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Assessment of Carbon Stock in Woody Vegetation for the Mitigation of Atmospheric CO_2 Emissions at Natitingou City in North Benin (West Africa)

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Abstract: The study aims at evaluating the potential of carbon sequestration by woody vegetation in the township of Natitingou. The phytosociological survey method was used to collect data in plots 344 of 1 ha each using the stratified random sampling technique. The use of the allometric model, developed for the Sudanian domain, made it possible to estimate the carbon of the different species inventoried. In total, 89 woody species, divided into 74 genera and 36 families were counted. The most representative families are *Leguminosae-Caesalpinioideae* (15%), *Moraceae* (9%), *Anacardiaceae* (7%), *Leguminosae-Mimosoideae* (7%). The urban woody vegetation of Natitingou produces on average 42.3 ± 4.1 tMs/ha of biomass for an average carbon stock rate of 20.6 ± 2.0 t/ha, of which the equivalent in trapped CO_2 is 75.5 ± 7.4 t/ha. *Afzelia africana* (7.8 t/tree) and *Adansonia digitata* (6.9 t/tree) have the highest average carbon values by species, while *Annona senegalensis* (0.008 t/tree) *and Senna alata* (0.006 t/tree) have the lowest values. The ecological value of vegetation in the urban environment of Natitingou is estimated at 803901 $. The atmospheric carbon reduction potential of urban vegetation in Natitingou was revealed and will serve decision makers and the public as a springboard for urban planning projects and as an opportunity for the carbon market in the REDD+ process.

Keywords: Urban Woody Vegetation, Biomass, Carbon Stock, Carbon Dioxide Emission, Natitingou

1. Introduction

Since 1950, the world has experienced a very strong acceleration of urbanization, which is reflected in the growth of urban populations and the geographic expansion of cities [1]. Africa has one of the highest urban growth rates in the world. Current trends show that land is growing faster than urban populations. Despite some benefits for humans, urbanization has adverse consequences for the environment and biodiversity [2]. Factors that influence the presence of urban biodiversity include the size, connectivity, and structural diversity of natural or semi-natural habitat patches, as well as the relative amount of tree cover and socioeconomic conditions. The place of nature in cities is well established. The advantages and benefits that vegetation brings to the urban environment are numerous: reduction of the urban heat island, energy consumption of buildings and the carbon footprint of cities, improvement of air quality, management and quality of stormwater, as well as biodiversity [1]. Among these different services, the carbon sequestration service presents high stakes, since the vegetation of terrestrial ecosystems stores more carbon than the atmosphere. This is the reason why the evaluation of adaptation measures to climate change requires a global approach to the urban system, called the *ecosystem* approach. Recognizing this diversity of function of urban vegetated areas, the concern of scientists for the creation of socially viable, economically livable and ecologically sustainable and attractive urban clusters is the preservation of urban vegetated areas.

The biodiversity of the township of Natitingou is no exception to this state of affairs. The urban woody reserves are under strong anthropic pressure linkedto rapid and poorly controlled urbanization, with its corollaries in infrastructure construction and massive mineralization of the soil of all kinds that promote the degradation of biological diversity and the disruption of ecosystems. Plateaus are favorable environments for vegetation development [3]. The city of Natitingou presents a beautiful landscape, classified, among the most visited tourist cities in Benin. It is one of the few cities in Benin with an urban forest in the heart of the city, a reforestation area of 22.9 ha. Despite its very uneven relief, the various plant species present in the city of Natitingou condition a multitude of ecosystem services among which figure prominently in the regulation of the microclimate through the phenomenon of carbon sequestration [4]. The vegetated spaces know the pressures increasingly strong in the Beninese cities. One of the major consequences of this phenomenon is air pollution, which is the main environmental problem in the world's major urban centers [5]. The pressures on the wooded areas of Benin's large cities have been highlighted [6]. In order to reduce anthropogenic pressures on biodiversity in general and woody plant species in particular, it is increasingly important to quantify the benefits that city dwellers derive from the presence of trees in order to provide decision-makers and populations with the necessary information that can lead to management and safeguard actions. In addition, apart from the work on the modeling of land use in the commune of Natitingou [3], which showed the degradation of natural plant formations in the district, no other study has taken into account the urban vegetated areas of Natitingou. There is an urgent need to quantify the potential of these spaces to improve the sustainability and resilience of the city. The present research proposes to evaluate the carbon stock of woody vegetation in the city of Natitingou for atmospheric CO_2 mitigation.

The hypothesis underlying this research is that vegetation in the urban environment of Natitingou has a better potential for carbonstorage.

2 Materials and Methods

2.1. Study Area

The city of Natitingou is located between 10°14'17" and 10°20'15" North latitude and between 1°21'45" and 1°24'23" East longitude. It corresponds to the urban districts of the district of Natitingou. Located in the northwest of the Republic of Benin in the Atacora department, it covers an area of 1774.77ha (Figure 1). Its relief is one of the most rugged in the country due to the presence of the Atacora mountain range. The landforms are diverse and varied and range from mountainous areas in the center of the city to plateaus and peneplains on the periphery that constitute favorable environments for the development of vegetation [3]. The city is placed under a Sudanian climate characterized by an abundant rainy season (June to October) followed by a dry season (November to May). Due to the influence of the topography, Natitingou is among the wettest cities in Benin with a minimum rainfall of 930 mm and a maximum height of 1495 mm recorded respectfully in 2000 and 2003, or an average height of 1187 mm of rain during the period of 1990 to 2020 [7]. Its hydrographic network is composed of streams, marigots and rivers (Yarpao, Koumagou, Winmou), most of which dry up between November and April. The minimum annual temperatures recorded between 1990 and 2020 vary from 20°C to 22°C and the maximums from 33°C to 34°C. Temperature affects respiration and photosynthesis [8]. The average annual duration of insolation is 2668 hours in the same period, with a maximum in November (286 h) and minimum in August (140 h), favors the production of biomass. The continental trade winds (harmattan) increase the air saturation deficit and accentuate the aridity conditions of the dry season and facilitate spatial dispersion in 90% of plant species, while the maritime trade winds (monsoon) revitalize vegetation. Finally, the geological substratum at the origin of the different types of soil in Natitingou is composed of quartzites and micaschists. Tropical ferruginous soils and soils that are not very advanced on quartzite and micaschist are derived from this. These soils are the support of plants and play the role of supplying air, water and mineral elements necessary for the good development of trees in the city. A multitude of socio-cultural groups cohabit and work for the development of the city, and their endogenous knowledge is essential to understand and appreciate the diversity of visions on the use of trees. The figure 1 shows the location map of the city of Natitingou.

