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Development Issues and Carbon Stock of Street Trees in the City of Brazzaville

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Abstract:

The issue of street trees in urban planning is being addressed in Brazzaville, Congo. The aim is to improve urban space, in particular resilience for the well-being of city dwellers, by making the most of trees. As little attention has been paid to spatiotemporal research into the place of avenue trees in urban planning, the study targets ecosystem services rendered to society, once the paving of communication arteries is effective. The methodology is based on the inventory and enumeration of arborescent woody plants $d1.30 \geq 10$ cm, present in 32 arteries, meeting precise criteria. Notwithstanding the measurement of $d1.30$ and tree height, the data collected includes the distance between trees and roadways, the area reserved for the plant and an assessment of the damage caused. The inventory lists 1,866 woody plants grouped into 41 species, 30 genera and 15 families. The allochthonous-dominated flora cohort includes several senescent individuals. Urban resilience and well-being are underpinned by above-ground biomass (81.68 t/ha/year) and sequestered carbon (40.84 t/ha/year). The carbon dioxide (CO₂) sequestered would be 386.69 tones. In terms of infrastructure destruction, *Terminalia mantaly* and *Terminalia catappa* come out on top.

Keywords: Alignment tree, Urban planning, Ecosystem services, Carbon sequestration, Brazzaville, Congo

INTRODUCTION

In sub-Saharan Africa, the management and development of cities is often beyond the control of political decision-makers, with worrying socio-ecological repercussions (Dutrève, 1997). Urban cities face major challenges in terms of sustainable development, linked to (i) improving citizens' quality of life, (ii) guaranteeing the balance between ecosystems; while remaining engines of economic development (Delahoulière, 1999). In the Congo, the demographic explosion in urban areas, supported by the rural exodus, is the foundation of a rapidly growing urbanization. The consequences of this urbanization are clearly visible in the urban environment, particularly in terms of plant cover. Indeed, the construction of roads and other physical infrastructures has led to the felling of trees growing in the affected areas. The direct damage caused to natural ecosystems continues to encroach on urban trees, which are reduced to marginal spaces in perpetual regression (Kimpouni *et al.*, 2014; Kimpouni *et al.*, 2020).

In a context marked by strong social demand for trees in urban environments, the issues of (i) climate change and sustainable development, (ii) impoverishment of citizens, (iii) anarchic occupation of space; arboriculture can constitute a salutary and appropriate objective in order to sustainably improve the quality of life of inhabitants within a more pleasant and resilient City

(Clergeau, 2007; Nzala and Miankondila, 2002; Decoupigny, 2017; Papin *et al.*, 2017), 2017), and the issue of sustainable development, at all institutional levels, includes trees in urban environments (Verchère, 2022). This approach, centered on the tree and its benefits, would be a major asset in the design of urban policies. As well as being picturesque, trees are essential to the balance of the urban environment, improving the living environment for city dwellers (Lessard and Boulfroy, 2008; Ségur *et al.*, 2011). However, the benefits derived from trees are very often overshadowed by the damage caused to others (Kimpouni *et al.*, 2023). These include, but are not limited to, the partial or total collapse of houses, cars and road infrastructure; and the unhealthiness and inconvenience caused by the degradation of dead leaves and fruit on and along roadways. Around the world, cities are sources of greenhouse gas emissions, leading to urban heat islands (Papin, 2017; Fouvret and Foissard, 2022). The scale of emissions makes urban cities the seat of atmospheric pollution that affects the well-being and health of populations (FAO, 2018). The consideration of environmental concerns in urban environments, notably adaptation to climate change and the preservation of biodiversity, is sparking renewed interest in the fate of the urban tree (Gros *et al.*, 2014). Trees in general, and urban trees in particular, provide humanity with benefits that are out of all proportion to the damage likely to be recorded, which has induced a new dimension to the theme (Clergeau, 2007; Larrère, 2015; Boeuf & Robert, 2017). In this context, a number of studies have been carried out on urban arboriculture in Brazzaville and the surrounding area, but the issue of street trees in the development of the city has not received enough support, in order to optimize urban tree development and management methods (Kimpouni *et al.*, 2013a, b, 2014, 2017b, 2018; Ifo *et al.*, 2016).

The aim is to explore the issue of sustainable tree management in urban environments, for a resilient city and the well-being of its inhabitants. Its foundation is the improvement of urban space, through sustainable management centered around the tree and the associated tangible and intangible benefits. Specifically, the study focuses on (i) the location of street trees in urban planning; (ii) the assessment of induced impacts on roadways and the fight against urban heat islands and/or climate change mitigation; (iii) and the typification of street trees in the urban planning process.

MATERIALS AND METHODS

Description of the Study Area

Brazzaville, which stretches between 15.2061 - 15.3175 East and - 4.2183 - 4.2992 South (Figure 1), covers an area of around 32640 hectares (or 326.4 Km²), 1/4 of which is formerly marshy plain and 3/4 plateau and hills (Vennetier, 1977). Maximum altitude is around 300 m.

The climate, of the Lower Congolese type, corresponds to Aw₄ in Köppen's classification (Köppen, 1900, 1936; Kottek *et al.*, 2006; Peel *et al.*, 2007; Belda *et al.*, 2014; Beck *et al.*, 2018). The main characteristics are: a cool, dry season from June to September; a warm, wet rainy season from October to May, with a marked slowdown in January and February (Samba, 2020; Vennetier, 1977; Samba-Kimbata, 1978). Annual rainfall is around 1,400 mm. With an average rainfall of over 200 mm, March, April and November are the wettest months. The average annual temperature is around 25°C, with a low thermal amplitude of barely 5°C (Samba *et al.*, 2008; Samba and Nganga, 2011). Heat peaks in March and April, but July and August are cool (Samba and Nganga, 2011; Samba *et al.*, 2008; Samba-Kimbata, 1978; Adjanohoun *et al.*, 1988). Relative humidity is over 70%, with absolute minimums in August and September, and relative minimums in February and March. Minima range from 50 to 60%, while maxima are between 88 and 94% (Makany, 1976; Vennetier, 1977).

