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Structure, carbon sequestration potential and anthropogenic pressure on tree species in Porto-Novo's green spaces (Benin)

Structure, potentiel de séquestration du carbone et pression anthropique sur les espèces d'arbres dans les espaces verts de Porto-Novo (Benin)

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Abstract

This study assesses the carbon sequestration capacity of urban green spaces in Porto-Novo, Benin, and examines the anthropogenic pressures impacting tree species diversity. A comprehensive inventory of 1,340 trees across 39 selected green spaces revealed a dominance of trees in social and educational institutions (35%), followed by public green spaces (19%). Tree diameter analysis showed a significant variation, with an average diameter ranging from 34.11 cm (street trees) to 79.28 cm (cemeteries), indicating the presence of both young and mature trees. The total aboveground biomass (AGB) was estimated at 2,270.42 Mg, corresponding to 1,299.53 Mg of sequestered carbon. Social and educational institutions contributed the most to carbon storage (484.60 Mg, 37%), followed by public green spaces (236.57 Mg, 18%) and landscaped natural areas (179.82 Mg, 14%). However, anthropogenic pressures severely affect tree health, with 154 cases (53.8%) of bark stripping, mainly on *Terminalia superba, Terminalia mantaly*, and *Khaya senegalensis*. Pruning (75 cases) and pollarding (44 cases) also impact tree growth and structure. These findings emphasize the need for sustainable urban planning that integrates biodiversity conservation and effective management strategies to enhance carbon sequestration and urban resilience.

Keywords: Carbon sequestration, urban green space, biodiversity, anthropogenic pressure, Porto-Novo.

Résumé

Cette étude évalue la capacité de séquestration du carbone des espaces verts urbains de Porto-Novo (Bénin) et analyse les pressions anthropiques affectant la diversité arborée. Un inventaire de 1 340 arbres dans 39 espaces verts a montré que les arbres sont majoritairement présents dans les établissements sociaux et éducatifs (35%), suivis des espaces verts publics (19%). L'analyse des diamètres a révélé une forte variabilité, avec une moyenne allant de 34,11 cm pour les arbres d'alignement à 79,28 cm dans les cimetières, soulignant la coexistence d'arbres jeunes et matures. La biomasse aérienne totale a été estimée à 2 270,42 Mg, représentant 1 299,53 Mg de carbone stocké. Les espaces sociaux et éducatifs sont les principaux contributeurs (484,60 Mg, 37%), suivis des espaces verts publics (236,57 Mg, 18%) et des espaces naturels aménagés (179,82 Mg, 14%). Cependant, les pressions anthropiques menacent cette séquestration, avec 154 cas (53,8%) d'écorçage, principalement sur *Terminalia superba, Terminalia mantaly* et *Khaya senegalensis*. L'élagage (75 cas) et l'étêtage (44 cas) fragilisent également les arbres. Ces résultats soulignent l'urgence d'une gestion durable des espaces verts intégrant la conservation des espèces et la lutte contre les impacts anthropiques pour renforcer la résilience urbaine et la séquestration du carbone.

Mots clés : Séquestration du carbone, espace vert urbain, biodiversité, pression anthropique, Porto-Novo.

1. Introduction

Africa is experiencing an unprecedented wave of urbanization, with cities growing at an extraordinary pace. This rapid expansion places significant pressure on urban green infrastructure, which is crucial for maintaining ecological balance, enhancing urban resilience, and improving residents' quality of life (Owojori & Okoro, 2023). Urban green spaces, such as parks, gardens, urban forests, and green belts, play an essential role in mitigating climate change by acting as carbon sinks. These spaces absorb carbon dioxide (CO_2) from the atmosphere, storing it in plant biomass and soil, thereby contributing to climate regulation (Stoffberg et al., 2010; O'Donoghue & Shackleton, 2013). However, the unchecked growth of urban areas, compounded by poor management practices, threatens the effectiveness of these green spaces in performing their vital ecological functions (Dossou et al., 2020).