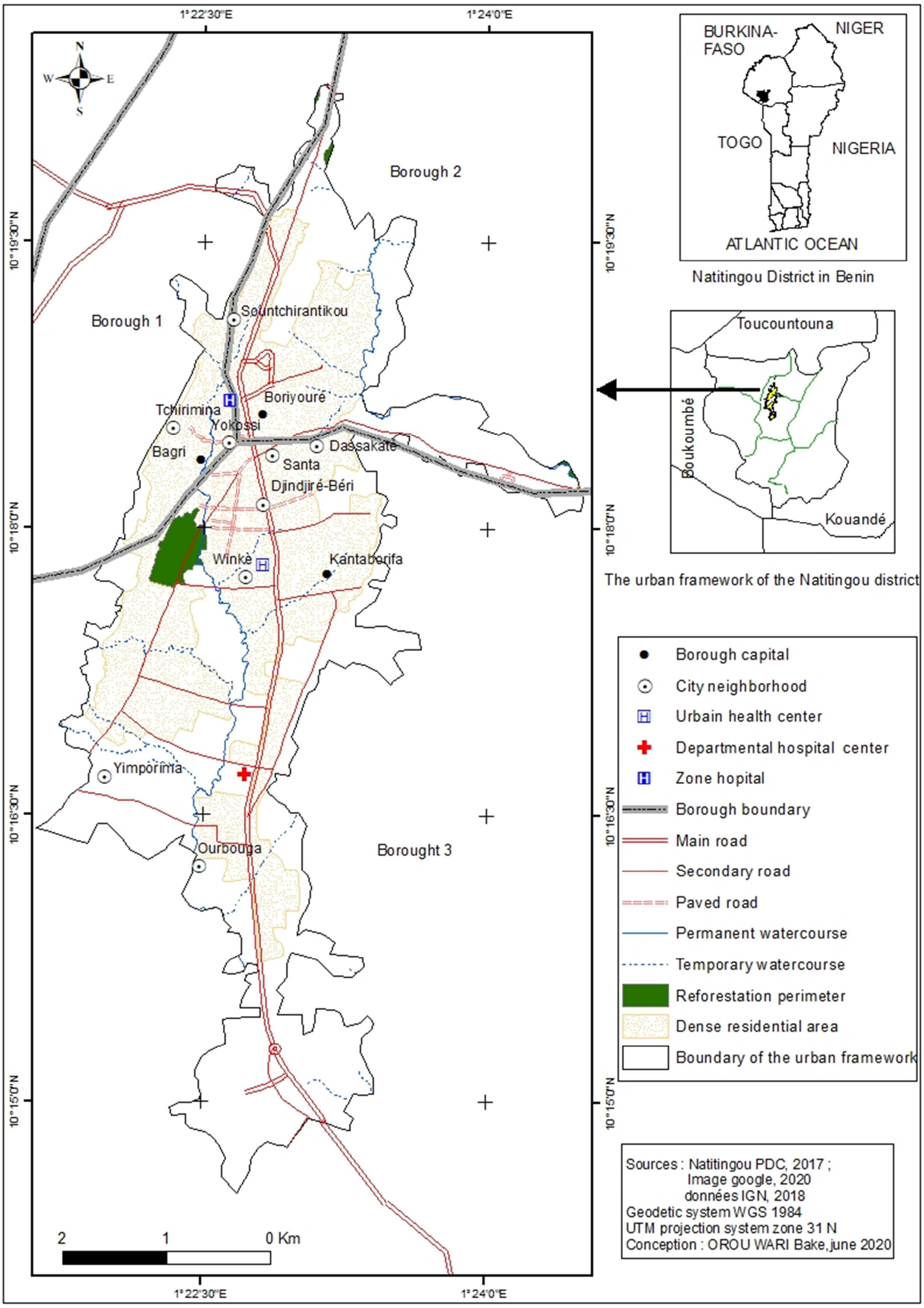

Figure 1. *Location of the Natitingou city.*

2.2. Material and Method

2.2.1. Material Used for the Collect Data

It includes the study material (woody vegetation) and the data collection and processing equipment. The data collection equipment includes: a GPS (*Global Positioning System)* receiver to connect the plots and take the geographic coordinates of the trees; an inventory form to record the data collected; a penta decameter to measure the circumference of the trees and the sighting distance; a clinometer to measure the height of the trees; and newsprint to create the herbarium Data processing and statistical analysis equipment includes: Excel spreadsheet, ArcGis 10.5, and SPSS 21 software.

2.2.2. Collected Data

The 2020 sentinel-2 images of 10 m resolution (geometrically corrected, georeferenced) and the 2020 google earth images are the planimetric data used to obtain the urban land cover. The data collected also include species, girth, height, north-south and east-west diameters of the trees surveyed.

2.2.3. Data Collection Methods

The sentinels-2 images are downloaded from the site: earthexplorer.usgs.gov in GEOTIFF format and the google earth images by SAS planet.

