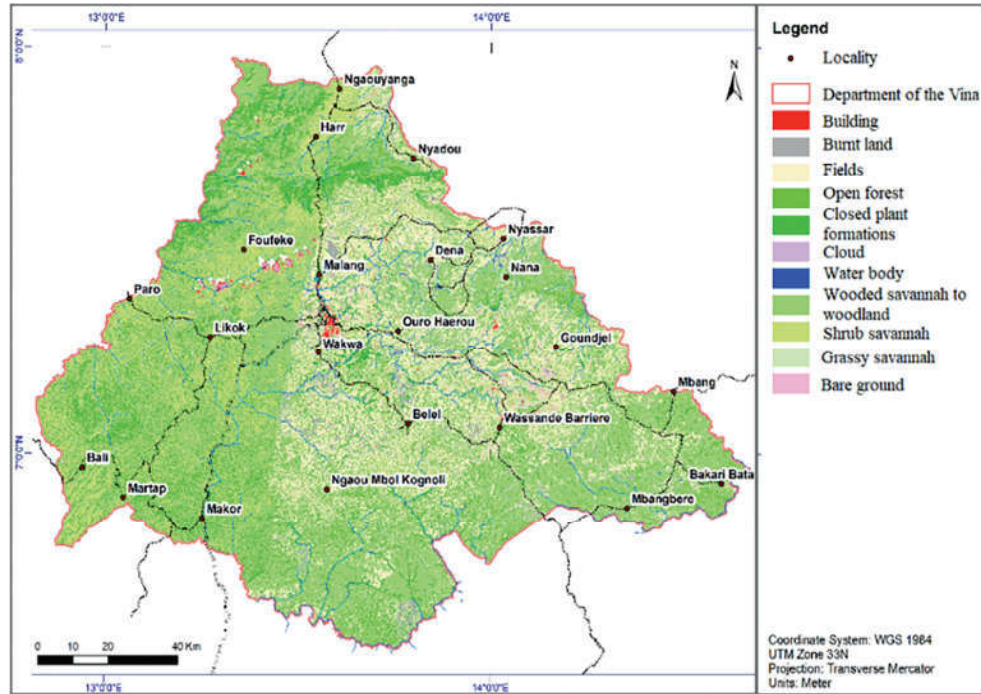


Figure 2.4 Land cover types

Figure 2.4 above shows the spatial distribution of closed-canopy areas 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 site of study.

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 (gallery forest, 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 study site (Lounis et Belhadj-Aissa 2014). 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 2.2). Thus, the closed-canopy areas of the Administrative Division of Vina cover an area of 145,678 ha and represent eighth of the total area of this Division.

Table 2.2 Area of different types of land use

N°	Land cover type	Area (ha)	Percentage (%)
1	Built environment	4,775	0.28
2	Cultivated fields	335,815	19.57
3	Tree savannah	848,626	49.45
4	Clear forest	42,555	2.48
5	Wooded savannah	247,165	14.40
6	Gallery forest	10,000	0.6
7	Grassy savannah	25,943	1.51
8	Burns	47,354	2.76
9	Closed-canopy areas	145,678	8.49
10	Unclassified	7,856	0.46
	Total	4,775	100

Floristic composition and carbon stock per species

In the closed-canopy areas sampled, 1,199 individuals were identified. They are divided into 27 families, 55 genera, 92 species with 11 indeterminate samples (Table 2.2). *Syzygium guineense*, *Vitex doniana* and *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 tonnes 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 tons of carbon with an average of 108.85 t/ha.

Table 2.3 Distribution of biomass and stored carbon by family

N°	Family	Quantities	Biomass (Kg)	Stored carbon (t)
1	Myrtaceae	284	156749.39	78.37
2	Euphorbiaceae	172	73056.79	36.53
3	Rubiaceae	98	56577.83	28.29
4	Verbenaceae	187	323918.17	24.06
5	Ebenaceae	67	35864.33	17.93
6	Moraceae	57	29903.63	14.95
7	Mimosaceae	51	27188.97	13.59
Total		916	703259.11	213.72

Species with less than 2 tons of carbon sequestered are ignored in the table.

Biomass and stocked carbon quantity estimation

The estimate of the biomass contained in all the closed-canopy areas of the site of study was based on the previous data summarized in the following Table 2.4.

Table 2.4 Summaries of data used to estimate the global carbon stock

Data	Values
Closed-canopy areas	145,678 ha
Gallery forest	10,000 ha
Sampled area	3.6 ha
Expansion factor	40,466
Total quantity of stored carbon on the site.	783,694.16 kg
Total quantity of stored carbon per sample.	253.95 kg C

The assessment of the biomass contained in all the closed-canopy areas 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-canopy areas 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 tonne of carbon dioxide reduction is equivalent to one tonne of carbon credit (Ecocredit 2013), we can estimate the total amount of carbon credit generated by marginal forests of Adamawa, Cameroon.

Carbon credit

There are several carbon assessments 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 (FA s.d.).

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.

2.6 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 Administrative Division of Vina, combined with the area covered by the closed-canopy areas 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.

2.7 Conclusion

The purpose of this work was to provide an accurate method of estimating the above ground biomass and quantity of Carbon sequestered in the closed-canopy areas and in Gallery Forest. The Administrative Division of Vina, located in Cameroon's Adamawa region has been selected as site of study. Taking into account the collection period of the phyto-geographic data, these plant formations sequester about 10 276 340,7 tons of carbon (tC) in May 2014 (year of field mission and image acquisition). The species that show the greatest carbon storage capacity are *Syzygium guineense* (77 tC), followed by *Bretonadia salicina* (27tC) and *Vitex doniana* (20 tC). This study can serve as a reference for future research. This research can be extended by integrating stocks of hypogenous 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. It is a major contribution to this issue.

