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Potential, economic advantages and constraints of agroforestry in the fight against global warming: the case of Djilor District (Fatick, Senegal)

Potentialités, avantages économiques et contraintes de l'agroforesterie dans la lutte contre le réchauffement climatique : cas de l'Arrondissement de Djilor (Fatick, Sénégal)

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Abstract

Global warming threatens the well-being of millions of people around the world. Faced with this situation, there has been renewed interest in understanding the role of ecosystem goods and services in mitigating this phenomenon. With this in mind, the aim of the present study was to assess the role of agroforestry in reducing CO_2 emissions and the economic advantage it offers populations in terms of carbon credits, while analyzing the local constraints linked to its practice. To achieve this, surveys were carried out in 513 households. Carbon stored in woody biomass was assessed using "allometric models", based on inventory data collected randomly on 72 plots of 1600 m^2. The number of plots was defined on the basis of a pre-inventory. The results revealed a species richness of 22 species characterized by an average diversity due to a Shannon index of 3.95 bits. Biological and phytogeographical species types show the dominance of mesophanerophytes and Sudanian and Sudano-Zambezian chorologies. The average stock of atmospheric carbon sequestered in this stand (7.5 $tC.ha^{-1}$), demonstrates the compensatory role of ligneous plants for anthropogenic CO_2 emissions. Assessment of the economic value of this potential, which amounts to 49,590.6 f CFA/tCO_2/ha, reveals the existence of an opportunity that farmers could exploit within the framework of carbon credits. There are, however, local constraints to the development of agroforestry in the area, chiefly the perception of the duality between trees and agricultural production, grazing practices, rainfall deficits and the lack of production factors. This work shows the effectiveness of agroforestry in the fight against global warming and the vulnerability of populations, with a view to improving the practice for the benefit of the planet and communities.

Keywords: Agroforestry, Woody stands, Climate change, Carbon and carbon credit.

Résumé

Le réchauffement climatique menace le bien être de millions de personnes dans le monde. Face à cette situation, la connaissance du rôle des biens et services écosystémiques à l'atténuation de ce phénomène a fait l'objet d'un regain d'intérêt. Dans ce sens, l'objectif de la présente étude a été d'évaluer le rôle de l'agroforesterie dans la réduction des émissions de CO_2 et de l'avantage économique qu'elle offre aux populations en crédit carbone, tout en analysant les contraintes locales lié à sa pratique. Pour y parvenir, des enquêtes ont été menée auprès de 513 ménages. Le carbone stocké dans la biomasse ligneuse a été évalué par l'utilisation de « modèles allométriques », à partir de données d'inventaire, collectées de manière aléatoire sur 72 placettes de 1600 m^2. Le nombre de ces placettes a été défini sur la base d'un pré-inventaire. Les résultats ont révélé une richesse spécifique 22 espèces caractérisée par une diversité moyenne en raison d'un indice de Shannon de 3,95 bits. Les types biologiques et phytogéographique des espèces montrent la dominance des mésophanérophyte et des chorologies soudaniennes et soudano-zambéziennes. Le stock moyen en carbone atmosphérique piégé dans ce peuplement (7,5 $tC.ha^{-1}$), démontre le rôle compensatoire des ligneux des émissions de CO_2 d'origine anthropique. L'évaluation de la valeur économique de ce potentiel qui s'élève à 49.590,6 f CFA/tCO_2/ha révèle l'existence d'une opportunité que les agricultures pourraient valoriser dans le cadre des crédits carbone. Il existe, cependant, des contraintes locales au développement de l'agroforesterie dans la zone dont principalement : la perception de la dualité arbre-production agricole, les pratiques de pâturage, les déficits pluviométriques et le manque de facteurs de production. Ce travail montre donc l'efficacité de l'agroforesterie dans la lutte contre le réchauffement climatique et la vulnérabilité des populations, en vue d'une amélioration de la pratique au bénéfice de la planète et des communautés.

Mots clés : Agroforesterie, Peuplement ligneux, Changement climatique, Carbone et Crédit carbone.

1. Introduction

Greenhouse gases (GHGs) are naturally present in the atmosphere. Through their radiative effect on terrestrial radiation, these gases help maintain the earth's average temperature at the thermal level (15°C instead of -18°C) required to sustain life on earth (Ramarson 2009).

However, since the industrial revolution, GHG concentrations in the atmosphere have been rising steadily. Indeed, it has been clearly established that their concentration has increased by around 70% compared with the pre-industrial era (IPCC, 2007). Carbon dioxide, the fourth largest component of the atmosphere and accounting for more than half of all greenhouse gases, has practically doubled from an estimated 270-280 ppm in the pre-industrial reference period (1750-1800), reaching 355 ppm in 1990 and 410.5 ppm in 2019 (IPCC, 2007 & 2021). Human activities, such as the use of fossil fuels and changes in land use through the conversion of woodland to cropland, have contributed significantly to this rise (Boer et al., 2002).

The result is an increase in the radiative effect of the heat emitted by the earth, leading to the phenomenon of climate change. This phenomenon manifests itself differently at different levels and has direct or indirect impacts on the functioning of natural ecosystems, while affecting the way of life of the living beings that make them up (Hartmann et al. 2013). Indeed, global temperature rises, which have increased globally at a rate of 0.10°C to 0.16°C per decade over the past fifty years, recurrent flooding, rising sea levels following the massive melting of glaciers, recurrent droughts and the temporal instability of climatic seasons, are all climate instabilities observed over recent decades that are causing concern and attention among many scientists (IPCC 2018).

Faced with these growing threats, the international community, under the Kyoto Protocol, the Paris Agreements and other agreements, has committed signatory countries to reducing and offsetting emissions through some clean development mechanisms. Among the mechanisms advocated to mitigate global warming is carbon sequestration in terrestrial ecosystems, mainly forests (Angelsen and al. 2013). In addition to their role as reservoirs of biodiversity and providers of ecosystem services, forests also contribute to reducing CO_2 emissions into the atmosphere by sequestering and storing carbon in living biomass (above-ground and below-ground biomass), dead wood, litter and soil (IPCC 2003).