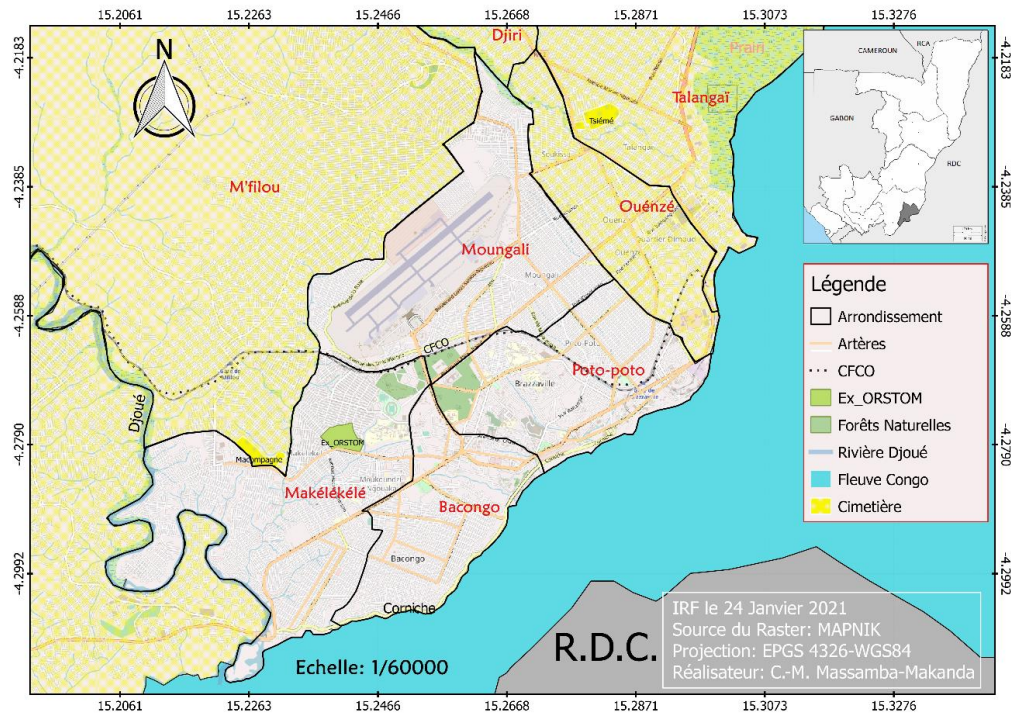


Figure 1: Location of study area

Vegetation and Flora of Brazzaville

The Brazzaville region belongs to the Léfini natural region, corresponding to the Léfini phytogeographical district (Descoings, 1975; Kimpouni *et al.*, 1992). Brazzaville's urban area currently includes two forest islands resulting from the degradation of the Patte-d'Oie Forest. Originally, Brazzaville and its surroundings were covered by forests and savannahs characterized by a *Trachypogon thollonii* and *Annona senegalensis* group with two subgroups: *Hyparrhenia diplandra* and *Bridelia ferruginea* indicate more clayey soils; *Loudetia demeusii* and *Hymenocardia acida* are typical of sandier soils (Makany, 1976; Schwartz, 1988). Forests develop on plateaus in the form of very small groves, often of anthropogenic origin. Degraded and secondarized mesophilic forests occupy around 5% of the surface. This forest type is also found in the hilly areas bordering the city, where gallery forests dominate (Makany, 1976; Schwartz, 1988).

The urban forest ecosystem is centered around riparian forests and, mesophilic and tropophilic islands resulting from the degradation of the Patte-d'Oie Forest (Kimpouni *et al.*, 2014, 2013a, 2013b). In addition to natural facies, artificial forests, mainly of *Corymbia* sp. and *Pinus* sp., coexist with:

- Lineal trees, planted in a linear, regular pattern along arterial roads, consisting mainly of: *Acacia mangium*, *Terminalia superba*, *Terminalia mantaly*, *Terminalia catappa*, *Mangifera indica*, *Millettia laurentii*, *Peltophorum pterocarpum* ;
- Courtyard trees, especially fruit trees, occupy the empty space next to the buildings: *Mangifera indica*, *Persea americana*, *Dacryodes edulis*, *Carica papaya*, *Ficus carica*, *Cocos nucifera*, *Trilepisium madagascariense*, *Elaeis guineensis*, *Spondias dulcis*, *Hura crepitans*, *Gardenia ternifolia* ;
- Fence trees that form living hedges delimiting private concessions: *Dracaena fragrans*, *Newbouldia laevis*, *Quisqualis indica*, *Clerodendron inerme*, etc.

- Garden trees (landscaped areas planted with trees and shrubs) which are : *Senna siamea*, *Millettia* sp., *Corymbia* sp., *Pinus caribaea*, *Lagerstroemia indica*, *Lagerstroemia speciosa*, *Terminalia catappa*, *Hura crepitans*, *Albizia lebbek*.

Material

The material consists of arborescent woody plants of "diameter at breast height ($d^{1.30} \geq 10$ cm" present along the arteries, for the study of phytodiversity. Tree and shrub identification is carried out in situ for common species and ex situ at the national herbarium (IEC) for other taxa (Kimpouni et al., 2017b). The nomenclature adopted results from Lebrun and Stork (1991-2015) and the taxonomic order from APG IV (2016). Depending on the level of development of the boroughs and the number of street trees, the thirty-two arteries selected have at least ten trees over a distance of 700 meters. The selection criteria have been met in Makélékélé, Baongo, Poto-poto and Mougali, where all avenue trees are included.

Study Method

The literature review enabled us to assess the current state of knowledge on topics related to urban and peri-urban forestry in general, and urban arboriculture in Brazzaville in particular. Finally, it enabled us to refine the development of data collection tools, in particular survey sheets and interview guides.

Phyto diversity Data Collection

This phase focuses on the systematic enumeration of all woody trees $d^{1.30} \geq 10$ cm, 32 arteries and the collection of dendrometric data ($d^{1.30}$ and height). Other parameters monitored include the vital space reserved for trees during development, and the distances separating (i) roadways from alignment trees, and (ii) between trees. Damage to infrastructure is also recorded.

Diametric Structure

Diameter structure indicates the number of stems inventoried per diameter class (Fournier and Sasson, 1983; Sonké, 1998). The persistence of a species in the forest community depends largely on its representation in the different diameter classes.