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3. Plant diversity and carbon stocks of estuaries: hotspots in the Atlantic forests of Cameroon

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Abstract

Forest ecosystems are the main global reservoirs of both biodiversity and carbon stocks. They purify the atmosphere of carbon dioxide through the mechanism of photosynthesis. However, work on the involvement of these ecosystems in climate change mitigation remains little explored in Cameroon. The objective of this study was to assess the woody diversity of Atlantic forests and their contribution to mitigating climate change through carbon storage. Plots of 900 m² were installed according to the representativeness of the types of vegetation in the Kribi Marine Park (KMP) and the Douala-Edéa National Park (DENP) for the counting of individuals of dbh ≥ 10 cm. Inside each plot, two quadrats of 25 m² nested north-east and south-west were installed for the counting of individual trees of dbh < 10 cm. The indirect method made it possible

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to assess the aboveground biomass. The results reveal that the Shannon index varies between 3.72 bits in the YSFs and 1.68 bits in the fallows for individuals of $\text{dbh} \geq 10$ cm. The floristic richness of individuals with $\text{dbh} < 10$ cm is 36 species distributed in 33 genera and 22 families. The aboveground carbon stocks of individuals with $\text{dbh} \geq 10$ are 229.01 tC/ha in mature forests (MF), 216.88 tC/ha in young secondary forests (YSF), 81.93 tC/ha in mature secondary forests (MSF) and 4.89 tC/ha in fallow land (FL). This study reveals a weak contribution of individuals with $\text{dbh} < 10$ in the mitigation of climate change. A better knowledge of other types of vegetation of the Atlantic forests could constitute a necessary basis for the establishment of the REDD+ mechanism in Cameroon and the conservation of these environments.

Key words: Atlantic forests, Cameroon, carbon stocks, floristic diversity, hotspots

3.1 Introduction

Considerations of carbon stored in forest ecosystems date back to the early 1980s, alongside scientific concerns about global climate change (Mounmemei 2016). In its gaseous form, carbon dioxide is the most important greenhouse gas (GHG) given its high concentration in the atmosphere, i.e., nearly 280 ppm in 1850, rising to 370 ppm in 2000 and then to 391 ppm in 2011 (IPCC 2013). This concentration continues to increase mainly due to human activity (Hansen and Sato 2004; Oubrahim 2015). This emission represents 15 to 20% of global emissions (Bellassen et al. 2008). The increase in these emissions is one of the concerns addressed in the Kyoto Protocol, as it is the main factor of climate change (IPCC 2007). Climate change is a major challenge facing humanity today. The consequences of this phenomenon are multiple, irreversible and exceed the response capacity of natural ecosystems, which risk being altered or permanently destroyed. These natural ecosystems, in this case forests and soils, are among the carbon reservoirs of the biosphere which, through carbon sequestration, would contribute to the mitigation of environmental upheavals. According to Dixon et al. (2009) these ecosystems have fairly significant carbon accumulation capacities, whether in vegetation, humus or soil. However, the REDD+ mechanism (Reducing Emissions from Deforestation and Forest Degradation, conservation, sustainable management and increase in forest carbon stocks) is a means of combating climate change (Flanery et al. 2022) by reducing the concentration of GHGs, increasing the absorption of these gases and stabilizing their concentration in the atmosphere (Mounmemei et al. 2022).

However, coastal forests refer to forests close to the sea or the ocean whose characteristics and dynamics are conditioned by this proximity (Favennec 1999). These ecosystems include mangroves, subservient to estuaries and muddy coasts of tropical climates. They have been threatened in recent decades by galloping demography, the construction of port infrastructures and the illegal exploitation of wood energy. Like other African countries, to sustain and properly conserve its natural resource, Cameroon has extended its biodiversity conservation strategy by creating fully protected areas. However, protected areas located in coastal areas have long been classified with a view to conserving biodiversity. The advent of the REDD+ mechanism draws the attention of researchers to the carbon stocks contained in these ecosystems. Estimates of carbon stocks in tropical ecosystems are of great importance for understanding the global carbon cycle, formulating and evaluating global initiatives to reduce global warming and managing ecosystems at carbon sequestration purposes. The objective of this paper is to assess the woody diversity

of Atlantic forests and their contribution to mitigating climate change via carbon storage. This requires estimating the carbon stocks of the two protected areas using different dedicated scientific methods.

In general, the vegetation and carbon stocks in the Atlantic forests remain little known in Cameroon. These environments represent priority conservation areas in the region. A detailed understanding of its woody diversity and sequestered carbon remains essential. Previous work on the assessment of carbon stocks in Cameroon in tropical forests has focused on dense semi-deciduous forests (Mounmemei et al. 2022; Zekeng et al. 2020; Kabelon et al. 2020) and in evergreen forests (Djomo 2015; Tabue et al. 2016; Loubota-Panzou et al. 2018; Ngo Makak 2021). These different studies have revealed that floristic diversity and carbon stocks vary from one type of forest to another. In addition, the importance of light palatability and leaf texture are still little explored biological characters during the assessment of carbon stocks. Consequently, the availability of reliable information on woody diversity and carbon stocks is an essential issue for the conservation, sustainable preservation and for the REDD+ mechanism of these forest ecosystems in Cameroon. The results of this study are discussed in terms of woody diversity and carbon stocks in the context of other tropical forest types in Cameroon.