Despite this important role, forests in tropical zones have suffered significant losses of area in recent decades, mainly to the benefit of agricultural land (Altey and Pengue 2006; FAO 2006; Vroh bi Trah Aimé and al. 2015; Folega et al. 2023). In countries such as Senegal, this situation, combined with demographic growth and the associated high demand for agricultural land, has led to changes in traditional land management systems. This is marked by the reduction and eventual disappearance of fallow periods (Gaye 2000). Similarly, post-independence agricultural intensification policies paid little heed to the presence of trees in the crops lands. This traditional practice of associating trees with agricultural crops was even considered a hindrance to the establishment of intensive, productive crops (Diatta 2013). As a result, these changes have profoundly accentuated the phenomena of land clearing, deforestation, soil erosion and biodiversity loss. In addition, relentlessly cultivated land has become poorer, resulting in lower yields despite the use of chemical fertilizers. Thus, with the failure of these productivist models based on commercial inputs and in the face of the climate emergency, numerous studies have sought to promote the conservation of trees in crops lands, as a tool for both restoring soil fertility and combating global warming (Sène 2004; Altieri and al. 2015, 2017; Paustian and al. 2015; etc). These agroforestry systems could also give rise to Payments for Environmental Services (PES) under climate agreements for Reducing Emissions from Deforestation and Degradation (REDD) (Ouattara N'Klo et al. 2010). However, these incentives for agroforestry practices in sub-Saharan zones seem to face obstacles in view of their lack of effectiveness or intensity in several agricultural areas of the groundnut basin in Senegal. In this respect, it would be interesting to gain a better understanding of the contribution of agroforestry to reducing CO_2 emissions, the economic value of its services and the constraints to its use. With this in mind, the aim of this study was to estimate the atmospheric carbon stock potential of agroforestry systems in the Djilor Arrondissement, and their carbon credit equivalence, while analyzing the factors constraining their implementation.

2. Materials and methods

2.1 Description of study area

The study was carried out in the Fatick region of west-central Senegal, between latitudes 13°09-14°10 N and 16°02-16°24 W (Figure 1). Fatick is located in the eco-geographical zone of Senegal's groundnut-growing basin. It covers an area of 876 km^2, of which 444.6 km^2 (50.1%) is cultivated. The relief is generally flat, with a few depressions incorporating the valleys and inlets of the Saloum and Diomboss rivers. These drainages give rise to two major geomorphological complexes: one amphibious and the other continental. The latter, the plateau zone, is characterized by tropical ferruginous soils, some of which are not or only slightly leached, others leached. The amphibious environment, corresponding to floodplains, is marked by hydromorphic soils classified as vertic, salty gley and halomorphic (CSE, 2000).

The region has a North Sudanian climate, with a short rainy season (3 to 4 months) and a long dry season (7 to 8 months) (Sagna, 2000). Average rainfall at the Fatick station over the series from 1930 to 2017 is 601.9 mm. The average temperature is 28°C, which dictates a bimodal thermal regime with two maxima in April (39.4°C) and November (34.1°C) and two minima in July (24.1°C) and January (16.8°C).

Soil and climatic conditions in the area have led to the establishment of savannah vegetation (Ndiaye et al., 2007) on the plateaus, with tree, shrub to tree and even shrub formations, a few forest galleries and scattered woody individuals in the fields; in the amphibious zones, the vegetation consists of mangrove and tanne grassland (Figure 1).

Population density averages 91.4 inhabitants/km^2. Agriculture, mainly under rainy conditions, as well as livestock breeding, fishing and trade are the main activities of the local population (ANSD, 2014).

2.2. Data collection method

2.2.1. Survey design

In order to assess biomass and gather information on people's involvement in agroforestry practice, data were collected by conducting household surveys and floristic inventories. This was carried out simultaneously, during the period from February 12 to July 22, 2019.

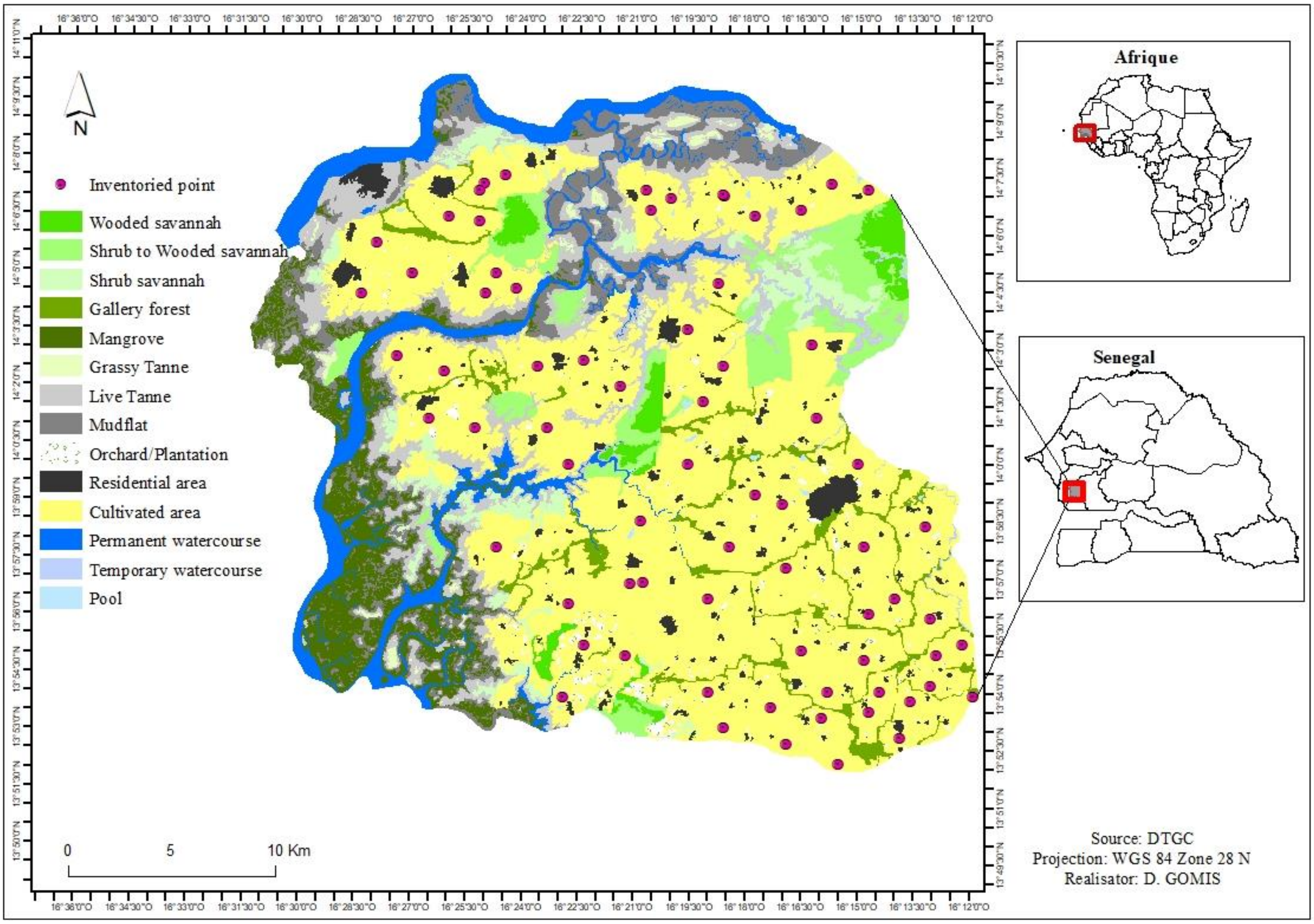

Figure 1. Location of the study area and distribution of surveys over the growing areas (Source: D. Gomis, 2018)

In view of the large number of villages in the Arrondissement, only 30% of the villages in each Commune were selected at random (Table 1).