The floristic inventory was conducted in 344 plots (Figure 2) installed following stratified random sampling [9, 10]. A systematic mesh [11] of the square-shaped map [12] of 100m x 100m [13], either 1 ha is made. The meshes (plots) are numbered from 1 to n [12] according to the area in ha of the city. After that, the sampling points are randomly generated by ArcGIS 10.5 software on the map of the city of Natitingou, according to the size of the strata [14]. The total number of plots installed is obtained by the formula established by [15], and used by [16] after the installation of 20 pre-sampling plots.

$$n_{=}\left[t_{1-\alpha/2}(cv/d)\right]^2$$

where n: total number of plots; cv: coefficient of variation of basal area of pre-sample plots: 92.7%; d: margin of error of basal area with d = 10 %; $t_{1-\frac{\alpha}{2}}$: value of the Student's t-statistic for a risk alpha of 0.05; $t_{1-\frac{\alpha}{2}} \approx 2$. The total number of plots inventoried is 344.

In the city of Natitingou, nine land use units were identified according to the level I and II classification (determining the number of classes according to the desired precision depending on the spatial resolution of the image) made by [17] and used by [14]. The visual interpretation of the *Sentinel* image, supported by the *Google Earth* 2020 image, allowed for a stratification of the urban fabric into nine land-use units, each of which corresponds to one or more urban vegetation typologies in Natitingou. The figure 2 shows the spatial distribution of plots by land use unit.

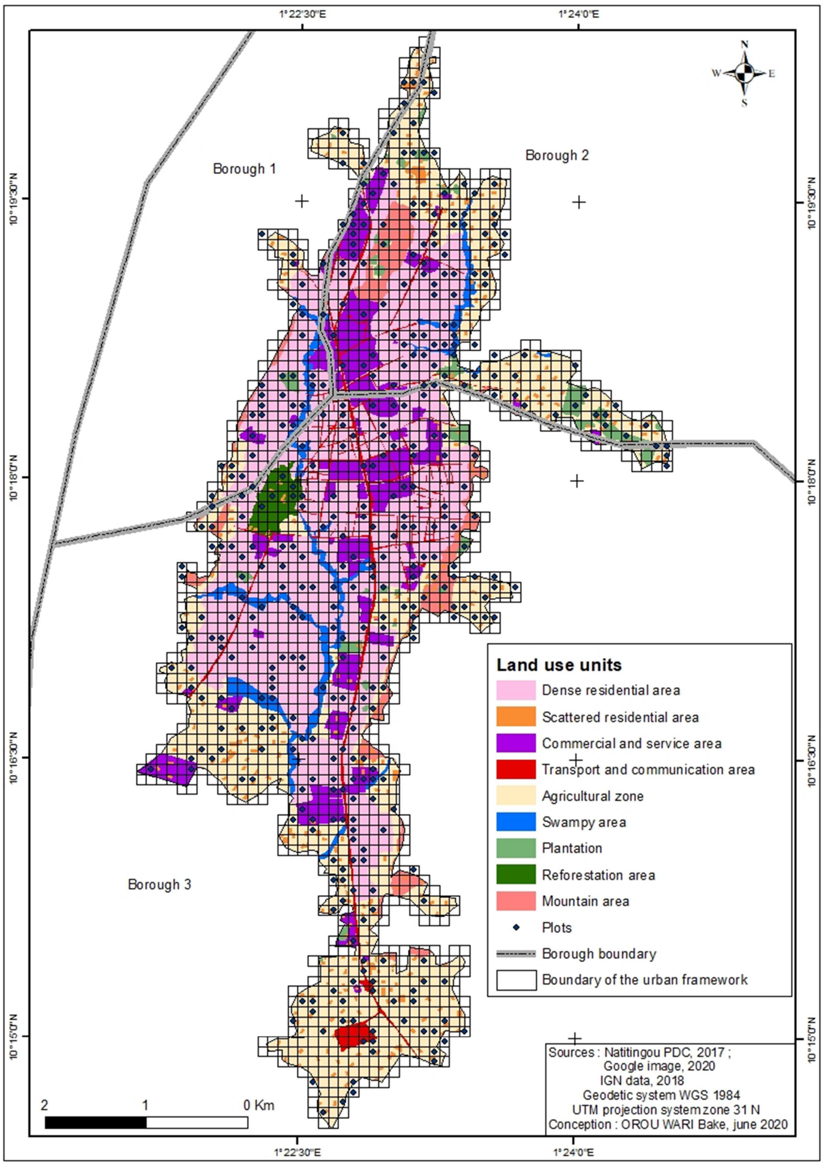

Figure 2. *Plots spatial distribution according to land cover units.*

2.2.4. Methods of Processing Floristic Data

The identification of species and the determination of their origin (endogenous or exogenous) were carried out using the Flores *"Flore analytique du Bénin"* [18] and "*Arbres et arbustes du Sahel: Leurs caractéristiques et leurs utilisations* [19].

2.3. Methods for Estimating Carbon in Urban Woody Vegetation

2.3.1. Methods for Estimating Woody Aboveground Biomass

Carbon stock assessment is based on allometric equations that directly estimate the total or partial biomass (above-ground biomass, below-ground biomass, etc.) of a tree based on predictors [20]. The most important predictors of biomass are, in descending order: stem diameter, wood density and total height [21]. In a study entitled "*Filling a gap in tropical forest biomass estimation: accounting for crown mass variation in pantropical allometries*" a significant improvement in biomass estimates was achieved by only including crown mass [22]. Regardless of the predictors considered, the estimation of tree biomass is always accompanied by an error that corresponds to the difference between the observed biomass values and the values predicted by the allometric model [22]. In general, three categories of errors are associated with tree biomass estimation [23]. Among these types of errors, the choice of the allometric equation is the most important source of error in biomass estimates [23] and 76% of the total error in tree biomass estimates in tropical Africa, are due to the choice of the allometric equation [24].