Biomass and Carbon Sequestration

Above-ground biomass was estimated using general allometric equations for urban trees, using the dendrometric parameters $d^{1.30}$ and height (Brown et al., 1989; Brown, 1997; Aguaron & McPherson, 2012). Depending on the wood's morpho-anatomical data, three specific allometric equations are applied. (i) The first concerns well-formed urban trees (hardwoods), (ii) the second stipe plants (Arecaceae) and (iii) the third conifers. Subsequently, carbon storage is obtained by multiplying total biomass by a constant equal to 0.5; and sequestered carbon dioxide (CO₂) is deduced by multiplying the amount of sequestered carbon by a constant equal to 0.27 (Malhi et al., 2004; Kouadio et al., 2016).

$\text{Biomass} = 0.16155 \times d^{1.30 (2.310647)}$	(equation "i" for hardwoods)
$\text{Biomass} = 1.282 \times (7.7 \times h + 4.5)$	(equation "ii" for stipe plants)
$\text{Biomass} = 0.035702 \times d^{1.30 (2.280671)}$	(equation "iii" for Gymnosperms)

Biomass is expressed in kg. stem⁻¹; H is the total height of the tree in meters; $d^{1.30}$ is the diameter at breast height expressed in cm.

RESULTS

Taxonomic Data on Artery Populations

The floristic inventory of the 32 arteries in the city of Brazzaville enabled us to record and identify 1866 trees and shrubs $d^{1.30} \geq 10$ cm divided into 15 families, 30 genera and 41 species (Table 1). The families with the greatest floristic contribution, with at least 100 individuals, are Arecaceae, Combretaceae, Fabaceae and Myrtaceae. However, Anacardiaceae, Annonaceae, Arecaceae, Combretaceae, Euphorbiaceae, Fabaceae, Malvaceae, Moraceae and Myrtaceae are dominant with at least 2 species. This flora is made up of 1/3 local species and 2/3 non-native species. The coverage of avenue trees, although evident, varies from one district to another. These differences reflect the level of development in each arrondissement. Apart from Moungali, which cannot be compared with the other three, the differences in number of individuals are on average twice as great. However, analysis of specific diversity reveals very marked differences between boroughs, and within them from one thoroughfare to another (Tables 2, 3).

Table 1: Floristic richness and spatial distribution of alignment ligneous plants

Taxons	Bacong o	Makélékél é	Moungali i	Poto- Poto	Total I
Anacardiaceae	8	8	-	60	76
<i>Mangifera indica</i> L.*	6	8	-	60	74
<i>Spondias mombin</i> L.*	2	-	-	-	2
Annonaceae	-	-	-	48	48
<i>Cananga odorata</i> (Lam.) Hook. f. & Thomson*	-	-	-	43	43
<i>Polyalthia longifolia</i> (Sonn.) Thwaites*	-	-	-	5	5
Arecaceae	35	3	37	94	169
<i>Borassus aethiopum</i> Mart.	-	-	1	5	6
<i>Cocos nucifera</i> L.*	6	-	-	43	49
<i>Elaeis guineensis</i> Jacq.	10	3	-	30	43
<i>Phoenix</i> sp.	3	-	1	-	4
<i>Roystonea regia</i> (Kunth) O.F. Cook*	16	-	35	16	67
Combretaceae	95	333	18	289	735
<i>Terminalia catappa</i> L.*	5	9	-	34	48
<i>Terminalia mantaly</i> H. Perrier*	78	324	17	254	673
<i>Terminalia superba</i> Engl. & Diels	12	-	1	1	14
Euphorbiaceae	9	4	-	1	14
<i>Euphorbia tirucalli</i> L.	9	4	-	-	13
<i>Ricinodendron heudelotii</i> (Baill.) Pierre ex Heckel	-	-	-	1	1
Fabaceae	223	128	30	265	646
<i>Acacia auriculiformis</i> A. Cunn. ex Benth.*	22	12	-	20	54
<i>Acacia floribunda</i> (Vent.) Willd.*	21	-	-	-	21
<i>Acacia mangium</i> Willd.*	9	14	-	2	25
<i>Albizia lebbbeck</i> (L.) Benth.*	13	20	4	67	104
<i>Delonix regia</i> (Bojer ex Hook.) Raf.*	5	4	-	7	16
<i>Milletia laurentii</i> De Wild.	72	34	26	53	185
<i>Millettia mannii</i> Baker	5	3	-	-	8
<i>Peltophorum pterocarpum</i> (DC.) K. Heyne*	15	-	-	63	78
<i>Pithecellobium dulce</i> (Roxb.) Benth.*	58	41	-	25	124
<i>Senna occidentalis</i> (L.) Link*	-	-	-	1	1
<i>Senna siamea</i> (Lam.) H.S. Irwin & Barneby*	3	-	-	26	29
<i>Tamarindus indica</i> L.*	-	-	-	1	1
Lauraceae	1	2	-	3	6
<i>Persea americana</i> Mill.*	1	2	-	3	6
Malvaceae	3	-	-	2	5

<i>Ceiba pentandra</i> (L.) Gaertn.*	1	-	-	2	3
<i>Sterculia</i> sp.*	2	-	-	-	2
Moraceae	16	1	-	10	27
<i>Ficus elastica</i> Roxb.*	6	-	-	1	7
<i>Ficus exasperata</i> Vahl	2	-	-	4	6
<i>Ficus polita</i> Vahl	-	-	-	1	1
<i>Ficus septica</i> Burm.f.	-	1	-	-	1
<i>Ficus vasta</i> Forssk.*	8	-	-	4	12
Myrtaceae	29	5	-	73	107
<i>Corymbia</i> sp.*	25	5	-	29	59
<i>Corymbia torelliana</i> (F.Muell.) K.D.Hill & L.A.S.Johnson*	4	-	-	44	48
Peraceae	1	-	-	-	1
<i>Chaetocarpus africanus</i> Pax	1	-	-	-	1
Pinaceae	5	-	-	12	17
<i>Pinus caribaea</i> Morelet*	5	-	-	12	17
Sapotaceae	3	-	-	-	3
<i>Manilkara</i> sp.	3	-	-	-	3
Strelitziaceae	4	-	-	2	6
<i>Ravenala madagascariensis</i> Sonn.*	4	-	-	2	6
Verbenaceae	6	-	-	-	6
<i>Tectona grandis</i> L.f.*	6	-	-	-	6
Total	438	484	85	859	1866

(*) Naturalized or non-native taxa

Diameter Structure of Avenue Trees

The diametric structure of the ligneous trees shows significant variations in the number of individuals depending on the diameter class (Figure 2). Diameter classes 1 to 4 are better provided for in the arteries studied, compared with ligneous trees of $d^{1-30} \geq 50$ cm, which are the least present in alignments. Without a well-thought-out management policy, monitoring and replacement of trees that have become too large in diameter, or even senescent, they are a major source of the damage observed on urban roadways.