Table 1. Number of villages to be surveyed per Commune in Djilor Arrondissement

Municipalities	No. of villages	Rate %	Sample
Municipality Djilor	44	30	13
Municipality M'bam	7	30	2
Municipality Diagane Barka	23	30	7
Municipality Diossong	40	30	12
Municipality Niassène	38	30	17

D. Gomis, 2017

For each village selected, the number of concessions to be surveyed was determined using Bernouilli's formula, with a margin of error of 10% to determine the sample size. This formula is expressed as follows:

$$n = \frac{(1,96)^2 \times N}{(1,96)^2 + l^2 \times (N-1)}$$

n = size of the sample to be interviewed; N = size of the universe under investigation; l = width of the range expressing the margin of error.

Starting from the sample size (457 concessions), the number to be surveyed per village was determined by establishing the ratio of concessions in the village to be surveyed to those in the sampled villages; the result was multiplied by the sample size. In each village, after presentation and discussion with the village chief, a list of all the concession chiefs was drawn up with him/her. On this basis, the first concession was selected at random, then time steps of three concessions were observed, and finally an exhaustive survey was carried out with the households found. The questionnaire was administered to the head of the household or, failing that, to a family representative. Questions focused on landscape dynamics, field tree conservation strategies and difficulties encountered. A total of 513 households were surveyed throughout the district.

The floristic inventory was carried out on the basis of random sampling. The number of surveys was determined firstly by carrying out a pre-inventory of 5 plots of 40m × 40m, then on the basis of the parameters measured, the formula below by Dagnelie (1998) was used, taking into account the coefficient of variation of the volume of trees measured and a margin of error of 20%.

$$n = t^2_{1-\alpha/2} \frac{CV^2}{d^2}$$

with n = sample size; t1-α/2 = Student's variable (read from a table for n-1 degrees of freedom); CV = coefficient of variation of a given parameter; d = error of a parameter estimated from the sample: 1% ≤ d ≤ 20%.

A total of 67 surveys were obtained which, added to those from the pre-inventory, makes 72 surveys carried out on 40 × 40m square plots (Table 2).

Table 2. Survey plan summary.

Site	Area in ha	Mean volume (m3)	Mean variance	Standard deviation	CV en%	Considered error	No. of plots
Cultivated area	44456	3,9	5	2,3	59	20	67

D. Gomis, 2019

Plots were randomly distributed in the cultivation areas on the basis of a grid (250 m × 250 m) with centroid points on which the choice of plot to be inventoried was made randomly by drawing lots. Data collection for the pre-inventory was carried out from March 16 to 18, 2018 and from April 05 to 29, 2018, and for the actual inventory from February 15 to July 22, 2019. In the field, plots were set up using the 3-4-5 method specific to the Pythagorean theorem for determining right angles. In each plot, measurements of dendrometric parameters [diameter at breast height (DBH), tree height, crown diameter (NS-E0) and distance between two trees using the nearest individual method] were taken for all individuals with a circumference greater than or equal to 10cm. The plants with a circumference of less than 10cm were counted and considered to be part of the regeneration.

Species identification was carried out in the field. Woody plants not identified in the field were sampled for subsequent identification in the laboratory, using Berhaut's "Senegal flora" (1967) and other works such as “Trees, shrubs and lianas of the dry zones of West Africa” by Arbonnier (2009), based on the biological nomenclature provided by the taxon names.

2.3. Data processing and analysis

The data obtained were processed using Excel spreadsheets, which were used to classify numerical data and draw up tables and graphs. The floristic list of species was compiled and then analyzed, for each species, by calculating frequency, ecological importance, biological and phytogeographical type, before proceeding with the analysis of stand diversity and structural parameters. The notion of frequency is defined by Gaussen E. (1963) and Gounot M. (1969) as the ratio between the number of records in which the species is represented and the total number of records. It provides information on the distribution of a species in a stand. It can be absolute or relative, using the following formula (Roberts-Pichette and Gillespie, 2002 cited by Ngom, 2013):

$$F = (Nri/Nr) \times 100$$

F = Frequency of occurrence expressed as a percentage (%), Nri = number of surveys where species i is found and Nr = total number of surveys.

Ecological importance or Importance Value Index (IVI), defined by Curtis and Mc-Intosh (1950), is a synthetic and quantified expression of the importance of a species in a stand. It is determined by the following relationship

$$IVI = (Relative\ density + Relative\ dominance + Relative\ frequency)\ /3$$

$$Relative\ density = (Number\ of\ individuals\ of\ species\ per\ ha/total\ density\ of\ species) \times 100$$

$$Relative\ dominance = (basal\ area\ of\ each\ species/Total\ basal\ area\ of\ all\ species) \times 100$$

$$Relative\ frequency = (Species\ frequency/sum\ of\ species\ frequencies) \times 100$$

Biological types and phytogeographical affinities of species were determined in terms of presence, abundance and dominance. Biological types refer to the set of morphological features that play a role in plant species' resistance to adverse conditions and localization (Melon S., 2015). The biological types (BT) used here are those defined by Raunkiaer (1934) and adapted for the study of tropical plant formations by several authors (Mbayngone and al. 2008b; Faye 2010, etc.). The woody stratum is essentially made up of phanerophytes, subdivided into: nanophanerophyte (nph: shrub 0.5-2m high); microphanerophyte (mph: shrub 2-8m high); mesophanerophyte (Mph: medium tree 8-30m high); and megaphanerophyte (MPh: large tree over 30m high).
Phytogeographical affinities were defined with reference to those established by White (1986), used by several authors for African phytochories (Sinsin 1993; Faye 2010; etc.). These are species with a wide distribution, African-American (Aa), Pantropical (Pan) and Paleotropical (Pal) species; African pluri-regional species grouping: Sudano-Guinean (Sg), Afro-tropical (At), Afro-Malagasy (Am), Sudano-Zambesian (Sz), African multi-regional (Pa) and Guineo-Congolese (Gc) and, finally, species with a Sudanese base, distributed in the regional center of Sudanese endemism.
Diversity was analyzed by calculating the Shannon-Weaver, Pielou and Simpson equitability indices.
Shannon's index (1949) expresses diversity by taking into account the number of species and the abundance of individuals within each species. The Shannon index ranges from 0 to log2S, i.e. 4.5 bits for a fairly rich community (Frontier and Pich-Viale, 1995). H is minimal (equal to 0) if all individuals in the stand belong to a single species; $H < 2.5$ = low diversity; $2.5 \leq H < 4$ = medium diversity; $H \geq 4$ = high diversity. It is maximum when each individual represents a distinct species (Legendre and Legendre, 1984). Its calculation is based on the following relationship:

$$H' = -\Sigma pi \times log2\ pi$$
$$Pi = ni/N = number\ of\ individuals\ /\ species\ per\ stratum$$

Piélou's (1966) regularity of distribution or equitability: this measures the distribution of individuals within species, independently of species richness. The more equitably species frequencies are distributed, the greater the diversity (Diédhiou 2018). Piélou's equitability index is calculated using the following formula:

$$E = H'/H\ max;$$
$$H = Shannon\ diversity\ index;$$
$$H\ max = maximum\ diversity\ index.$$

Where $E < 0.6$ = low; $0.6 \leq E \leq 0.7$ = medium; $E \geq 0.8$ = high (Garba et al. 2017).