Choice of the allometric equation:

In Africa, the carbon footprint of cities is neglected in biomass or carbon estimates. As a result, there is an almost total absence of allometric models specific to the African city. The few authors who have addressed carbon estimation in cities have used allometric models developed by trees in forests. In the present research the allometric equation of [25] was used for the estimation of woody above-ground biomass due to the fact that it integrates the Sudanian climate domain to which the city of Natitingou belongs. In addition, the DBH parameter ($5.15 \leq D \leq 41.5$ cm of the model) encompasses the data of the present research up to 78,43% of the inventoried individuals. The equation (1) is stated as follows:

$$\mathrm{AGBa} = 1{,}929 * \mathrm{D} + 0{,}116 * D^2 + 0{,}013 * D^3 \quad (1)$$

with $R^2 = 0.934$; RSE = 0,183 as the performance parameters of the equation; AGB_a: biomass aerialand; D: diameter at 1.3m.

Since this equation is developed from forest trees, and taking into account the results of the work of several authors [26, 27] a correction factor of 0.8 is applied to isolated trees whose stem structure is different from that of trees in forests. Therefore, aboveground biomass is obtained by the formula:

$$\mathrm{AGBa} = 1{,}929 * \mathrm{D} + 0{,}116 * D^2 + 0{,}013 * D^3 * 0{,}8 \quad (2)$$

2.3.2. Below Ground Biomass (AGBr) of Standing Woody Plants

The estimation of root biomass of standing woody plants is evaluated following the method indicated in the guidelines established by the Intergovernmental Panel on Climate Change [20] and used by. Indeed, according to [28], the root biomass equivalence of standing woody plants is found by multiplying the value of aboveground biomass (AGBa) by a coefficient R (stem/root ratio) whose value is estimated to be 0.24.

$$\mathrm{AGBr} = \mathrm{AGBa} * \mathrm{R} \quad (3)$$

where AGBr: root biomass; AGBa: aerial biomass and R: coefficient (stem/root ratio).

2.3.3. Total Standing Woody Biomass

The total biomass (AGBt) of standing woody plants is estimated as follows:

$$\mathrm{AGBt} = \mathrm{AGBa} + \mathrm{AGBr} \quad (4)$$

where AGBa is above-ground biomass, AGBr is belowground biomass.

2.3.4. Estimation of Sequestered Carbon Stock

For the estimation of the amount of carbon, the specific conversion factor applied in Benin was used [29]. This conversion factor has a value of 0.487 [29]. Thus, the amount of carbon is deduced as follows:

$$Ct = AGBt * fc \quad (5)$$

With *Ct:* carbon and AGBt: total biomass; *fc:* biomass to carbon conversion factor.

2.3.5. Estimation of the Amount of Carbon Dioxide

The amount of CO_2 was calculated by land use type in the city. To determine the amount of gas absorbed in CO_2, equivalent it is necessary to multiply the amount of total carbon by the conversion factor 44/12 (ratio of the molecular masses of CO_2): $Q_{CO2} = Ct * 44/12$ *(6); with* Q_{CO2}*: amount of* CO_2*; Ct: total carbon; 44/12: conversion factor of carbon to carbon dioxide.*

2.3.6. Ecological Value Releated to Carbon by the Urban Woody Vegetation of NATITINGOU

The ecological "carbon" value of the city was calculated using the equivalent ton of CO_2 sequestered in the Clean Development Mechanism (CDM) market which is 6 $ [30, 31]. The average carbon stocks sequestered by land cover unit were related to the area of each land cover unit before being converted to ecological value as advocated by the carbon market in REDD+ to obtain the Reduced Emissions Certificates (REC) which are translated into equivalent tons of CO_2 which is the currency of exchange on the carbon market by applying a value of 6 $.

2.4. Calculation of the Uncertainty of the Carbon Estimate

The uncertainty is the estimated difference between the calculated value and the actual value. It is used in the form of the percentage error and is used to assess the credibility of the estimated carbon in the carbon market. If its value is significantly greater than 10%, the calculated value for the carbon stock may be less accurate than desirable [32].

In the case of this research the total uncertainty in carbon estimation was calculated at the city scale using the city average carbon stock per carbon pool (above and below ground) following the steps [33]: formula for the average of observations ($\bar{x}$):

$$\bar{x} = \frac{1}{n}\sum_{i}^{n} x_{\text{i}} \quad (6)$$

formula for standard deviation (S):

$$S = \sqrt{\frac{1}{n-1}\sum_{i}^{n}(xi - \bar{x})^2} \quad (7)$$

formula for the standard error (SE$\bar{x}$):

$$\text{SE}\bar{x} = \frac{S}{\sqrt{n}} \quad (8)$$

formula for 95% confidence interval:

$$CI = t * \text{SE}\bar{x} \quad (9)$$

formula of the uncertainty as percentage error (U)

$$U = \frac{CI}{\bar{x}} \quad (10)$$

and formula for total uncertainty (Ut):

$$Ut = \frac{\sqrt{(U1*\bar{x}1)^2 + (U2*\bar{x}2)^2}}{|\bar{x}1 + \bar{x}2|} \quad (11)$$

where $\bar{x}$ average carbon stock in all plots, n: number of plots, x: carbon stocks in each plot, S = standard deviation, SE$\bar{x}$ standard error of the mean, 95%CI: confidence interval, t = 1.96: factor representing the area under the normal distribution curve for the 95% confidence interval and SE$\bar{x}$ standard error, U: uncertainty per carbon pool, U1: uncertainty of aboveground carbon, U2: uncertainty of root carbon, $\bar{x}1$: average of aboveground carbon, $\bar{x}2$: average of root carbon.

2.5. Statistical Analysis

Statistical Analysis System version 9.2 (SAS v.9.2) was used for statistical analysis. Biomass carbon and dioxide stocs were subjected to a one-way ANOVA taking into account the Natitingou urban land cover. the Student Newman-Keuls test at the 5 % threshold (probability level) was used for the separation of means.