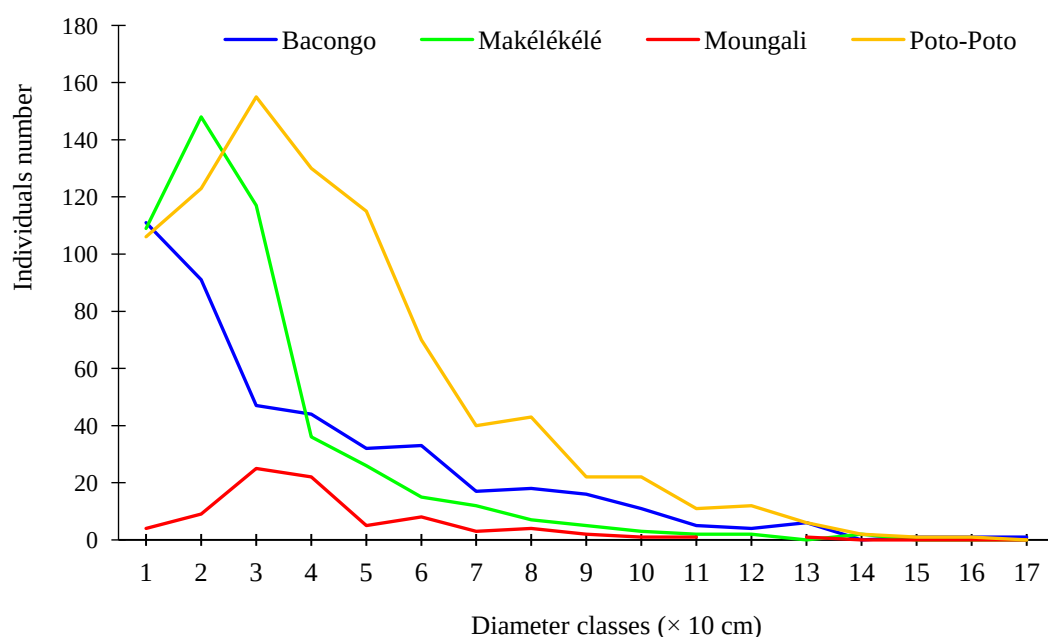


Figure 2: Evolution of the diametric structure of woody plants

Estimated Total Biomass

The dry above-ground biomass produced by all avenue trees in Brazzaville's four communes amounts to 2864.39 tones (or 81.68 t/ha/year). In average terms, these values correspond to 1.54 tones. tree⁻¹. The corresponding quantity of sequestered carbon is 1432.19 tones (40.84 t/ha/year) and the sequestered carbon dioxide (CO₂) is equivalent to 386.6g tones (Table 2). Plant biomass and carbon quantity would appear to be proportionally correlated with $d^{1.30}$; thus, the most striking are observed in subjects with $d^{1.30} \geq 50$ cm. These include *Terminalia mantaly*, *Millettia laurentii* and *Peltophorum pterocarpum* (Figure 3). Combretaceae and Fabaceae are the families that sequester the most carbon in the Brazzaville alignments. Depending on the size of the tree population and the species in alignment, sequestration varies from one artery to another (Figure 4). Overall, the quantity of carbon sequestered by street trees in Brazzaville is not negligible in the fight against climate change in general and urban heatwaves in particular. This contribution is a direct gain to urban resilience and the well-being of populations.

According to the categorization of taxa, dicotyledonous hardwoods are the best represented in terms of individuals and the most involved in carbon sequestration (Tables 3, 4). The palm type (Arecaceae) in terms of carbon sequestration, within the city, presents values twice as high as conifers. This observation would be a call to recommend the use of broadleaved dicotyledons in alignment, for better carbon sequestration performance.

Table 2: Urban distribution of taxa and carbon stocks

Neighborhoods	Arteries	Families	Genera	Species	Total		Area (m ²)	Biomass (t/ha/an)	Carbone stock (t/ha/an)
					Number of trees	Rate (%)			
Baongo	All. du Chaillu (zone Baongo)*	4	8	9	19	1,02	5696	13,14	6,57
	Av. De Brazza*	5	7	7	18	0,96	3666	2,60	1,30
	Av. de la Libération de Paris*	4	5	5	13	0,70	1692	18,95	9,48
	Av. de la Motte*	3	7	8	35	1,88	2652	60,26	30,13
	Av. de la Promenade*	5	5	6	16	0,86	2770	73,26	36,63
	Av. de l'Auberge Gascogne*	4	4	4	53	2,84	5920	49,38	24,69
	Av. de l'O.U.A. (zone Baongo)	4	6	6	26	1,39	29546	37,41	18,70
	Av. des Ecoles*	6	6	6	25	1,34	3806	105,57	52,79
	Av. des Premiers Jeux Africains (zone Baongo)*	3	3	5	36	1,93	5865,75	116,24	58,12
	Av. du Général de Gaulle*	2	3	3	12	0,64	5436	53,12	26,56
	Av. Simon Kimbangu*	3	5	5	26	1,39	1800	28,59	14,30
	Av. U'Tamsi (zone Baongo)*	1	1	1	6	0,32	1984	3,22	1,61
	Blvd DSN (zone Baongo)	9	14	15	80	4,29	20825,7	33,69	16,84