3.2 Material and methods

3.2.1 Presentation of the study sites

The present investigation took place in the Douala-Edéa National Park and the *Manyanga na Elombo-Campo* National Marine Park (Figure 3.1). Douala-Edéa National Park was

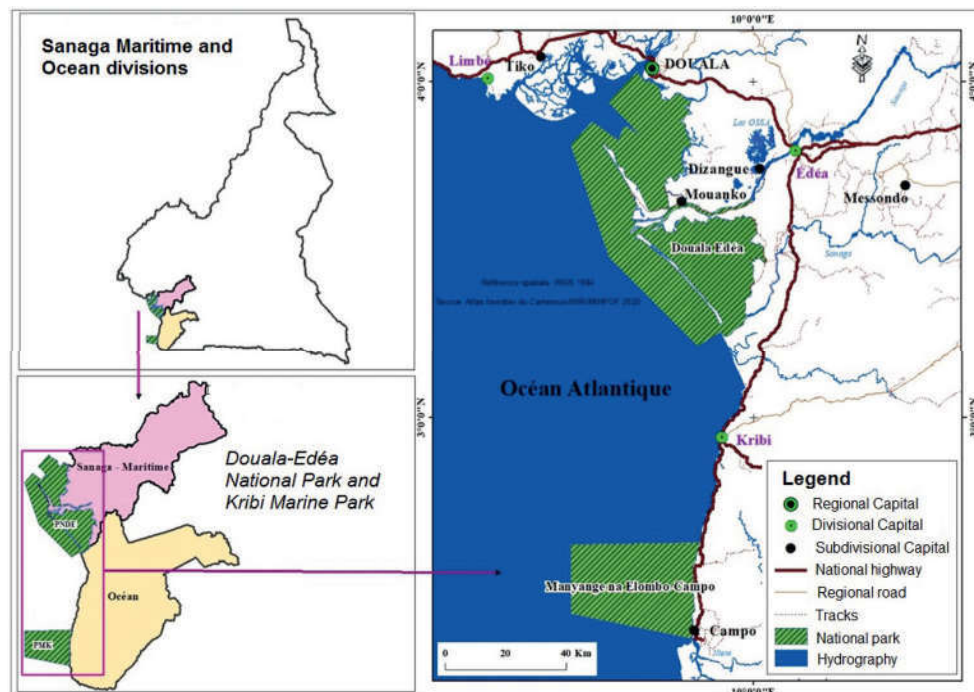


Figure 3.1 Location of the study area

created on November 19, 1932 under the name of Douala-Edéa Fauna Reserve with an area of 160,000 hectares. This reserve became on October 11, 2018 the Douala-Edéa National Park. It is located in Wouri and Sanaga Maritime Divisions of the Littoral region. It covers a total area of 262,935 hectares. The altitude varies between 0 m and 50 m. The *Manyange na Elomibo-Campo* National Marine Park was created on June 9, 2021 and covers an area of 110,300 hectares. It is located in the Campo district of the Ocean Division in the south Region of Cameroon. The altitude varies between 0 m and 50 m. From a phytogeographical point of view, the vegetation of these two parks is that of coastal Atlantic forests (Letouzey 1985).

3.3 Methods

The line transects method was adopted in this study. A 30 × 30 m quadrats, equidistant by 500 m were installed in a row along a 2,650 km transect for the inventory of all individuals with a diameter greater than or equal to 10 cm at Chest Height (DBH). Inside each quadrat, the 5 m × 5 m nested north-east and south-west sub-quadrats (Figure 3.1) were installed at both ends to identify all individuals with a diameter of less than 10 cm taken at 50 cm from the ground. This method is widely used when the area of the plot is large, because it allows better ventilation of the forest stand (Picard et al. 2012). A total of 30 quadrats distributed along six transects were sampled in each park. Transects have been placed in order to be as homogeneous (floristic and physiological homogeneity) and representative as possible in all the parks.

For each tree identified, parameters such as diameter, scientific or vernacular names and/or trade names were noted. All trees were identified on the basis of their discriminating characters using the floras and the identification keys. The taxonomic nomenclature adopted is the Phylogenetic Botanical Classification of Angiosperms (APG IV).

3.3.1 Data analysis

Characterization of floristic diversity in the two parks

To characterize the floristic diversity, a list of ligneous species inventoried in each site was drawn up. Indices such as the Shannon diversity index, Pielou's evenness index, Simpson's index, the Fisher-Alpha index, the species importance value index (IVI) and species density were calculated in each park.

Shannon diversity index (H)

The Shannon diversity index expresses the diversity of species within plant communities. It is calculated using the following formula:

$$H' = -\sum \frac{n_i}{N} \ln \frac{n_i}{N} \quad (\text{Shannon 1949}) \quad (3.1)$$

Where H' is the Shannon index; n_i the number of individuals of a species i ; N the total number of individuals of all species.

Simpson's Diversity Index

This index measures the probability that two randomly selected individuals belong to the same species. Its mathematical formula is:

$$D = 1 - \sum_{i=1}^s p_i^2 \quad (3.2)$$

With p_i : the number of individuals of species i ; S : the total number of individuals of all species.

Pielou Evenness Index

The Pielou evenness index corresponds to the ratio between the diversity obtained and the maximum diversity that can be obtained. As a result, this index expresses intra-community variations (Pielou 1966). The mathematical formula is as follows:

$$E = \frac{H'}{\ln S} \quad (3.3)$$

Where E is the Pielou equitability index; S the total number of species; H' is the Shannon index.

Fisher-alpha index

The Fisher-alpha index expresses the heterogeneity of a plant community. It is expressed by the following formula:

$$S = \alpha \ln (1 + N/\alpha) \quad (3.4)$$

Where S : species richness, N : number of individuals; α : Fisher-alpha index.

Species Importance Value Importance

It is given by the formula: $IVI = \text{Relative density} + \text{Relative dominance} + \text{Relative frequency}$

Basal area (BA)

It designates the surface of the cross-section of this tree at 1.30 m above the ground and at 0.30 above the buttresses for the species possessing them. The formula applied is as follows:

$$BA = \frac{\pi D^2}{4}; \text{ with } \pi = 22/7 \text{ (Sonké 2004);} \quad (3.5)$$

Where D (cm) is the diameter of the tree.