3 Results

3.1. Floristic Composition of the Inventoried Species

The forest inventory of the 344 plots in the Natitingou city allowed the identification of 89 species grouped in 74 genera and 36 families. These species are composed of 46% exotic versus 54 endogenous. The most represented families are *Leguminosae-Caesalpinioideae* (15%), *Moraceae* (9%), *Anacardiaceae* (7%) and *Leguminosae-Mimosoideae* (7%). The floristic composition of the different land use units in Natitingou is detailed in the Table 1.

Table 1. *Floristic composition by land cover unit in Natitingou city.*

UOT	Exotic and local			Local specie			Dominant families (Number of species)
	Species	Generas	Families	NId	Es	NId	
DRA R	62	55	32	1663	25	175	Leguminosae-Caesalpinioideae (7), Moraceae (5)
SRA	56	53	30	1656	23	264	Leguminosae-Caesalpinioideae (10), Anacardiaceae (4), Verbenaceae (4), Leguminosae-Mimosoideae (4)
SCA	51	46	24	1115	20	147	Leguminosae-Caesalpinioideae (6), Leguminosae- Mimosoideae (5)
TCA	37	34	22	443	10	36	Leguminosae-Caesalpinioideae (5), Arecaceae (3) Rutaceae (3)
AA	48	46	27	1196	21	393	Leguminosae-Caesalpinioideae (7), Arecaceae (4)
SA	48	46	27	611	19	70	Leguminosae-Caesalpinioideae (8), Anacardiaceae (3)
PL	50	44	26	670	23	112	Leguminosae-Caesalpinioideae (8), Moraceae (5)
RA	15	15	10	615	5	10	Anacardiaceae (3), Verbenaceae (2)
MA	10	10	8	33	5	9	Anacardiaceae (2), Verbenaceae (2)

UOT: Land Cover Units; Nid: Number of individuals; Es: species; DRA: Dense residential area; SRA: Scattered residential area; CSA: Commercial and service area; TCA: Transport and communication area; AA: Agricultural area; SA: Swampy area; PL: Plantation; RA: Reforestation area; MA: Mountainous.
Source: Field results, Natitingou 2020.

From the analysis of the table 1, it appears that the total number of individuals of local species per unit of land cover is significantly lower than the total number of individuals of exotic species, even though the number of local species does not show a large difference.

3.2. Estimation of Urban Woody Biomass Per Land Cover Units

The figure 3 shows tree biomass by land use unit.

From the analysis in figure 3, it is apparent that the biomass of the trees surveyed is significantly different ($p<0.001$) by urban land cover unit. The reforestation area (AGBa: 255.7±99.6; AGBr: 61.4±23.9 and AGBt: 317±123.5 tMs/ha) shows the highest values of biomass, while the mountain area (AGBa: 5.9±4.9; AGBr: 1.4±1.2 and AGBt: 7.4±6.1 tMs/ha) show the lowest values of above, below and total biomass. On the other hand, no significant difference is observed between biomass values in residential area (DRA, SRA), agricultural area; swamp area, plantation and the overall city biomass average. The same finding is observed in the commercial and service area; the transport and communication area which have statistically similar biomas.

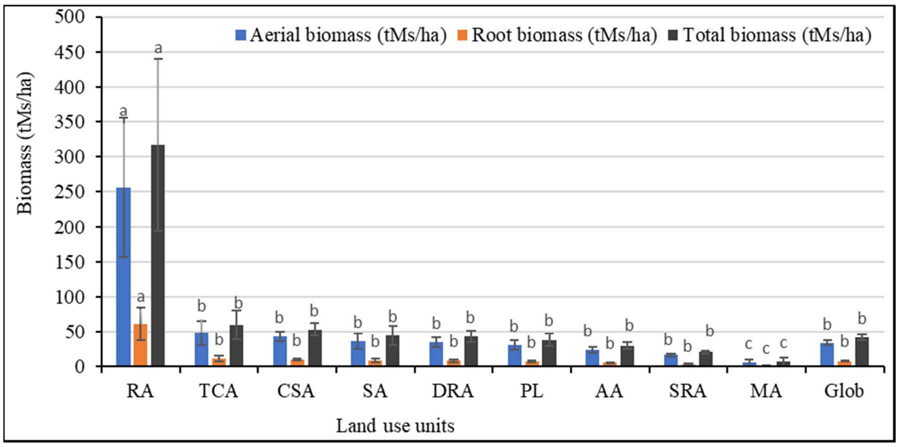

Figure 3. *Tree biomass surveyed by land cover unit.*

AGBa: Above-ground biomass; AGBr: Root biomass; AGBt: Total biomass; t/ha; tonne per hectare; UOT: Land use units; DRA: Dense residential area; SRA: Scattered residential area; CSA: Commercial and service area; TCA: Transport and communication area; AA: Agricultural area; SA: Swampy area; PL: Plantation; RA: Reforestation area; MA: Mountainous area; Glob: Overall biomass of the city. *Values with the same letter or combination of letters (a, b, or c) are not significantly different at the 5% level (Scheffé's mean value structuring test).*

3.3. Estimation of the Carbon and Carbon Dioxide Stock of Trees Per Land Cover Units in the City of Natitingou

Table 2. *Carbon stock, carbon dioxide stock, and total area by land cover units.*

UOT	Average stock		Sup (ha)
	C (t/ha)	CO_2t (t/ha)	
DRA	21 ± 4.2^b	76.2 ± 15.2^b	657,39
SRA	10.1 ± 1^b	37 ± 3.7^b	63,88
CS	26.1 ± 4.3^{ab}	95.5 ± 15.8^{ab}	196,69
TCA	29.4 ± 10.3^{ab}	107.6 ± 37.7^{ab}	60,24
AA	14.6 ± 2.3^b	53.5 ± 8.6^b	584,47
MA	22 ± 6.7^b	80.7 ± 24.7^b	71,14
PL	18.7 ± 4.2^b	68.7 ± 15.5^b	43,11
DRA	154.4 ± 60.1^a	566 ± 220.5^a	22,86
MA	3.6 ± 3^c	13.2 ± 10.9^c	75,03
Global	$20,6 \pm 2,0$	75.5 ± 7.4	1774.80
Prob	<0.001	<0.001	