	Av. Maréchal Liautey (zone Bacongo)*	1	1	1	5	0,27	8749	3,61	1,80
	Rue Mbiémo*	7	9	11	34	1,82	2920	18,82	9,41
	Rue Père Bessieux*	6	10	12	34	1,82	4150	45,68	22,84
	Sous-total 1	-	-	-	438	23,47	107478,45	71,93	35,97
Makélékélé	Av. de l'O.U.A. (zone Makélékélé)	4	6	8	52	2,79	39314	21,07	10,53
	Av. des Premiers Jeux Africains (zone Makélékélé)*	3	5	6	54	2,89	5865,75	83,53	41,77
	Av. du 5 février*	3	4	4	298	15,97	2388	112,29	56,15
	Av. Fulbert Youlou*	8	10	11	24	1,29	1500	68,83	34,41
	Av. Terinkyo	5	6	7	45	2,41	16170	26,70	13,35
	Av. U'Tamsi (zone Makélékélé) *	3	3	3	11	0,59	1984	29,41	14,70
	Sous-total 2	-	-	-	484	25,94	67221,75	62,49	31,25
Moungali	Av. de la Paix (zone Moungali)	3	4	5	58	3,11	25074	17,99	8,99
	Blvd DSN (zone Moungali)	2	2	2	27	1,45	18858	33,60	16,80
	Sous-total 3	-	-	-	85	4,56	43932	24,69	12,34
Poto-Poto	All. du Chaillu (zone Poto-Poto) *	2	2	2	5	0,27	5696	0,41	0,21
	Av. de France	2	2	2	85	4,56	10260	118,33	59,17
	Av. de la Paix (zone Poto-Poto)	2	2	3	23	1,23	14406	24,27	12,13
	Av. de la Pointe Hollandaise*	5	9	10	53	2,84	9024	52,27	26,13
	Av. de l'Amitié	6	13	15	60	3,22	11310	72,52	36,26
	Av. de l'Indépendance*	2	2	2	92	4,93	8288	121,53	60,77
	Av. du Cardinal Emile Biayenda*	4	6	7	81	4,34	8040	247,67	123,84
	Av. du Parc Zoologique*	3	7	7	39	2,09	6480	48,10	24,05
	Av. George Balanger ex Oxy*	1	1	1	12	0,64	2392	15,98	7,99
	Av. Mgr Augouard (DGPN)*	8	11	13	59	3,16	5922	130,57	65,28
	Av. régiment Blindé*	7	10	11	34	1,82	4656	55,99	28,00
	Av. Sergent Malamine*	3	3	3	16	0,86	4380	81,29	40,64
	Blvd DSN (zone Poto-Poto)	7	14	14	138	7,40	27552	58,02	29,01
	Av. Maréchal Liautey (zone Poto-Poto)	6	12	13	149	7,98	11323	327,44	163,72
	Rue Alfassa*	1	1	1	13	0,70	2340	39,93	19,96
	Sous-total 4	-	-	-	859	46,03	132069	118,33	59,16
	Total général				1866	100	350701,2	81,68	40,84

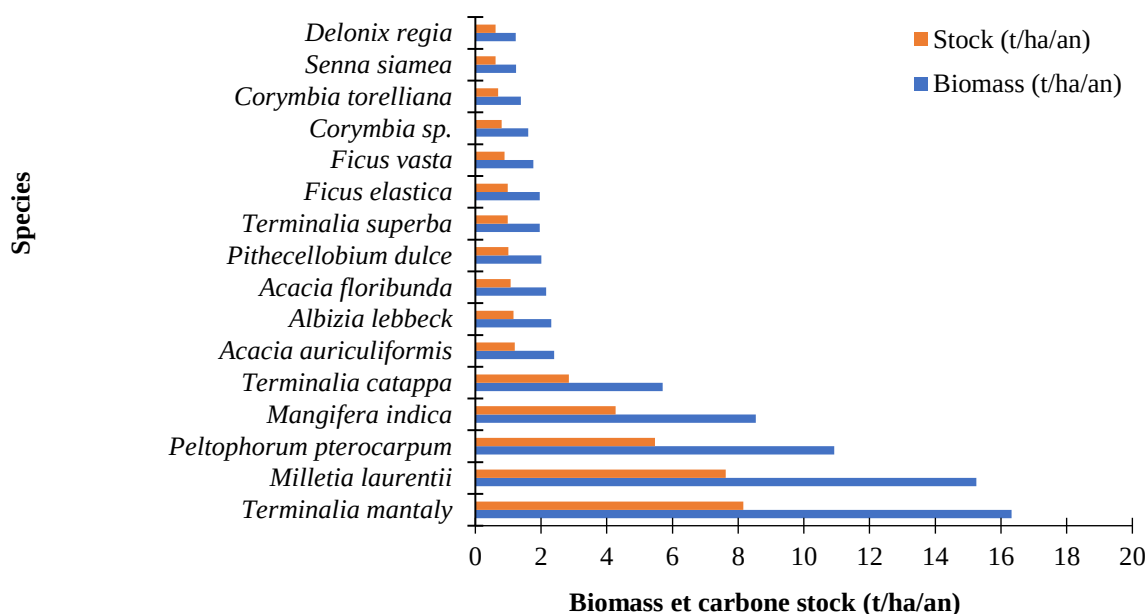
(*) area less than one hectare, biomass and carbon stock not per unit area.

Table 3: Synopsis of biomass by district and plant type

Groups		Dicotyledons	Gymnosperms	Palm trees	Total
Baongo	Biom(t)	766,30	1,74	5,08	773,11
	Stock C (t)	383,15	0,87	2,54	386,56
Makélékélé	Biom(t)	419,81	0,00	0,26	420,07
	Stock C (t)	209,91	0,00	0,13	210,04
Moungali	Biom(t)	106,21	0,00	2,24	108,46
	Stock C (t)	53,11	0,00	1,12	54,23
Poto-Poto	Biom(t)	1550,06	5,52	7,17	1562,75
	Stock C (t)	775,03	2,76	3,58	781,37
Total	Biom(t)	2842,38	7,26	14,75	2864,39
	Stock C (t)	1421,19	3,63	7,37	1432,19