Biomass estimate

Aboveground biomass was estimated using the non-destructive method. The evaluation of the biomass of individuals with a diameter greater than 10 cm was

carried out using the allometric equation of Fayolle et al. (2018). The mathematical equation is as follows:

$$e^{(a+bx\log(\rho)+cx\log(D)+dx(\log(D))^2+exE)} \quad (3.6)$$

With BA: Epigeal biomass in Kg; D: Diameter (cm); ρ : specific density of a species expressed in g/cm³; E: climatic index; a, b, c and d are coefficient estimates

$$(a = -2,3027; b = 1,1599; c = 3,0484; d = -0,0807; e = 0,3197).$$

The biomass of 5 < dbh < 10 cm individuals was estimated from the allometric equation of Chave et al. (2014). The equation is:

$$BA = e^{(-1,803-0,976E+0,976\ln(\rho)+2,673\ln(D)-0,0299(\ln(D))^2)} \quad (3.7)$$

With BA: Epigeal biomass in Kg; D: Diameter (cm); ρ : specific density of a species expressed in g/cm³; E: climatic index.

The biomass of individuals smaller than 5 cm was assessed using the equation developed by Ntomen (2020).

$$BA = \text{Exp}(-2,145+2,451 \times \ln(D)+1,120 \times \ln(WD) \times CF) \quad (3.8)$$

With D: diameter (cm); WD: specific density of a species; CF: expansion factor (CF = 0,09).

Belowground biomass

Root biomass was estimated from the equation of Fayolle et al. (2013) as follows:

$$BS = \text{Exp}^{(-2,331+2,596 \times \ln(D))} \quad (3.9)$$

D: diameter (cm); BS: belowground biomass.

Assessment of carbon stocks

Carbon stocks were deduced from the aboveground biomass by multiplying it by the constant 0,475 (Zapfack et al. 2013).

Definition of biological parameters

Biological parameters such as light palatability and leaf consistency or leaf texture were defined according to the classification of Evrard (1968).

3.3.2 Statistical tests

An analysis of variances and comparison of means was applied to the various calculated parameters, to observe any significant differences between the plots at the 5% threshold ($p < 0.05$), or the absence thereof. The averages of the diversity indices were compared from one type of biotope to another, through one-factor variance analysis tests (ANOVA 1). When the differences between the means of the parameters are significant ($p < 0.05$), post-hoc tests (Tukey test and Kruskal-Wallis test) were carried out to classify and know which of the groups are different.

3.4 Results

3.4.1 Identification of land-use types

In the two parks sampled, four types of land use were identified, namely: (1) mature forests (MF); they are characterized by the dominance of species such as *Santiria trimera* (Oliv.) Aubrév., *Irvingia excelsa* Mildbr. and *Strombosia scheffleri* Engl.; (2) mature secondary forests (MSF), the species characteristic of these environments are *Symphonia globulifera* L. f., *Staudtia kamerunensis* Warb. and *Pycnanthus angolensis* (Welw.) Warb.; (3) Young secondary forests (YSF) are characterized by species such as *Anthocleista schweinfurthii* Gilg, *Ficus mucosa* Welw. ex Ficalho and *Macaranga hurifolia* Beille; (4) Fallows (FL) in which the characteristic species are *Harungana madagascariensis* Lam. ex Poir., *Musanga cecropioides* R. Br. and *Dialium bipindensis* Harms.

3.4.2 Species richness and alpha diversity

In the different types of land use (LUT) sampled in the two parks sampled, the taxonomic richness of all individuals with Dbh ≥ 1 cm varies between 32 and 103 taxa. MSFs are LUT in which the greatest number of taxa are encountered (103), while fallows are those in which the fewest species are encountered. The generic richness varies between 28 genera in the fallows and 83 genera in the MSF. According to Table 3.1, the families are more diversify in the YSFs (53 families) and less diversify in the fallows (15). The Kruskal-Wallis test indicates that there is no significant difference between the values ($p = 0.39$).

The diversity indices vary from one land-use type to another. The Shannon index is high in the YSFs (the extreme values which oscillate between 3.58 and 3.77 bits) and low in the fallows (1.76 bits) ($p = 0.58$). Species diversity is more heterogeneous in YSFs (Fisher-Alpha index = 27.13) and less heterogeneous in fallows (Fisher-Alpha = 6.48). When considering the Pielou equitability index, the value is higher in the MSFs (0.76), while the fallows (FL) the value is lower (0.36). There is a significant difference between the mean values ($F = 19.28$; p -value = 0.048).

Although the sampling rate was not the same in the different LUTs, there was considerable sampling effort in the two parks (Figure 3.2).

Table 3.1 Species diversity and taxonomic richness

Parameters	MF	MSF	YSF	FL
Specific Diversity				
Shannon	2,96 (2,87–3,13)	3,16 (3,08–3,28)	3,67 (3,58–3,77)	1,76 (1,55–2,07)
Simpson	0.93 (0.32–0.95)	0.95 (0.93–0.96)	0.96 (0.94–0.96)	0.71 (0.65–0.8)
Pielou	0.69 (0.65–0.82)	0.76 (0.71–0.85)	0.48 (0.44–0.53)	0.36 (0.34–0.52)
Fisher-Alpha	17.3 (14.98–17.3)	20.1 (18.78–20.2)	27.13 (26.18–27.13)	6.48 (4.16–6.48)
Taxonomic Richness				
Taxa	84 (79–84)	103 (99–103)	82 (80–82)	32 (28–32)
Genus	81	83	73	28
Families	35	45	53	15

MF: Mature forest; MSF: Mature secondary forest; YSF: Young secondary forest; FL: Fallow lands