C: Carbon; CO_2: Carbon dioxide; t/ha: ton per hectare; Sup: Area; UOT: Land use unit; DRA: Dense residential area; SRA: Scattered residential area; CSA: Commercial and service area; TCA: Transport and communication area; AA: Agricultural area; SA: Swampy area; PL: Plantation; RA: Reforestation area; MA: Mountainous area. Values with the same letter or combination of letters (a, b, or c) are not significantly different at the 5% level (Scheffé's mean value structuring test).
Source: Field results, Natitingou (2020).

The analysis of the Table 2 shows that the carbon and carbon dioxide density of the surveyed trees are significantly different ($P<0.001$) among the urban land cover units. However, no significant difference ($p>0.05$) is observed between the average carbon and carbon dioxide stocks in two residential areas (RA and RA1), agricultural, wetland and urban plantations on the one hand and between commercial and service areas, transport and communication areas on the other hand. The highest values of carbon stock (154.4 ± 60.1 tC/ha) and carbon dioxide (566 ± 220.5 t/ha) are observed in the reforestation area. While the mountain area (3.6 ± 3 and 13.2 ± 10.9 t/ha) present the lowest values of average carbon and carbon dioxide. Considering the area of the different land cover units, it is noticed that the residential area (DRA: 657.39 ha) and the agricultural area (AA: 584.47 ha) have the largest areas, while the reforestation area (22.86 ha) has the smallest area. The figure 4 shows the relationship between the number of individuals, basal area, biomass and carbon stock of urban woody vegetation in Natitingou by circumference class.

From the analysis of the figure 4, it can be seen that basal area, biomass and carbon stock are intimately related to tree circumference. It can be seen that the circumference class ≥ 300 cm records the highest value of basal area and the highest amount of carbon. In Natitingou city, the largest number of individual trees surveyed are between 30 cm and 120 cm, but have a low carbon stock.

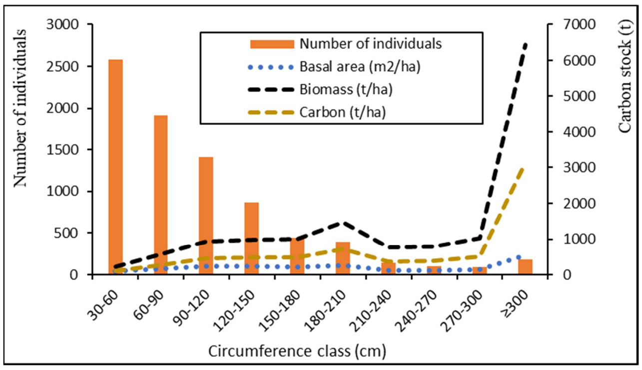

Figure 4. *Relationship between the number of individuals, basal area, biomass and carbon stock of urban woody vegetation in Natitingou by circumference class.*

3.4. Average Carbon Stock Per Species in the City of Natitingou

Figure 5 shows the average carbon per species in the city of Natitingou.

Analysis of figure 5 shows that *Afzelia africana* (7.8 t/tree) and *Adansonia digitata* (6.9 t/tree) have the highest average carbon values by species. They are followed by *Khaya senegalensis* (3.50 t/tree), *Ceiba pentandra* (2.8 t/tree), *Ziziphus mauritiana* (2.6 t/tree) and *Spondias mombin* (2 t/tree). On the other hand, low values are observed for *Leucaena leucocephala* (0.009 t/tree), *Vernonia amygdalina* (0.009 t/tree), *Annona senegalensis* (0.008 t/tree) *and Senna alata* (0.006 t/tree).