Simpson's index, 1949 (D): represents the probability that two individuals drawn at random from an infinite population belong to the same species (Simpson 1949). The maximum diversity for this index is represented by the value 1 and the minimum diversity by the value 0. It is calculated by the following formula:

$$D' = 1 - \frac{Ni(Ni-1)}{N(N-1)}$$

Ni = number of individuals in species i;
N = total number of individuals

In order to establish the structure of woody stands, the following parameters were calculated.
Observed density or true density, obtained by dividing the total number of individuals in the sample (N) by the area sampled (S).

$$Dobs = N/S$$

The mean diameter (Dg) expressed in cm is calculated according to the formula of Bonou and al. (2009).

$$Dg = \sqrt{\frac{1}{n}\sum_{1=1}^{n} di^2}$$

n = total number of trees in the plot;
di = diameter of species i (cm).

The average Lorey height (HL) expressed in meters (m) is the average height of individuals weighted by their basal area:

$$HL = \frac{\sum_{i=1}^{n} gi \times hi}{\sum_{i=1}^{n} gi} \quad \text{where } gi = \frac{\Pi}{4} di^2 \text{ (Rondeux 1999).}$$

Basal area or basal cover, which designates the surface area of the tree evaluated at 1.3 m. It is expressed in square meters per hectare ($m^2.ha^{-1}$) and is obtained from the following formula:

$$St = \frac{\sum \pi(\frac{d}{2})^2}{SE}$$

St = basal area; d = diameter at breast height; SE = sample area in ha.

Tree crown cover is the area of the tree crown projected vertically onto the ground. It is expressed in square meters per hectare ($m^2.ha^{-1}$). It is calculated using the formula below:

$$C = \frac{\sum \pi(\frac{dmh}{2})^2}{SE}$$

C= woody cover;
dmh= average crown diameter in m;
SE= sample area in ha.

The biomass estimate is the basis for carbon calculations. The quantities of above-ground biomass of the various individuals were determined using the pantropical regression model of Chave and al, (2005). The mathematical expression of this model is as follows:

$$BA = \rho \text{ x } \exp(-0.667 + 1.784 \ln(dbh) + 0.207(\ln(dbh))^2 - 0.0281 (\ln(dbh))^3$$

BA being the dry aerial biomass;
ρ the dry wood density in g/cm^3;
and dbh the diameter at breast height in cm.

The specific densities of the various species sampled were collected from the Global Wood density database (Zane and al., 2009). For species with unknown wood density, the default density value (0.58 g/cm^3 for African tropical forests), recommended by Reyes G. and al. (1992) and used by B-T. Vroh and al. (2015) was chosen. However, as this model does not take palm trees into account for the estimation of their biomass, the model proposed by Brown and al., (1997) was used. The mathematical expression of the latter is as follows:

$$BAi\ (Kg) = Exp\ (-2.134 + 2.530 \times \ln\ (DHPi))$$

Hypogeous biomass was deduced from above-ground biomass using the model of Cairn and al, (1997):

$$BGB = exp\ [-1.0587 + 0.8836 \times In\ (AGB)]$$

BGB = root biomass
AGB = above-ground biomass
ln = natural logarithm.

From the biomass resulting from these calculations, the quantity of carbon stored was deducted by applying the IPCC (2006) coefficient of 0.5.

The CO_2 equivalent of the carbon stock was obtained by multiplying the quantity of carbon by the fraction of carbon dioxide on carbon.

The economic value of the carbon sequestered and stored in trees here refers to their selling price on the carbon market. To obtain this value, the tonnes of $C0_2$ equivalent were multiplied by the average carbon credit sale price of a tonne of CO^2, the monetary value of which, as considered by Peltier and al (2007), was taken into account in this study for a value of: 3 USD.tCO_2^{-1}, i.e. 1796.8 F CFA / tCO_2^{-1}.

3. Results

3.1. Floristic composition

The inventory carried out on the cultivated areas of the study zone identified 22 species, divided into 22 genera and 14 families. The best represented families are Mimosaceae, Combretaceae and Anacardiaceae, with three species each. They are followed by Bombacaceae and Fabacaceae with two species each. The other families have a single species. The same is true for genera (Table 1). Among the species, analysis of the ecological parameters (frequencies and IVI) reveals that the most frequent are: *Cordyla pinnata* (17.9%), *Faidherbia albida* (14.3%), *Tamarindus indica* (8.3%), *Azadirachta indica* and *Anacardium occidentale* (7.1%), *Ficus sycomorus* (5.9%), *Borassus aethiopum* (4.8%), *Anogeissus leiocarpus* and *Combretum glutinosum* (3.6% ex). These results are somewhat similar to the IVI values, which show that the most important species from an ecological point of view are, in decreasing order: *Cordyla pinnata* (16.5%), *Faidherbia albida* (10.6%), *Tamarindus indica* (8.0%), *Anacardium occidentale* (7.7%), *Diospyros mespiliformis* (6.7%), *Borassus aethiopum* (6.5%) and *Ficus sycomorus* (5.9%). With more than half of the IVI (62%), these species represent the most important physiognomic features of the stand (Table 3).

Table 3. List of species with their frequency and IVI.

Families	Genus	Species	Ph	B. T	Fr %	IVI %
Anacardiaceae	Anacardium	*Anacardium occidentale* L.	Pan	MsPh	**7,1**	**7,7**
	Mangifera	*Mangifera indica* L.	Pan	MsPh	2,4	2,2
	Heeria	*Heeria insignis* (Del.) O. Ktze	Sg	McPh	1,2	1,8
Annonaceae	Hexalobus	*Hexalobus monopetalus* (A,Rich.) Engl. & Diels	SZ	NnPh	4,8	3,2
Bombacaceae	Adansonia	*Adansonia digitata* L.	SZ	MsPh	1,2	3,5
	Bombax	*Bombax costatum* Pellegr.	Su	MsPh	1,2	1,8
Cesalpiniaceae	Cordyla	*Cordyla pinnata* (Lepr. Ex A. Rich.) Milne-Redhead	SZ	MsPh	**17,9**	**16,5**
Combretaceae	Combretum	*Combretum glutinosum* Perrott. ex-DC	Su	McPh	3,6	3,0
	Anogeissus	*Anogeissus leiocarpus* (DC.) G.et Perr.	Su	MsPh	3,6	3,1
	Terminalia	*Terminalia macroptera* Guill. & Perr.	Su	McPh	1,2	2,1
Ebenaceae	Diospyros	*Diospyros mespiliformis* Hochst. ex A DC.	Pal	MsPh	2,4	**6,7**
Fabaceae	Tamarindus	*Tamarindus indica* L.	Pan	Msph	**8,3**	**8,0**
	Dichrostachys	*Dichrostachys cinerea* (L.) Wight & Arn.	Pan	McPh	2,4	2,1
Meliaceae	Azadirachta	*Azadirachta indica* A.Juss.	Pal	McPh	**7,1**	4,4
Mimosaceae	Faidherbia	*Faidherbia albida Del.*	SZ	McPh	**14,3**	**10,6**
	Prosopis	*Prosopis africana* (Guill. & Perr.) Taub.	Su	MsPh	2,4	2,5
	Acacia	*Acacia seyal* Del	Su	McPh	2,4	2,1
Moraceae	Ficus	*Ficus sycomorus* L.	SZ	MsPh	**6,0**	**5,9**
Palmaceae	Borassus	*Borassus aethiopum* Mart.	SZ	MsPh	4,8	**6,5**
Rhamnaceae	Zizyphus	*Zizyphus mauritiana* Lam.	Pal	McPh	2,4	2,1
Rubiaceae	Gardenia	*Gardenia erubescens* Stapf.	Su	NnPh	2,4	2,4
Zygophyllaceae	Balanites	*Balanites aegyptiaca* (L.) Delile	SZ	McPh	1,2	1,8