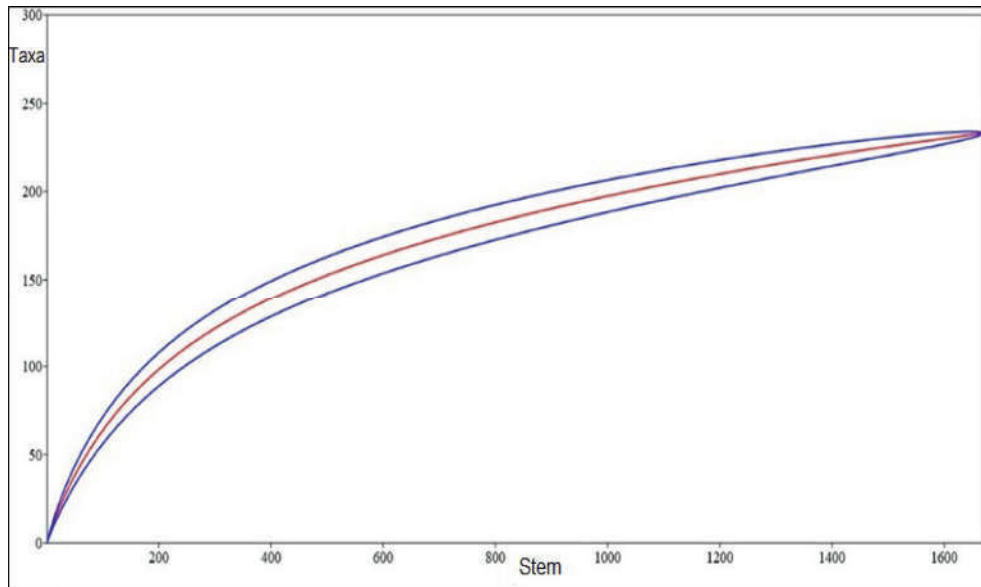


Figure 3.2 Species accumulation curve

3.4.3 Floristic characterization

Trees density in Atlantic Forests is closely linked to land-use types. The values of individuals with $Dbh \geq 10$ cm are between 389 ± 38 stems/ha in MF with a basal area of 33.91 ± 0.81 m²/ha and 256 ± 15 in fallow land (FL) for a basal area of 7.48 ± 0.1 m²/ha. The Kruskal-Wallis test shows a significant difference between the median values ($p = 0.0037$) of the densities in the different types of land use. Similarly, there is a significant difference between the basal area values ($F=13.36$; $dl=3.18$; $p<0.0001$).

For individuals with $Dbh < 10$ cm, the density of individuals is higher in the YSF (1745 ± 64) with a basal area of 4.31 ± 0.19 m²/ha and lower in the fallows (400 ± 94) for a basal area of 1.05 ± 0.29 m²/ha. The statistical test shows a significant difference between the density values ($p=0.026$).

The Family Importance Value (FIV) analysis of individuals with $Dbh \geq 10$ cm reveals the importance of Olacaceae (1.98), Fabaceae (1.77) and Burseraceae (1.76) in MF; Fabaceae (1.89) and Myristicaceae (1.44) in MSFs; Irvingiaceae (10.18), Phyllanthaceae (8.72) and Malvaceae (7.45) in the YSF; and finally Phyllanthaceae (2.8) and Myristicaceae (1.46) in the fallow lands. The results reveal Apocynaceae (6.9) and Sapindaceae (3.6) to be of significant importance in MF; Clusiaceae (1.35) and Myristicaceae (1.36) in the MSFs; the Phyllanthaceae (12.1) and the Annonaceae (9.2) in the YSF; and finally the Fabaceae (1.7) and the Olacaceae (1.6) in fallow areas.

The analysis of the palatability of individuals of $Dbh \geq 10$ cm highlights the abundance of hemi-sciaphytes (34.78%) in the mature forests of the study area. This reveals the predominance of plants in the undergrowth of forests still enjoying relatively decent amounts of light. The same is true for the abundance of heliophytes in the MSFs (49.27%). YSFs and fallows are mostly represented by heliophytes with values of 66.51% and 91.17% respectively. These plants enjoy full light and reflect the abundance of pioneer species that first colonize a disturbed environment.

For trees with $D_{hb} < 10$ cm, sciaphytes (51.23%) are more represented in mature forests. The characteristic species of this biological type are *Barteria fistulosa* Mast. and *Trichilia welwitschii* C. DC. We note that heliophytes are more represented in MSF, in YSF and in fallows. In decreasing order, the proportions are respectively 89.56% in fallows, 61.20% in YSFs and 59.22% in MSFs.

The distribution of species according to leaf consistency shows that the proportion varies from one ecosystem to another and from one diameter class to another. With regard to individuals of $D_{hb} \geq 10$ cm, Table 3.2 shows a clear dominance of leaves with cartaceous blades (37.14%), i.e., blades that have the texture of parchment in MF. Leathery lamina leaves come second with 34.28%. In the MSF, YSF and fallow land, there is a high proportion of leaves with papery blades, i.e. thin and rigid like a sheet of paper. This biological character is a typical quality of pioneer species in environments that have seen a degree of anthropogenic influence. In decreasing order, the proportions are respectively 77.94% in fallows, 33.72% in YSFs and 28.98% in MSFs. Characteristic species are *Tabernaemontana crassa* Benth. and *Psydrax arnoldiana* (De Wild. & T. Durand) Bridson.

The consistency of the leaves is highly variable for trees with a diameter of less than 10 cm. Leaves with leathery blades, i.e. hard blades or blades that have the consistency of leather, are in the majority in MF (48.61%) and in YSF (78.11%). The high proportion of leathery blades is found much more in hemi-sciaphytes and heliophytes. It is noted that the leaves with leathery lamina belong by preference to the plants of the undergrowth, that is to say the individuals with a small diameter. Papery lamina leaves are more represented in MSFs (40.77%) and in fallows (59.17%).