Table 4: Biomass and carbon stock data by district and plant type

Groups		Dicotyledons	Conifers	Palm trees	Total
Baongo	Biomass (t/ha/an)	71,30	0,16	0,47	71,93
	Stockage C (t/ha/an)	35,65	0,08	0,24	35,97
Makélékélé	Biomass (t/ha/an)	62,45	0,00	0,04	62,49
	Stockage C (t/ha/an)	31,23	0,00	0,02	31,25
Moungali	Biomass (t/ha/an)	24,18	0,00	0,51	24,69
	Stockage C (t/ha/an)	12,09	0,00	0,26	12,34
Poto-Poto	Biomass (t/ha/an)	117,37	0,42	0,54	118,33
	Stockage C (t/ha/an)	58,68	0,21	0,27	59,16
Total	Biomass (t/ha/an)	81,05	0,21	0,42	81,68
	Stockage C (t/ha/an)	40,52	0,10	0,21	40,84

**Figure 3: Species contribution to biomass and carbon storage**

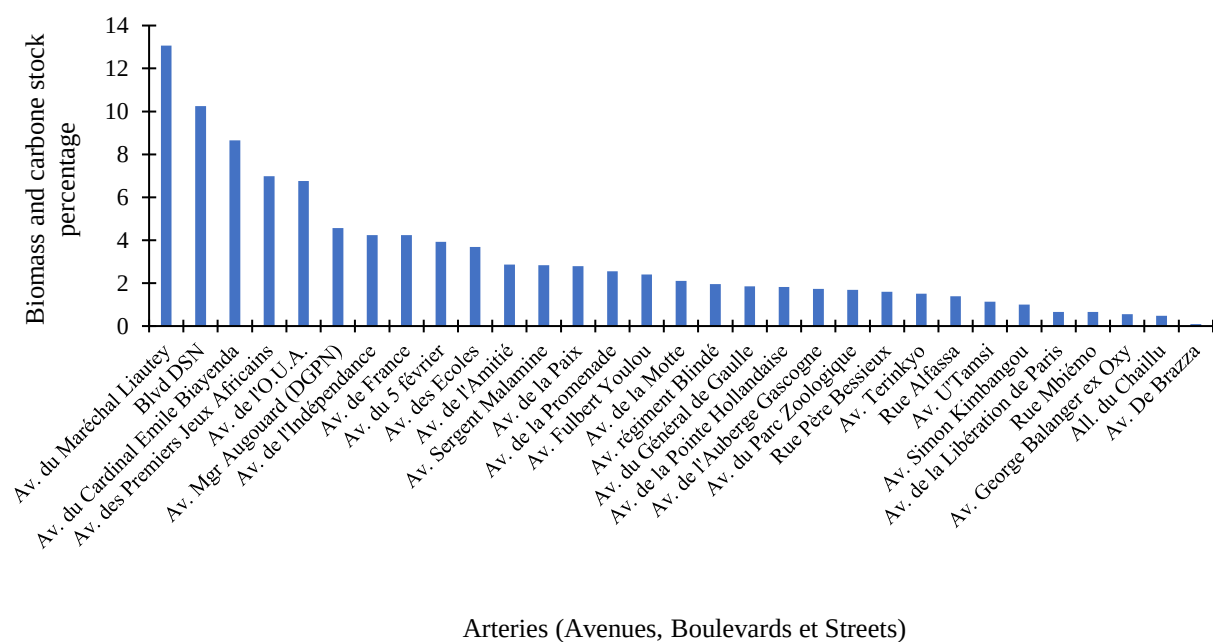


Figure 4: Contribution of arteries to the biomass and the carbon storage

Destruction of Infrastructures and Structures by Trees

Urban trees not only support a wide range of benefits known as ecosystem services, but also a host of concerns. To avoid the pitfalls associated with aligning trees on infrastructures or even roadways, certain rules of the art must be satisfied. These include (i) species selection, (ii) rate of replacement, (iii) spacing from structures and infrastructure, and (iv) adequate living space. When these elements are neglected, avenue trees cause structural damage to communication infrastructures and other roads, and even to people and their property. A total of 258 trees (13.82%) on 21 arterial roads caused damage to various public structures. These trees belong to 7 species (Figure 5). The most frequently observed effects are the detachment and cracking of sidewalk pavements, the demarcation of taxon living areas and rainwater outlets, or even their collapse. This weakness is a source of unplanned expenditure, the consequence of which is that roadways are not extended and mobility in urban areas is not facilitated.

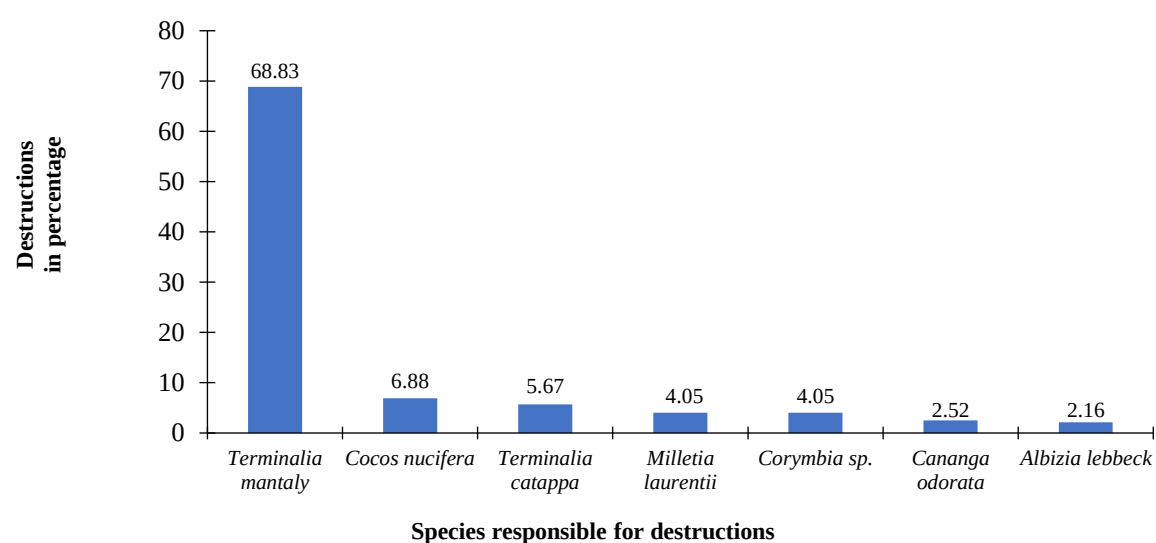


Figure 5: Destruction caused by avenue trees in Brazzaville

Alignment Trees and Living Space

Shaft Spacing:

The choice of species is of prime importance, since not all species have the same biometric and developmental performance. This parameter should determine the spacing between plants and even their distance from the structures. In Brazzaville, staking (spacing between trees) is poorly adapted and varies greatly from one artery to another, from one tree to another. Data recorded on spacing varies from 1.60 to 21.70 meters, depending on the artery and tree species. This variation could be explained by the non-replacement of dead or vandalized woody individuals.