Source: D. Gomis, 2019. McPh (Microphanerophytes); MsPh (Mesophanerophytes); NnPh (Nanophanerophytes); Su (Sudaniennes); GC (Guinean-Congolese); Pal (Paléotropicales); Pan (Pantropicales); Aa (Afro-American); A (African); PA (Pluri-regional African), SG (Sudano-Guinean); SZ (Sudano-Zambézian); Ss (Sahelo-Sudanian); At (Afro-tropical); Fr (Frequency); IVI (Importance Value Index); Biological type (BT); Phytogeography (Ph)

3.2. Specific diversity and phytogeographical and biological types of woody flora

The diversity index values obtained for the stand are 3.95 bits for the Shannon index, 0.88 bits for the Pielou equitability index and 0.92 bits for the Simpson index (Table 4).

Table 4. Specific diversity

Diversity index	Value
Shannon index	3,95
E. Pielou	0,88
Simpson index	0,92

Source: D. Gomis, 2019

From a chorological point of view, the results reveal a numerical dominance of Sudanian and Sudano-Zambézian species, which are tied at 31.8%. They are followed by species with pantropical, paleotropical and Sudano-Guinean phytogeographical affinities, with rates of 18.2%, 13.6% and 4.3% respectively. However, in terms of abundance, species with a Sudano-Zambian chorology are the most important (45.1%), followed by pantropical (25.5%), Sudanian (15.7%), paleotropical (12.7%) and finally Sudano-Guinean species, which represent the lowest proportions (1%) (Table 5).
Biological types, concerned here exclusively with phanerophytes, showed that mesophanerophytes, with half the species (50%) and the bulk of individuals (61.8%), are the most represented, followed by microphanerophytes (40.9% and 30.4%) and finally nanophanerophytes (9.1% and 7.8%) (Table 5).

Table 5. Species diversity, biological and phytogeographical types

Typological indicator			Nbr of spe %	Nbr of ind %
Biological type	Phanerophytes	MsPh	**50**	**61,8**
		McPh	40,9	30,4
		NnPh	9,1	7,8
Phytogeographical type	EBS	Su	**31,8**	**15,7**
	ELB	Pal	13,6	12,7
		Pan	18,2	25,5
		Aa	-	-
	EPRA	SG	4,5	1,0
		SZ	**31,8**	**45,1**

Source: D. Gomis, 2019. McPh (Microphanerophytes); MsPh (Mesophanerophytes); NnPh (Nanophanerophytes); Esp (species); EBS (Sudanian-based element); ELD (Broadly distributed element); EPRA (African multi-regional species); Su (Sudanian); Paleotropical (Palaeotropical); Pan (Pantropical); Aa (African-American); PA (Pluri-regional African), SG (Sudano-Guinean); SZ (Sudano-Zambezian); Ss (Sahelo-Sudanian); Ind (individual); Spe (Species); ind (individual)

3.3. Structural parameters and atmospheric carbon sequestration

The results of the dendrometric parameters reveal an average density of 7.6 individuals/ha. Diameter, an important criterion for assessing stand characteristics, averaged 48.5cm, while tree height averaged 10.9m. The average basal area obtained was 1.6m^2/ha, and the projected area of cover of the woody stand surveyed gave an average plant cover rate of 5.8%. The average biomass values obtained were 15.0 tms.ha.$^{-1}$, including 13.3 tms.ha^{-1} for above-ground biomass and 1.7 tms.ha^{-1} for below-ground biomass. This corresponds to an average sequestered carbon stock of 7.5 tC.ha^{-1} , of which 6.6 tC.ha^{-1} above ground and 0.9 tC.ha^{-1} below ground (Table 6).

Table 6. Dendrometric parameters and carbon potential of the woody stand

Dendrometric parameters and biomass	Average values
Average density (Individuals /ha)	7,6
Average diameter (cm)	48,4

Average basal area (m²/ha)		1,6
Average height (m)		10,9
Average cover (%)		5,8
Biomass (tC. ha^{-1})	AGB	13,26
	BGB	1,75
	Total	15,01
Carbon Stock (tC.ha^{-1})	AGB	6,63
	BGB	0,87
	Total	7,51

Source: D. Gomis, 2019. AGB: Above Ground Biomass; BGB: Below Ground Biomass

3.4.Carbon distribution by species and families

Cordyla pinnata and *Borassus aethiopum* have the highest proportions of carbon sequestration by species: 133.9 tC.ha^{-1} and 131.2 tC.ha^{-1}, followed by *Faidherbia albida* (63.4 tC. ha^{-1}), *Tamarindus indica* (47.1 tC.ha^{-1}), *Diospyros mespiliformis* (37.9 tC.ha^{-1}), *Anacardium occidentale* (15.5 tC.ha^{-1}) and *Anacardium occidentale* (11.6 tC.ha^{-1}) (Figure 2).