3.5 Assessment of carbon stocks

The carbon stock analysis states that carbon stocks vary from one type of land use to another and from one carbon pool to another (Table 3.3). The statistical test shows a significant difference between the mean values of the aerial carbon stocks (ANOVA test: 9.196; $p=0.046$). On the other hand, there is no significant difference between the median values of underground carbon stocks (Kruskal-Wallis test: $p=0.121$) at the level of the different types of land use. Figure 3.3 shows that aboveground carbon stocks vary between 4.91 ± 0.12 tC/ha and 229.01 ± 43.83 tC/ha. The stored carbon is higher in MF (229.01 ± 43.83) and lower in fallows (4.91 ± 0.12) ($F=2.45$; $p=0.257$).

From the point of view of the carbon stored by the families of individuals of $D_{bh} \geq 10$ cm, it varies from one family to another. The Fabaceae (45 ± 10.5 tC/ha) and the Humiriaceae (44.98 ± 6.45 tC/ha) are those which store more carbon in the MFs, i.e., 39.38% of the total carbon. Myristicaceae store more carbon (10.26 ± 2.16 tC/ha) in MSFs and Olacaceae those which store less carbon (0.02 ± 0.003 tC/ha). The statistical test shows that there is a significant difference (Kruskal Wallis test: $p=0.08$) between the median values of the different families in the MSFs (Table 3.3).

With regard to the light palatability of the species, we note that the heliophytes and the hemi-heliophytes share the majority of carbon stored in the MFs. They store about 85.9% of the total aboveground carbon. The results show heliophytes and hemi-heliophytes are the main species that sequester more carbon in the different ecosystems of the study area. This high representativeness of light species with respect to carbon sequestration highlights the importance of the photosynthesis carried out by these species in the environment.

The analysis of leaf consistency shows that plants with cartaceous, leathery and papery blades are the most frequent in the different types of land use because of the first and

Table 3.2 Characterization of the ligneous diversity of the Atlantic forests

Diameter class	LUT	Density (stem/ha)	Basal area (m ² /ha)	Family (FIV)	Light palatability (%)	Leaf consistency (%)
Dbh>10 cm	MF	389±38	33.91±0.81	Olacaceae (1.98);	Hemi-sciaphytes (34.78);	Cartaceous (37.14);
				Fabaceae (1.77);	Hemi-heliophytes (30.43)	Leathery (34.28)
				Burseraceae (1.76)		
	MSF	256±15	24.42±0.44	Fabaceae (1.89);	Heliophytes (49.27);	Papery (28.98);
				Myristicaceae (1.44)	Hemi-sciaphytes (21.73)	Cartaceous (27.96)
	YSF	365±6	33.72±1.54	Irvingiaceae (10.18);	Heliophytes (66.51);	Papery (33.72);
Dbh<10 cm	FL	337±35	7.48±0.1	Phyllanthaceae (8.72);	Hemi-sciaphytes (20.37)	Cartaceous (28.57)
				Malvaceae (7.45)		
				Phyllanthaceae (2.8);	Heliophytes (91.17);	Papery (77.94);
	MF	1465±73	4.31±0.19	Myristicaceae (1.46)	Hemi-heliophytes (5.88)	Cartaceous (14.7)
				Apocynaceae (6.9);	Hemi-sciaphytes (41.36);	Leathery (48.61);
				Sapindaceae (3.6)	Sciaphytes (51.23)	Papery (31.89)
	MSF	533±101	0.83±0.17	Clusiaceae (1.35);	Heliophytes (59.22);	Papery (40.77);
				Myristicaceae (1.36)	Hémi-sciaphytes (20.38)	Leathery (34.95)
	YSF	1745±64	5.38±0.21	Phyllanthaceae (12.1);	Heliophytes (61.20);	Leathery (78.11);
				Annonaceae (9.2)	Hemi-sciaphytes (20.6)	Cartaceous (16.8)
	FL	400±94	1.05±0.29	Fabaceae (1.7);	Heliophytes (89.56);	Papery (59.17);
				Olacaceae (1.6)	Hemi-heliophytes (6.89)	Cartaceous (35.6)

LUT: land-use types; FIV: Family Importance Value; MF: Mature Forest; MSF: Adult Secondary Forest; YSF: Young Secondary Forest; FL: Fallow lands.

Table 3.3 Carbon stocks assessed

Carbon pools	LUT	Total Carbon stocks (tC/ha)	Family (tC/ha)	Light palatability (tC/ha)	Leaf Consistency (tC/ha)
Epigeal Carbon	MF	229,01±43,83	Fabaceae (45.21±10.5); Humiriaceae (44.98±6.45)	Heliophytes (112.05±14.95); Hemi-heliophytes (84.68±21.71)	Cartaceous (111.35±29.97); Leathery (74.5±15.8)
	MSF	81,96±10,46	Myristicaceae (10.26±2.16); Irvingiaceae (9.33±1.58)	Heliophytes (41.03±0.77); Hemi-heliophytes (21.19±6.64)	Cartaceous (44.87±4.82); Leathery (18,63±2,82)
	MSF	216,54±11,82	Irvingiaceae (96.14±9.49); Malvaceae (24.84±3.49)	Hemi-heliophytes (105.89±10.16); Heliophytes (89.54±4.48)	Leathery (117,81±8,53); Cartaceous (35,38±2,41)
	FL	4,91±0,12	Phyllanthaceae (1.86±0.86); Myristicaceae (0.71±0.17)	Heliophytes (3.88±0.56); Hemi-heliophytes (0.91±0.42)	Papery (2,55±1,48); Cartaceous (1,59±0,75)
Underground carbon	MF	56,11±7,52	Fabaceae (11.07±2.07); Humiriaceae (11.02±2.51)	Heliophytes (27.45±7.33); Hemi-heliophytes (20.75±8.95)	Cartaceous (27,28±7,34); Leathery (18,25±3,47)
	MSF	20,1±2,56	Fabaceae (6.39±1.93); Myristicaceae (2.51±0.53)	Heliophytes (10.05±0.19); Hemi-heliophytes (5.19±1.62)	Cartaceous (10,99±2,05); Leathery (4,56±1,19)
	MSF	53,06±2,89	Irvingiaceae (23.55±2.32); Malvaceae (6.09±0.86)	Hemi-heliophytes (25.94±2.48); Heliophytes (21.93±1.1)	Leathery (28,86±2,09); Cartaceous (8,67±0,59)
	FL	1,2±0,03	Phyllanthaceae (0.45±0.21); Myristicaceae (0.17±0.06)	Heliophytes (0.95±0.09); Hemi-heliophytes (0.22±0.11)	Papery (0,62±0,25); Cartaceous (0,39±0,18)