Spacing Between Trees and Roads:

Spacing between roadways and aligning trees is generally very narrow, and not constant from one artery to the next. Spacings vary from 0.15 to 6.65 m for gutters, and from 0.50 to 9.10 m for pavements. The situation is far from rosy for the (i) water distribution networks, which are badly damaged by the powerful roots of the trees, and (ii) electrical and telephone cables, which are encased by the tree crowns, causing major inconvenience to the provision of services. This practice stems from a lack of expertise in the operation and morpho-physiological knowledge of the species selected. This observation is more than plausible in view of the damage caused by alignment taxa to roadworks (gutters, pavements, water pipes, electricity and telephone networks, etc.).

Tree Anchoring Area:

The planting pit is the space designed to anchor the trees and provide them with water and minerals. This vital space is valid regardless of the model chosen: (i) paved or (ii) unpaved pits. The pits encountered in the alignments are not uniform and do not offer the same vital area to the plants. Circular pits have diameters ranging from 0.75 to 2.50 m; square pits have sides measuring 0.80 and 0.98 m; and rectangular pits have dimensions ranging from 0.79 m x 0.83 m to 2.80 m x 2.58 m. It's worth pointing out that this vital space is often wedged between the pavement and the rainwater outlet. In line with standard urban planting standards, the volumes of pits (paved and unpaved) provided for taxa in Brazzaville are well below the suggested minimum values of 9 to 25 m³. This minimum standard must be adapted to the constraints of the site, the species and its development.

DISCUSSION

Floristic Analysis of Avenue Trees and Urban Landscaping

Data on the flora lining Brazzaville's arterial roads reveal a high diversity, with most trees being senescent (Kimpouni *et al.*, 2017b, 2020, 2023). This essentially allochthonous floristic diversity is the result of the colonial imprint sublimating the indigenous value of the local flora (Kimpouni *et al.*, 2017b; Haddad, 1997). Compared with other cities in the Central African sub-region, the Congolese capital is said to have the highest taxonomic diversity in terms of alignments in its arteries (Makumbelo *et al.*, 2002; FAO, 2009). However, taking into account the number of trees per thoroughfare, Brazzaville does not rank among the continent's most densely wooded cities (Dutrève *et al.*, 1998; Sène, 2000). The reason for this is the decline in both natural and artificial woodland. Intra- and peri-urban natural woodland formations, lush and flourishing until the 1970s, have drastically lost in terms of plant cover and diversity (Kimpouni *et al.*, 2013b, 2014). At the same time as the natural forest was being degraded, the flora used to decorate arterial roads fell victim to urban development, and even to the incivism of the local population. These acts are materialized by the extinction in rows of taxa such as *Spathodea campanulata*, *Schizolobium parahybum*, *Jacaranda mimosifolia*, *Aleurites moluccana* and *Hymenaea courbaril*, and the

rarefaction of taxa such as *Enterolobium cyclocarpum* (Kimpouni et al., 2017b). In addition to this element, let's mention the reduction and/or disappearance of paved areas (alignment trees), without exhaustiveness, the rue Moukouloulou, the avenues leading to the Jésus Ressuscité church and the Cité de 17, in Moungali; the rue Dr Blachet and the boulevard Denis Sassou N'guesso in Mpila; to the corridors of the lycée technique 1^{er} mai-Rectorat-ENS.

This skimming of woody vegetation along the arteries calls into question the efforts made by the colonial urban administration. In fact, the impetus given since then to urban planning for a resilient city, where the well-being of the population is at the heart of development, has not been internalized by the city's successive managers. This reflection is fuelled by the absence of an appropriate policy, putting the tree and its place at the heart of urban planning and sanitation (Kimpouni et al., 2020). In fact, since the 1960s, the surface area of paved arteries in Brazzaville has barely increased, except for decreasing in relation to the colonial legacy. This observation is supported by the distribution of public gardens and parks, which remain the panacea of the older neighborhoods involved in this study (Kimpouni et al., 2020).

The predominance of certain taxa along arterial roads can be explained by various factors, the main ones being: (i) the policy of renewing and developing avenue trees, which seems to vary from one arrondissement to another; (ii) historical factors in the various arrondissements; (iii) rapid growth and a more attractive aesthetic feature, giving the trees an exotic appearance. These same reasons would underpin the numerical differences in taxa from one arrondissement to another (N'zala and Miankondila, 2002).

Diametric Structure and Carbon Sequestration Capacity

The diametric cohort of range trees in Brazzaville is dominated by small and medium classes. This result is similar to those of Kouassi et al. (2018) and Kimpouni et al. (2023), respectively in Daola (Côte d'Ivoire) and Brazzaville (Congo), and is justified by recent developments that obscure old trees that have become senescent (Cordon, 2023). In Brazzaville, these senescent taxa, which are more vulnerable to natural hazards, include *Mangifera indica*, *Terminalia superba*, *Terminalia catappa*, *Delonix regia* and *Peltophorum pterocarpum* (De Bruyn, 2016; Kimpouni et al., 2017b, 2020, 2023). This vulnerability would be the result of the absence of urban tree renewal and development policies, ostensibly depriving the city of mechanisms to combat urban heat islands and other phenomena associated with global climate change (Kimpouni et al., 2023; Molnár et al., 2018; Savić et al., 2013).

In the absence of appropriate urban planning policies, cities quickly lose their ability to sequester carbon. In fact, young trees in full growth have very good carbon sequestration aptitudes and capacities, unlike old trees that are reputed to store carbon but have lost their sequestration potential or power (Bouget et al., 2020). The system for renewing or even replacing senescent trees in avenues and recreational areas is a major contribution to the fight against climate change in urban environments.