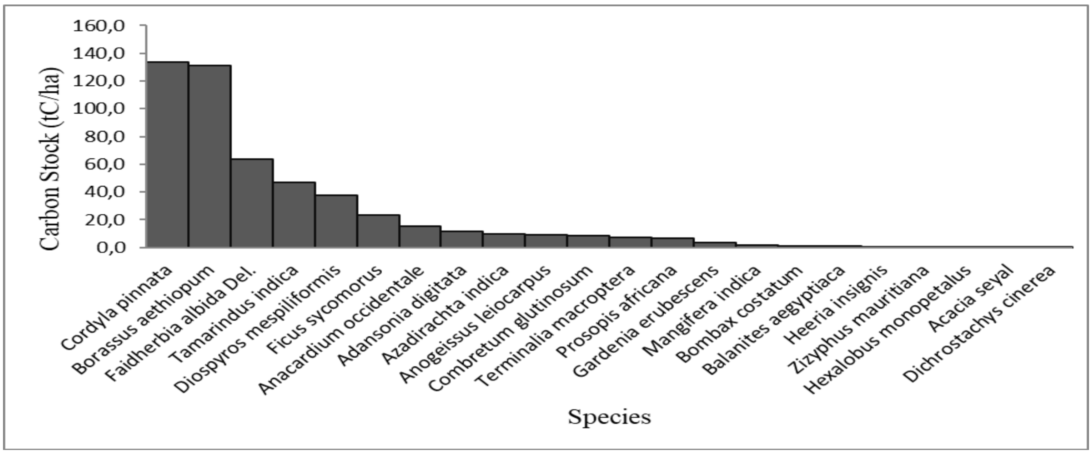

Figure 2. Carbon distribution by species (Source: D. Gomis, 2019)

Among the families, most of the carbon is held, in descending order and relative value, by: Cesalpinaceae (26%), Palmaceae (26%), Mimosaceae (14%), Fabaceae (9%) and Ebenaceae (7%) (Figure 3).

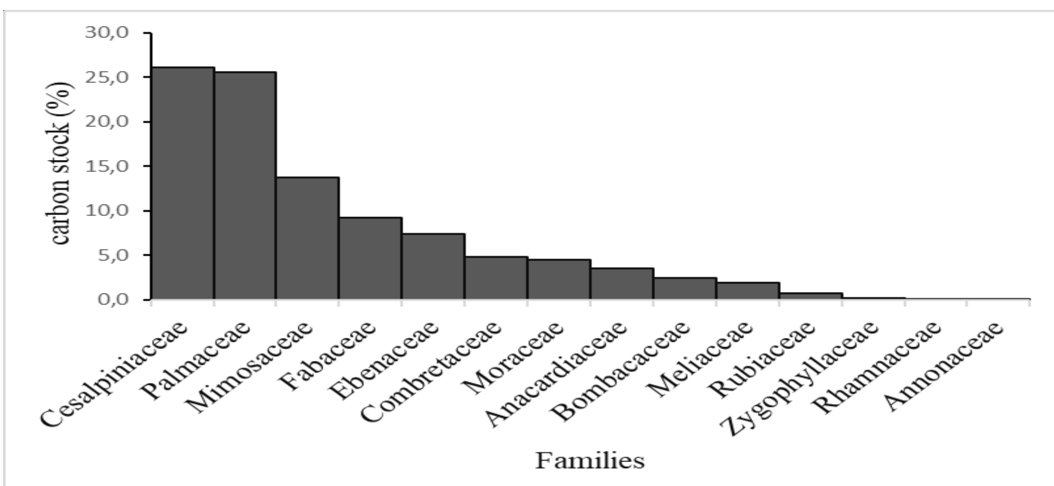

Figure 3. Carbon distribution according to families (Source : D. Gomis, 2019)

3.5.Carbon distribution by diameter class

The results presented in Figure 4 give an overall view of the diameter structure of the woody stand surveyed. They show an irregular structure with a dominance of large trees marked by a modal class corresponding to the ≥50cm diameter class category. Analysis of the carbon distribution in these different diameter classes shows that the greatest quantity of carbon is found in adult individuals, and that it increases with increasing diameter and abundance of individuals in its class.

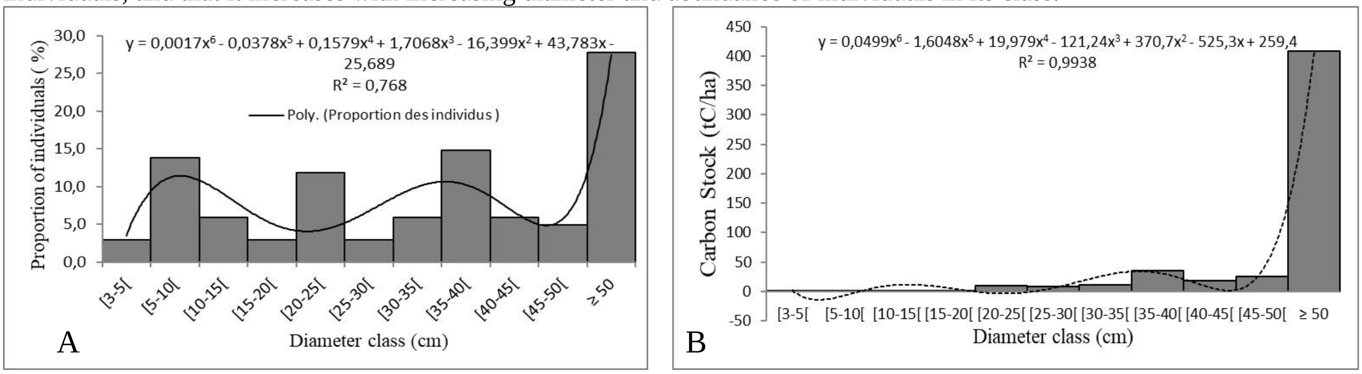

Figure 4. Distribution of individuals (A) and their carbon stock (B) by diameter class (Source: D. Gomis, 2019)

3.6.Correlation between carbon stock, species richness and certain structural parameters

In order to assess the relationship between carbon stock, species richness and certain dendrometric parameters, including true density, basal area and crown cover, correlation tests were carried out for each plot (Figure 5). For these different parameters, positive correlations were observed between carbon stock - basal area ($R^2 = 0.66$) and carbon stock - cover, despite being very weak for the latter ($R^2 = 0.01$). However, these correlations remain zero between carbon stock - true density and carbon stock - species richness.

3.7.Economic value of sequestered carbon

The contribution of agroforestry to global warming mitigation depends on its proven carbon sequestration potential. In this case, the average quantity of carbon sequestered is estimated from the results obtained at 7.5 $tC.ha^{-1}$ or a CO^2 equivalent of 27.6 $tCO^2.ha^{-1}$. Considering the area of cultivated land in the study zone, estimated at 44,472.99 ha, the total carbon dioxide removed from the atmosphere by this unit would be 1,227,454.5 tCO^2. Assessment of the economic value of the carbon dioxide sequestered, at a cost of 3USD/ tCO^2 (Peltier and al., 2007), would yield, if the carbon credit were to be paid at 10USD/ tCO^2 in terms of carbon credit compensation, a total of 82.8USD/ha, or 49,590.6 CFA francs/ha (1USD = 598.92 CFA francs) corresponding to a total of 2,105,441,190.5 CFA francs for all the cultivated areas in the study zone (Table 7).