LUT: land-use types; FLV: Family Importance Value; MF: Mature Forest; YSF: Young Secondary Forest; FL: Fallow lands.

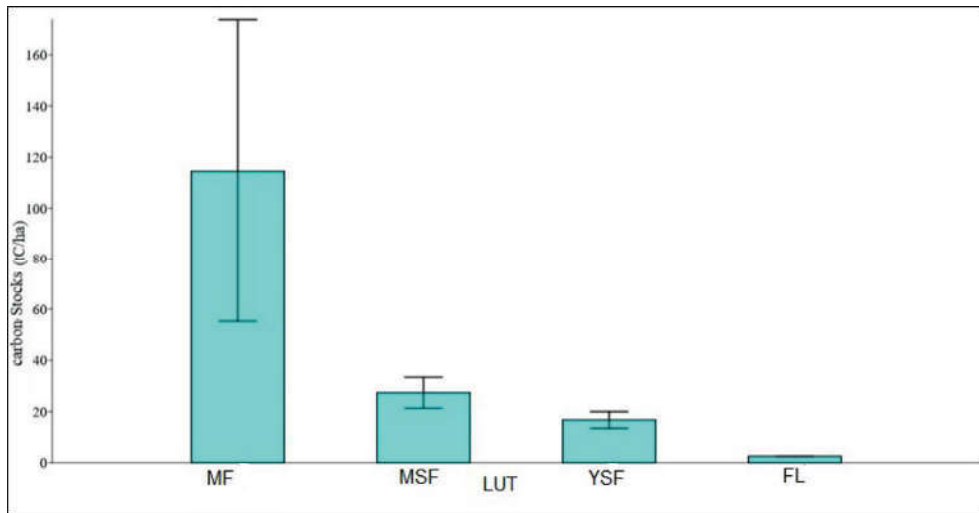


Figure 3.3 Distribution of carbon stocks by land-use types.

LUT: land-use types; MF: Mature Forest; MSF: Mature Secondary Forest; YSF: Young Secondary Forest; FL: Fallow

second position they occupy. Species with hard or soft leaves are those that sequester more carbon in a given medium. The proportion of cartaceous and leathery blades is 81.15% of the total aerial carbon stocks stored in the MFs. Species with leathery leaves store about 54.41% of the total carbon in the YSFs.

The increase in carbon stocks is proportional to the average basal area occupied by the species (Figure 3.4). The statistical test illustrates a significant difference between the values ($p < 0.0001$). The Spearman rank correlation coefficient ($r = 0.889$) denotes that carbon stocks correlate with dominance.

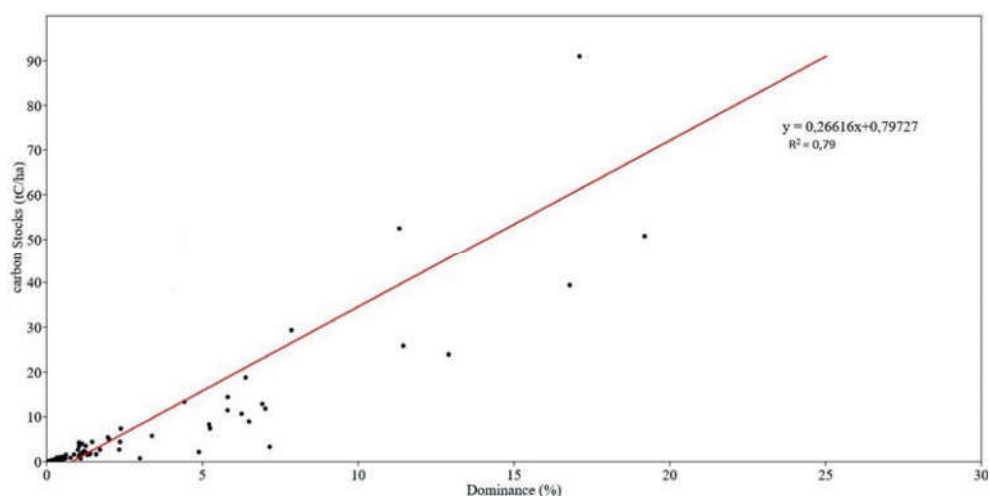


Figure 3.4 Correlation between carbon stocks and species dominance

3.6 Discussion

The characterization of the vegetation cover made it possible to identify four types of land use, namely mature forests, adult secondary forests, young secondary forests and fallow land. These results are similar to those of Mounmemi et al. (2022) in dense semi-deciduous forests, which identified mature forests, young forests, swamps and plantations. Kabelong et al. (2020) obtained six types of land use at the ring road of Deng-Deng National Park namely agro-forests, residual forests, riparian forests, secondary forests, old-growth secondary forests and young fallows. These results are different from those obtained in the present study. These differences could be explained by the fact that the areas that are close to the sea are less coveted by the population because the soils that shelter them are from time to time waterlogged.