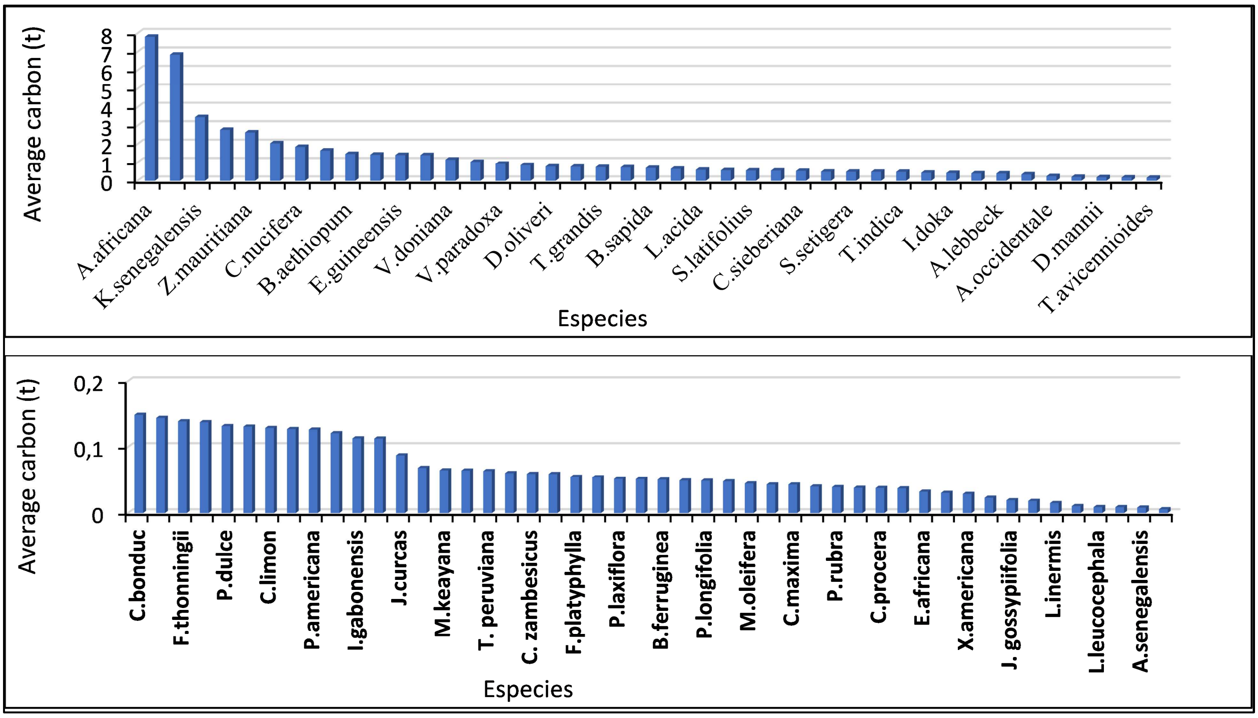

Figure 5. *Average carbon by tree species in the Natitingou city.*

3.5. Evaluation of the Mitigation Potential of CO_2 Emissions and Ecological Value of Woody Vegetation in the City of Natitingou

The table 3 shows the total amount of CO_2 trapped by urban vegetation in Natitingou.

Table 3. *Total quantity of CO_2 trapped by urban vegetation in Natitingou.*

UOT	Total stock		Ecological value (EV)
	Ct (t)	CO_2t (t)	EV ($)
DRA	13774.17	50505.28	303031.66
SRA	643.81	2360.63	14163.79
SCA	5123.11	18784.72	112708.32
TCA	1768.05	6482.86	38897.16
AA	8524.50	31256.49	187538.92
SA	1564.93	5738.09	34428.56
PL	808.08	2962.97	17777.83
RA	3529.46	12941.34	77648.05
MA	270.93	993.42	5960.54
Global	36540.97	133983.54	803901.23

UOT: Land use units; $: Dollars; Ct: Total carbon; CO_2t: Total carbon dioxide; t; tonne; t/ha: ton per hectare; DRA: Dense residential area; SRA: Scattered residential area; CSA: Commercial and service area; TCA: Transport and communication area; AA: Agricultural area; SA: Swampy area; PL: Plantation; RA: Reforestation area; MA: Mountainous area.).
Source: Field results, Natitingou 2020.

The analysis of the table 3 shows that the woody vegetation of Natitingou city stores 34746.5 t of carbon, which corresponds to 1 133983.54 t of CO_2. Total stocks vary by vegetation type, with the highest values in the residential area. The surface area of the different land cover units significantly influences the carbon stock sequestered in Natitingou city. Indeed, despite the high average carbon and carbon dioxide stock values recorded at the reforestation perimeter and in the transport and communication area, the highest total carbon stock value at the city scale is obtained in the dense residential area.

The ecological value of carbon sequestered by trees in the different land cover units, relative to their area, varies from 5961 $ in the mountain area to 303032 $ in the dense residential area (RA) of the Natitingou city. In addition, the ecological value of carbon sequestered by woody vegetation in the Natitingou city is equal to 803901 $.

3.6. Calculation of the Uncertainty Related to the Estimation of the Carbon Stock of Natitingou City

The Table 4 shows the uncertainty in the carbon stock estimate.

Table 4. *Uncertainty in carbon stock estimation.*

Carbon reservoir	NP	Cm (t/ha)	S	ES (S/√n)	95%IC (1.96*ES)	Inc	U (%)
Ca	344	15.74	27.43	1.48	2.16	0.14	11.63
Cr	344	3.78	6.59	0.36	0.70	0.18	

Ca: Above-ground carbon; Cr: Root carbon; NP: Number of plots; Cm: Mean carbon; S: Standard deviation of mean carbon; ES: Standard error of mean carbon; CI: Confidence interval l; Inc: Uncertainty related to each carbon pool; U (%): Total uncertainty related to carbon stock estimation.
Source: Field results, Natitingou 2020.

The analysis in Table 4 shows that the total uncertainty in the carbon estimate is 11.6%. This value, close to 10%, shows the accuracy and credibility of the carbon estimate for urban trees in Natitingou.

4. Discussion

4.1. Floristic Composition of the Woody Vegetation of the City of Natitingou

A total of 74 genera and 36 families of 89 woody species were counted. The most representative families *are Leguminosae-Caesalpinioideae* (15%)*, Moraceae* (9%), *Anacardiaceae* (7%), *Leguminosae-Mimosoideae* (7%). The distribution of floristic composition by land cover units indicates that residential area (DRA: 61, SRA: 56 species) are more diverse. On the other hand, the lowest numbers of species are found in the mountain area and the reforestation perimeter with 10 and 15 species respectively. This diversity of urban trees in Natitingou resulting from the present research is the result of the biophysical and socioeconomic conditions of the city. Thus, the high amount of rainfall that the city receives is likely to favor the planting and development of several species. On the other hand, the unfavorable texture of the city's soil, despite its nutrient composition in places, limits plant biodiversity. For, the floristic composition and structure of forest stands are both related to soil texture and chemical composition [34]. These results show the great diversity of plant species in Natitingou city compared to other cities. Much lower results are obtained in the city of Malanville (66 species) [14], in the city of Brazzaville where 43 species belonging to 33 genera were counted [35]; in Bobo-Dioulasso in Burkina Faso 42 specie sare listed [36].

Also, studies on urban forestry revealed that the plant population of the city of N'Djaména is composed of 32 species, divided into 16 families [36]. The cities of Sokoto in Nigeria and Thane in India are less diverse than Natitingou with respectively a total of 30 species inventoried [38], then 29 species recorded [39]. However, the tree diversity of Natitingou (89 species) is similar to that of Nagpur city in India where 86 species were recorded in the eight land cover units classes [40]. This plant diversity in Natitingou city may not only be related to the different uses [16, 41], but also to the diversity of the population of Natitingou, because the diversity of species in the city is correlated to the heterogeneity of the urban landscape in terms of urban population [42].