Table 7. Economic value of carbon stock trapped by woody plants in fields

Biotope	Area (ha)	Carbon stock (tC/ha)	Equivalent in $tCO_2.ha^{-1}$	Total $tC0_2$	Economic value in $USD/tCO_2/ha$	Economic value in $CFA/tCO_2/ha$	Economic value Total in CFA
Zone de culture	44.472,99	7,52	27,5984	1.227.454,5	82,8	49.590,6	2.105.441.190,5

Source: D. Gomis, 2019

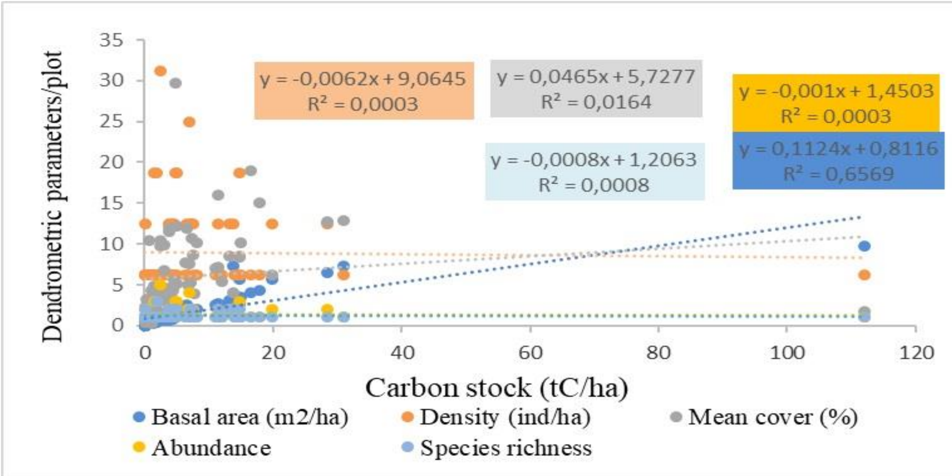

Figure 5. Correlation per plot between carbon stock and dendrometry parameters (Source: D. Gomis, 2019)

3.8.Constraints to introducing trees into fields

The surveys revealed a number of constraints to the introduction of trees in cultivated areas (Figure 6). Among these constraints, the ones most frequently cited were the concern about shade from trees on rainfed crops (70%), cattle roaming (62%) and rainfall deficits (35%). Next come lack of seedlings (14%), salinization (13%), lack of technical means and tools (10%), forestry legislation (10%), rodents, especially palm ras (8%) and lack of time (6%). The least cited constraints are lack of motivation (2%) and lack of strength (1%).

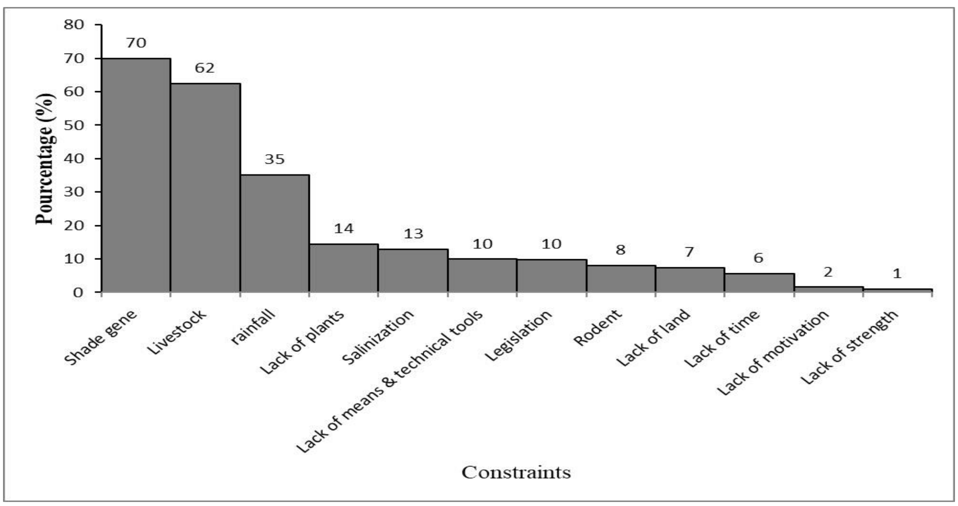

Figure 6. Constraints to agroforestry practice (%) (Source: D. Gomis, 2019)

4. Discussion

The study revealed that the woody flora of the cultivated areas of the study zone contains a specific richness largely dominated by species belonging to the Mimosaceae, Combretaceae and Cesalpinaceae families. The predominance of these families in the Sudano-Sahelian zone, i.e. North Sudan, is shared by several authors (Moussa and Mahamane 2015; Sarr 2014; etc.). This predominance could result from their adaptability, their mode of dissemination, their regeneration and above all their usefulness. Indeed, as Fall 2017 confirms, in the groundnut basin, the place of the tree within a plant stand is explained by its role in the rural system. These reasons would certainly explain the values of the various ecological parameters (Frequency, IVI) obtained between species. In terms of species richness, the value of Shannon's diversity index obtained (3.95 bits) reveals an average diversity of the woody stand. The Simpson (0.92 bits) and Pielou (0.88 bits) indices show a good distribution of individuals within species, despite the high abundance of *Cordyla pinnata* and *Faidherbia albida*. It should also be remembered that, according to Diallo et al. 2013, Pielou's equitability index, when its value exceeds the 70% threshold, as is the case here, reflects a relatively stable environment. In other words, an environment marked by very little competition between individuals, due in particular in this case to spacing for agricultural crop space requirements. Phytogeographical types reveal that species with a Sudano-Zambézian distribution, although equal in number of species to Sudanian species, remain more important than pantropical species in terms of abundance of individuals. This chorological situation reflects the image of a disturbed flora that is losing its specificity (Sinsin 2001), due on the one hand to anthropic practices such as grazing, which favours the expansion of species such as *Faidherbia albida*, and on the other to the introduction of exotic species (*Azadirachta indica*, *Mangifera indica*, etc.) through reforestation, and on the other hand to natural constraints, mainly rainfall deficits. In terms of biological types, their analysis shows the importance of mesophanerophytes, reflecting the arboreal character of the stand. The same observation was made by Sarr O., 2014 in Koungheul, leading him to consider field trees to be the most affluent compared with those in natural plant formations. This situation could be explained by the protection provided by farmers to the species they choose to mark the landscape of their fields, as they are involved in human and livestock nutrition, pharmacopoeia, handicrafts, and are also sources of income through the marketing especially of non-timber products (Sarr 2013).