Biomass and Carbon Storage

The quantity of biomass and the carbon storage capacity of Brazzaville's avenue trees are key factors in assessing the functioning of this urban ecosystem. This storage capacity, although lower than that of forests, contributes to mitigating the adverse effects of climate change (Molnár et al., 2018; Schimel et al., 1995). Compared with other African urban cities, carbon storage values in Brazzaville are higher than those in Yamoussoukro, but lower than those in Abidjan and Daloa

in Côte d'Ivoire (Gnagne *et al.*, 2019; Kouadio *et al.*, 2016; Kouassi *et al.*, 2018). The source of inter-agglomeration and inter-arrondissement storage differences is found to be: (i) the numerical variation of individuals on arterial roads; (ii) the scale of paved areas in arrondissements and agglomerations; (iii) the structure and typology of arterial road stands; (iv) the number and length of inventoried arterial roads; (v) the definition of the individual measurement diameter set for each study (Kouassi *et al.*, 2018). The major contribution of certain families to carbon storage is explained by the abundance and type of taxa evolving along the arteries.

Brazzaville, once known as "la verte" (the green) due to its dense forest cover, has lost some of its superb character as a result of expansion and haphazard, indiscriminate development. The corollary of these operations is the disappearance of the Tsiéme, Glacière, Ravin du Tchad and Corniche Forest massifs, and the regression of the intra-urban forest of the Patte d'Oie reserve, from 240 ha to less than 10% in the space of 50 years (Kimpouni *et al.*, 2013b, 2014). Like the forests, the number of paved arterial roads has declined and the level of paved roads has regressed. According to the selection criteria for arterial roads, only the old districts existing at independence meet this requirement, despite the certified regression in paved areas. As with the distribution of recreational spaces (public gardens, squares, parks, etc.), the paving of Brazzaville's arteries follows the same trend (Kimpouni *et al.* 2020). While vegetation cover in older neighborhoods is declining in tandem with biomass and carbon stocks, no measures have been taken in new neighborhoods to perpetuate the efforts made since the colonial period, for the benefit of the local population. Efforts aimed at urban well-being and resilience, effectively combating urban heat islands and the effects of global climate change (Molinár *et al.*, 2018; Savić *et al.*, 2012).

Better avenue tree management can significantly increase the city's capacity to sequester carbon (Molinár *et al.*, 2018). In addition to this capacity, avenue trees constitute a particular ecological niche of urban biodiversity via the regulation of a microclimate (Molinár *et al.*, 2018; Milošević *et al.*, 2016; Konijnendijk *et al.*, 2012; Savić *et al.*, 2012). This achievement of results should take into account the valuation of local flora alongside allochthonous. Without being exhaustive, we would test, in strict compliance with the rules of the art, taxa with non-spinescent trunks that are cylindrical at the base or even conical, such as *Spathodea campanulata*, *Markhamia tomentosa*, *Cassia mannii*, *Piliostigma* sp., *Erythrina* sp., *Strombosia* sp., *Parinari* sp.. Fruit trees such as *Persea americana*, *Mangifera indica* or *Tamarindus indica* should be avoided in alignments, as they are too prone to accidents (Ying *et al.*, 2011).

Worrying Tree Situations

The main purpose of planting avenue trees is to ensure the well-being of riverside populations (Kimpouni *et al.*, 2020; Molinár *et al.*, 2018; Laille, 2016; Verchère, 2022; Konijnendijk *et al.*, 2012). However, beyond the environmental services rendered, trees can become a major concern, even a danger when infrastructure and tree management are poorly ensured (Kimpouni *et al.*, 2023, 2019, 2017a; Vasseur and Tabeaud, 2003; TDAG, 2016). In Brazzaville, avenue trees often cause damage of varying degrees, from the destruction of infrastructure to fatal accidents. These harms stem from: (i) poor choice of taxa, such as *Terminalia mantaly* or *Terminalia catappa*, responsible for over 68% of infrastructure destruction recorded; (ii) failure to take into account scientific information (morphological and physiological data) on the various taxa; (iii) failure to respect the minimum living space of the alignment taxon and its distance from infrastructures and/or roadways; (iv) the absence of any silvicultural management after establishment; (v) inadequate urban planning policies that do not focus on the full dimension of the tree (Arsalan, 2019; Peyrat,

2014; Haddad, 1997). Indeed, how can we understand that species that can reach 1 m in d^{1.30}, bearing shoulders, footings or even buttresses and with a powerful tracer root system, are confined to 40 cm x 40 cm paved pits and less than 1 m from infrastructure or roadways (Haddad, 1997). This situation makes it easy to understand why trees are the casualties of even the slightest development work.

The damage caused by street trees is not limited to the inconvenience caused to the population, but also translates into very high financial costs for the municipality. Proper consideration of the tree dimension in urban planning policies would have a triple benefit: (i) making funds available for new investments; (ii) guaranteeing well-being for populations in a resilient city through mitigation of the effects of global climate change; (iii) safeguarding and increasing urban biodiversity (Molnár et al., 2018; Savić et al., 2013).

CONCLUSION

The city of Brazzaville is experiencing a reduction in both natural and artificial wooded areas, and a concomitant reduction in avenue trees. While natural and artificial forests, and even recreational areas, are fairly well explored, the problem of avenue and avenue trees is of only minor concern. Alignment flora in Brazzaville is highly diversified and essentially based on allochthonous species, to the detriment of local species that have been little tested. Despite this diversification, the areas planted are small and most of the taxa are senescent. This observation reveals that the city of Brazzaville, through its avenue trees, has a very high carbon storage capacity, for a low sequestration capacity. A sound urban planning policy, taking into account the place of trees in society, would turn this situation around and significantly improve the city's carbon sequestration capacity. In this way, the city would acquire the best tools for combating urban heat islands and mitigating the effects of global climate change.

Better selection of the trees involved in paving and strict adherence to the rules of the art is a source of savings for cash-strapped municipalities, which will have to cope with the damage and inconvenience caused by avenue trees. By providing a variety of ecological niches for urban biodiversity, avenue trees, coupled with intra-urban forests, guarantee the well-being of city dwellers and make an effective contribution to mitigating the effects of climate change, for a resilient city.

Declaration of Conflict of Interest

The authors declare that there is no conflict of interest.

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