The quantitative and qualitative analysis of the flora and vegetation of the Atlantic forests of Cameroon reveal strong disturbances within different formations. The floristic procession varies from one type of land use to another. There are 103 species distributed in 83 genera and 45 families in the MSFs, and 32 species distributed in 28 genera and 15 families in the fallows. The low specific richness recorded in the fallows better explains the strong degradations observed in the study environment due to human influence. These values are lower than the 140 species found by Murray-Smith et al. (2008) in Atlantic forests in Brazil. Compared to other forest types the taxonomic diversity is less rich, with 146 species found by Biwolé (2015) in evergreen forests. The species richness of adult secondary forests is much lower than the 214 species recorded by Tabue (2018) in the secondary forests of the Dja Reserve and 136 species obtained by Kabelong et al. (2020) in old-growth secondary forests. In view of the different values, it appears that the Atlantic forests have low species richness. This could be justified by the fact that the estuaries of the Atlantic forests being subject to strong ecological constraints (saline environment, sandy soils poor in nutrients and easily flooded) see their number of species reduced. The density of trees in the different formations of individuals with a diameter greater than 10 cm varies between 389 ± 38 and 256 ± 15 stems/ha. These values are similar to those of Mounmemi (2021).

As ecology is concerned, diversity indices are the best characterization parameters for a stand (Ramade 1994). The high values of the diversity index of Shannon and Simpson in the YSF denote a rich floristic diversity in these forest ecosystems. The high value would be due to anthropogenic action which plays an important role in regeneration. On the other hand, the Fisher-alpha diversity index shows a specific dissimilarity in the types of land use. The high value justifies its strong heterogeneity with respect to the other types. The low value of Shannon and Simpson in fallows confirms the low diversity and degradation of this environment.

Light palatability and leaf consistency are far from being the only parameters that illustrate the ability of a species to occupy different synusiaes of the phytocenosis. Hemi-sciaphytes are relatively abundant in mature forests (34.78%). This situation can be explained by the high density of the lower strata of certain humid forests. Heliophytes are more represented in MSFs, YSFs and fallows of individuals with a diameter greater than 10 cm. The abundance of heliophytes shows the strong representativeness of woody plants with considerable heights in almost all these formations. This strong presence of heliophytes offers hope for the natural reconstitution of degraded plant formations. However, there is no doubt that the category of heliophytes is favored by the light received in the vicinity of open water tables on the one hand and by the low density of trees on the other hand which favors the forest atmosphere and boosts the growth of full-light species.

The main foliar characters examined in the MF are cartaceae and coriaceae. It should be noted that MFs are encountered on dry land; this could justify the abundance of these two leaf characters. The strong presence of species with papery leaves in the MSFs, the YSFs and in the fallows reflects a prevalence of flooded areas poor in mineral elements. Trees diversity, density and diameter are important indicators for assessing aboveground forest biomass and other ecological processes in tropical forests.

These indicators vary according to regions, types of vegetation, habitats and species. Above-ground carbon stocks are between 229.01 tC/ha and 4.91 tC/ha, for a total of 532.46 tC/ha. Moreover, these values are higher than those obtained by Loubota-Panzou et al. (2018) in the semi-deciduous forests of Mindourou in Cameroon (347.6 tC/ha), by Zapfack et al. (2016) in Lobéké National Park in Cameroon (372.2 tC/ha). These discrepancies in the value of carbon stocks obtained by different authors may be due to the different allometric equations used, the types of forest or the method applied. These variations in carbon stocks could also be explained by the types of management, by the structure linked to anthropogenic disturbances and/or to edaphic gradients. Indeed, several authors have reported the variation of carbon stocks in tropical forests (Fayolle et al. 2016; Figueres et al. 2019). For these authors, the variations in carbon stocks are due to the different types of dense forests of Central Africa, the floristic composition and the structural variables (basal area, density of stems per hectare, allometry-height – diameter, etc.). Zhu et al. (2018) show that external factors such as climate change could also influence the ability of forests to sequester carbon and offset forest productivity effects.

3.7 Conclusion

The objective of this contribution was to present, estimate and characterize the carbon stocks of the two protected areas, the Douala-Edéa National Park and the Kribi Marine Park. This estimate was made possible by the use of various dedicated scientific methods. It appears from the study that the specific richness varies between 32 and 103 taxa. The Shannon diversity index is higher in YSFs (3.67 bits). We notice the dominance of Irvingiaceae (10.78) in the YSF. Above-ground carbon stocks present in the biomass vary between 4.91 tC/ha and 229.01 tC/ha in the LUTs. Fabaceae and Humiriaceae are the main families that store more carbon in MF, i.e., 39.8%. The species with cartaceous and leathery leaves are those that store more aerial carbon (81.15%) in the MFs.

The analysis of the flora in the Atlantic forests indicates strong disturbances within the plant formations. The taxonomic richness and the specific diversity of the estuaries of the Atlantic forests remain generally weak with regard to the types of forest because of the anthropic actions and the edaphic conditions. Analysis of light palatability shows an abundance of hemi-sciaphytes in MF; heliophytes in MSFs, YSFs and fallows. This work highlights the urgency of implementing efficient management practices to restore Atlantic Forest estuaries. Data used in the present study are part of a general database for Atlantic Forest species in Cameroon. However, the presence of small trees suggests a probable reconstitution of the degraded plant formations if the disturbances stopped. If necessary, there will be a loss of resilience of the flora and significant emissions of GHGs. The analysis indicates that the variation in carbon stocks is a function of land-use types, families, light palatability and leaf consistency. The results of this investigation will make it possible to raise the broader questions that arise with regard to the developments to be proposed and the means to be implemented as a priority to ensure the expression of maximum plant biodiversity.

3.8 References

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