The structural parameters of the woody stand give an average density value of 7.8 ind/ha. This value remains low compared to that obtained by Sarr (2013), which is 10 ind/ha, which could reflect differences in terms of settlement and intensification of agricultural activity. However, in these areas, it testifies to the priority given by farmers to cultivation and yield optimization over all other endeavors, since, for most of them, this is their only source of income and food. This is reflected in the basal area which, despite a large average diameter of 48.4 cm, remains low (1.6 m^2/ha), as does the canopy cover (5.8%) due to the low density of individuals. The average carbon stock calculated for this stand is 7.51 $tC.ha^{-1}$, of which 6.63 $tC.ha^{-1}$ for above-ground stock and 0.87 $tC.ha^{-1}$ for below-ground stock. This result is still higher than that obtained by Diatta and al. 2016, in the southern groundnut basin, who found an average value of 2.40 $tC.ha^{-1}$. This situation could be explained by differences in the maturity of individuals, with a greater frequency of trees with a diameter greater than 30 cm in this study. In fact, several authors have shown the influence of large-diameter trees on the carbon predominance of stands compared with others with medium-diameter individuals. However, the value obtained remains below the range 10-60 $tC.ha^{-1}$ contained in the live above-ground biomass of cocoa agroforestry systems in Costa Rica (Valentini 2007). It is also lower than the carbon stock of 9.8 $tC.ha^{-1}$ obtained by Diatta and al. (2016) in agroforestry parks in the semi-arid Niayes area of Senegal. These differences are probably due to the diversity of environments and tree densities, but also to the different allometric equations used. Within the stand, there are variations in carbon stock between species. The most representative are *Cordyla pinnata*, *Borassus aethiopum* and *Faidherbia albida*, certainly due to their abundance and dominance in individuals. This is reflected at family level by the predominance in carbon of Cesalpinaceae, Palmaceae and Mimosaceae. However, the high carbon content of *Borassus aethiopum* on *Faidherbia albida* could be explained by differences in the equations. The equation by Chave et al, (2005) does not take palms into account, and the model by Brown, (1997), which is used for palms because it does not include wood density, consequently produces higher values. Despite the irregular structure of the stand, the diameter distribution of carbon also reveals a concentration of carbon in large trees, and its increase with diameter classes and their abundance in individuals. The size of individuals therefore plays an important role in biomass production, certainly in addition to specific density, which is decisive in calculating this parameter (Chave and al., 2005). This situation would explain the positive correlation obtained between tree carbon stock and basal area, which, according to the results, is 66% dependent on the latter. However, no direct relationship was observed between specific diversity and carbon stock. Indeed, good species richness and diversity does not necessarily mean a high carbon stock. The same observation was made with regard to the relationship between plot cover and individual density, due in particular to pruning practices and the bon effect of the quantity of biomass produced when tree diameter exceeds the 17 cm threshold. The latter is explained by Mbow, (2009) by the fact that a *Pterocarpus erinaceus* individual with a diameter of 6 cm produces 13.6 kg of biomass, that of 11.3 cm; 63.7 kg, while the same individual at 19 cm produces 148 kg of biomass, i.e. 12 times more than a diameter of 6 cm. This means that a low-density plot with large trees can have more carbon than a dense plot with medium-diameter trees.

The evaluation of the economic value of the carbon stock obtained, as recommended by the carbon market as part of the REDD+ initiative, remains encouraging. Indeed, the REDD+ initiative aims to provide financial compensation for non-deforestation, and agroforestry plays an additional role in this respect, thanks to its carbon potential. Thus, for the study area, assuming a carbon credit value estimated at 3USD per tonne of CO^2, or around 10USD per tonne of carbon (Peltier R. and al. 2007), this would represent a payment of 82.8USD per hectare, or 49,590.6 F.CFA/ha. This amount may seem derisory, but it could be used to pay premiums to farmers to encourage them to enrich their agroforestry practices. It could also increase their income, reducing their vulnerability to the adverse effects of climate change on agriculture. At district level, these carbon credits would represent a considerable sum (2,105,441,190.5 CFA francs), which could also help communes, as part of the decentralization process, to boost the green economy through sustainable practices such as agroforestry, in such a way that, in addition to the carbon credit amounts, other sources of income such as the sale of non-timber products could be added to their earnings.

Despite these advantages, there are still a number of constraints that do not encourage the introduction of trees in the fields (shading, livestock rambling, rainfall deficits, lack of seedlings, salinization, lack of technical means and tools, forestry legislation, rodents, lack of land and motivation...). Indeed, although trees are useful for improving soil quality, farmers feel that they reduce yields, notably because their tops compete for light with rain-fed crops. This perception, although recognized by studies (Gala and al. 2017) in fallow land in Cacao, could also be a consequence of so-called "modern" agriculture, which for a long time was intended to be treeless. Livestock farming, as practiced extensively in the area, is also a major constraint, since to protect the plants from grazing or encroachment by animals, iron barbed wire will have to be laid, which remains costly to set up, or live hedges, which require significant and ongoing maintenance work, not to mention the pruning practices of transhumant herders who, for reasons of livestock survival, especially as winter approaches, do not take into account the two-year pause observed by most field owners before repeating another pruning operation on the same tree, which can lead to its death. These results confirm those obtained by Sanogo and al. 2004, who show that animal divagation is a major constraint to the adoption of new agroforestry technologies. Similarly, the region to which the study area belongs is marked by rainfall variability, the decrease in which accentuates salinization, making the soil unsuitable for the development of halophobic plants. As for the remaining constraints, the lack of means of production (plants, capital and technical tools, strength, land) accounted for 31% of all constraints. These results confirm those of Bruno Devresse and al. 2014, who cite land tenure insecurity as a hindrance to agroforestry. Indeed, in the study area, the heads of households surveyed, who rent fields in return for a few end-of-season gifts, indicate that planting trees on loaned land carries the risk of being interpreted by the field owner as a desire to appropriate the land, and may result in immediate withdrawal from the plot. Also, from the point of view of forestry legislation, farmers cannot cut down trees in their own fields for fear of being fined by forestry officers, which discourages them from letting the seedlings grow in their fields, an observation shared by Zarafi et al., 2002. In fact, the State is still the official owner of the trees and has the power to impose fines on people who cut down trees without a permit, even if it is the field owner who has planted and maintained the tree until it reaches maturity. The effect of rodents, particularly palmetto rats which eat the seedlings, is also a not inconsiderable fact.

5. Conclusion

The ecological techniques of floristic inventories combined with allometric models made it possible to estimate the atmospheric carbon reduction potential of the agroforestry park in the study area. These results revealed a significant quantity of atmospheric carbon trapped by the park. The equivalence of this quantity of stored carbon in monetary value reveals the existence of an economic opportunity which, if valorized within the framework of carbon credits, could enable local populations to benefit from additional income and thus provide the State with the means to better manage these parks. However, surveys carried out among the local population reveal the existence of a number of technical, natural and social constraints that need to be overcome before agroforestry can be fully and intensively implemented in the study area. Indeed, agroforestry is not effective in all crop fields. As well as assessing the carbon stock potential of agroforestry's woody biomass, this study has shown its economic value and the obstacles to its implementation. As a result, improvement strategies in response to these various challenges should be found, for the greater benefit of the planet and local populations.

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Contributor's role	Authors' names
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Data management	Daniel GOMIS
Formal analysis	Daniel GOMIS

Survey and investigation	Daniel GOMIS
Methodology	Daniel GOMIS
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Writing - Preparation	Daniel GOMIS
Writing - Revision	Agnès Daba THIAW-BENGA, Sidia Diaouma BADIANE, Babacar Faye

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