The direct implication of this plant diversity is the increase in the resilience of the city to the impacts of climate change, the multiplicity of ecosystem services in a sustainable manner [43], not to mention that the city is thereby an important habitat for biodiversity conservation [44]. However, in the city of Ziguinchor in Senegal, 132 species gathered in 95 genera and 32 families are inventoried [45]. Similarly in the city of Kumasi in Ghana, a high diversity of plant species 176 species and 46 families are obtained [11]. The cities of Niamey and Maradi in Niger have 112 species and 111 species respectively [16]. In Togo, of Lomé city is not on the fringe in terms of plant diversity, where 93 species belonging to 79 genera and 47 families have been recorded [46]. These different results show that efforts still need to be made to reforest for plant diversification in Natitingou. With regard to floristic diversity by urban land use unit, our results corroborate those of the cities of Maradi and Niamey in Niger, where more species were counted in residential areas [16]. In any case, the results of our research on medium-sized cities (Malanville and Natitingou) compared to the existing literature on large cities in the sub-region allow us to conclude that the surface area, the population and the rate of urbanization are intimately linked to the diversity of trees in cities.

4.2. Carbon Stock of the Urban Vegetation of Natitingou

The tree biomass in the city of Natitingou is estimated at 42.3 tMs/ha, or a total carbon stock of 20.6 t/ha, equivalent to 75.5 t of CO_2/ha. However, the total carbon stock of vegetation in the urban environment of Natitingou is estimated at 34746.5 t for a total of 1133983.5 t of atmospheric carbon dioxide trapped. The results thus obtained are explained by the preponderance of isolated trees with low density per hectare. The reforestation perimeter and the plantation (126 and 43 trees/ha) with the highest density values have small areas (22.8 and 44 ha). The predominance of small circumference species also explains the different results obtained. The average carbon stock in the city of Natitingou is much lower than that of the city of Shenyang in China which is 33.32 t/ha [49]. Several authors have obtained significantly higher values in African cities [47, 48, 11] respectively in Kpalimé in Togo (87.5 t/ha), Lomé (58.1 t/ha) and Kumasi in Ghana (228 t/ha). The large difference observed between the results can be explained primarily by the surface area of the plots installed for the inventory and the rate of vegetation cover in the study city. As vegetation in urban areas is not homogeneous, the generalization of any plot size smaller than one hectare leads to overestimations of biomass. Secondly, the choice of the study site identified within the city partly explains the difference observed. It should be noted that most of the research that have undertaken biomass estimation in cities have chosen green spaces (recreational areas) of the cities considered [36]. Furthermore, the rate of carbon sequestered and the rate of CO_2 sequestered varied across the gradient of urban land cover. The highest average carbon stocks are observed at the reforestation perimeter with 154.4 t/ha and the lowest values at the mountain area with 3.6 t/ha. This estimated carbon rate was reported at the city scale taking into account the area of each land cover unit and the results show that the dense residential and agricultural area have sequestered more carbon either RA: 13774.17 t and AA: 8524.50 t. The area of land cover units also has a significant influence at the city scale. Thus, open areas with lower vegetation cover density stored carbon better at the city scale [4]. These results corroborate those from the city of Sokoto in Nigeria with high values of total carbon stock in built-up areas (266.54 t/ha) and then the low values are recorded in agricultural area (21.23 t/ha) [37]. Indeed, based on land use types, significantly lower results than ours are found: 14.08 tC/ha in residential areas and 11.57 tC/ha in parks and recreational areas [4]. Similarly, similar results of carbon stock per unit area are obtained in the city of Shenyang in China, with respect to some land cover units such as avenue trees (Road forest stock 34.95 tC/ha) [49] against 29.5 tC/ha in the transport and communication area (TCA) of Natitingou. On the other hand, in Togo, in the city of Kpalime, low average carbon stock values are observed in settlements (6.25 t/ha), roadways (3.66 t/ha) and concessions (2.15 t/ha) [47]. These results demonstrate that the urban woody vegetation of Natitingou constitutes an important carbon sink. Its sequestration capacity will increase with a conservation and maintenance effort that will allow the identified trees to reach maturity. The results show a predominance of small circumference trees, which are in their growth phase. The larger the circumference of a tree, the greater its basal area and the better its carbon storage.

5. Conclusion

The present study allowed to appreciate the woody vegetation of Natitingou, composed of 8872 individuals, distributed in 89 species, 74 genera and 36 families. The results show that the residential area and the commercial and service area are the most diversified. The reforestation area, with a high density of trees and basal area, stores more carbon in the city, either 123.5 (tC/ha). Similarly, in terms of carbon density, it is followed by the commercial and service area and then the transport and communication areas, which have the highest values of average circumference. However, the high values of total carbon stock are recorded in residential areas due to the area they occupy in the urban framework. The study revealed that the city of Natitingou has a diversity of trees with varying capacities of atmospheric carbon stock. The local authorities of Natitingou must therefore focus both on reforestation actions and on the preservation of existing trees, as most of them are in their growth phase. The results obtained, related to the qualitative and quantitative value of urban trees, constitute a database that can be used to plan and promote urban forestry in Natitingou. These results will also serve as a springboard to know the dynamics of urban carbon in Natitingou.

Conflict of Interest

The authors unanimously declare that there are no conflicts of interest related to this article.

Author's Contributions

BOW is the principal author of this research and participated in all phases of the work. The validation of the inventory methodology, the choice of the study site and the correction of the manuscript were carried out by SZ, MD, WKC, DB, IY, BAHT, under the supervision of ITI, principal supervisor of this research.

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