Porto-Novo, the administrative capital of Benin, is no exception to the widespread trend of rapid urbanization in African cities. This growth has led to the gradual degradation of urban green spaces and a decline in biodiversity, especially among tree species that are critical to carbon sequestration (Akanvou et al., 2022). Prior research has pointed out that converting green areas into agricultural land, residential developments, or infrastructure severely diminishes their capacity to function as carbon sinks (Rambon et al., 2021). Furthermore, Ndiaye et al. (2024) demonstrated the importance of an integrated approach to managing ecosystem services for ensuring ecological sustainability in urban environments. Their study of the Hann Forest and Zoological Park in Senegal highlighted the interconnectedness of biodiversity, governance, and human well-being.

In the context of global climate change, the situation becomes even more concerning, as urban areas are significant contributors to greenhouse gas emissions (Nowak et al., 2013). Nonetheless, urban green spaces provide a wide array of ecosystem services beyond carbon sequestration: they improve air quality, regulate temperatures, mitigate the urban heat island effect, conserve biodiversity, and enhance the well-being of urban populations (Clark et al., 1997; Gómez-Baggethun et al., 2014). The effectiveness of these services is largely influenced by the diversity and health of the vegetation, as well as the management practices implemented (Jones et al., 2018).

In southern Benin, culturally protected forests and sacred groves provide significant ecosystem services, serving as vital reservoirs of biodiversity and carbon sinks (Obenakou et al., 2024). These traditional worship spaces contribute not only to the preservation of local biodiversity but also play an essential role in mitigating climate change. Furthermore, innovative technologies, such as the improved Casamance kiln, have proven effective in reducing greenhouse gas emissions within urbanizing contexts, as evidenced by Nabine et al. (2024) in Togo.

Recent research underscores the importance of incorporating both social and ecological factors into the sustainable management of urban forests and agroecosystems. Studies have shown that farmers' perceptions of fragmentation in areas like the Mbao Classified Forest significantly influence local management strategies (Cissé et al., 2024). In addition, agroforestry practices have been identified as crucial for enhancing the climate resilience of rural communities in Benin, contributing not only to the mitigation of climate change but also to the promotion of carbon storage (Gnonyi et al., 2024).

Despite the presence of several green spaces in Porto-Novo, few studies have specifically assessed their carbon sequestration capacity or the anthropogenic pressures that affect their ecological functioning. Recent research underscores the necessity of sustainable urban planning that incorporates green infrastructure and promotes tree species with high carbon sequestration potential (Dossa & Miassi, 2024). The carbon sequestration capacity of trees depends on various biological and ecological factors, such as growth rate, wood density, and lifespan (McPherson, 2006; Jones et al., 2018).

This study aims to fill the gap in data regarding Porto-Novo's green spaces and to inform strategies for sustainable urban management. The primary objective is to quantify the carbon stock present in these spaces and analyze the anthropogenic pressures exerted on the tree species that make up these green areas. The analysis will assess the capacity of urban trees to sequester carbon and identify human-related factors that influence their growth, health, and ability to contribute to climate change mitigation. By addressing both the ecological and human dimensions, this study seeks to provide valuable insights that can enhance the management of green spaces and bolster the ecological resilience of the city.

2. Materials et Methods

2.1 Study area

The study area presents the geographical location of Porto-Novo as well as its ecological, environmental, and social characteristics. This section will show the distribution of green spaces in Porto-Novo as much as possible.

Porto-Novo is located between 6°25' and 6°30' North latitude and between 2°34' and 2°40' East longitude (Figure 1). It covers an area of 52 km², representing 0.05% of the national territory (Tohozin and Orekan 2017). The climate is subequatorial, characterized by two rainy seasons and two dry seasons, with an average annual rainfall of 1300 mm and an average temperature of 27.5°C (Adam and Boko 1993). The city's natural vegetation consists of marshes and sacred forests (Akionla 2012; Osseni *et al.* 2020). Anthropogenic vegetation, composed of green spaces, includes a few fruit trees, kapok trees, cashew trees, and cotton trees. Porto-Novo is home to 263,616 inhabitants, spread over an area of 52 km², with a population density of 5,069 inhabitants per km² (INSAE 2013).

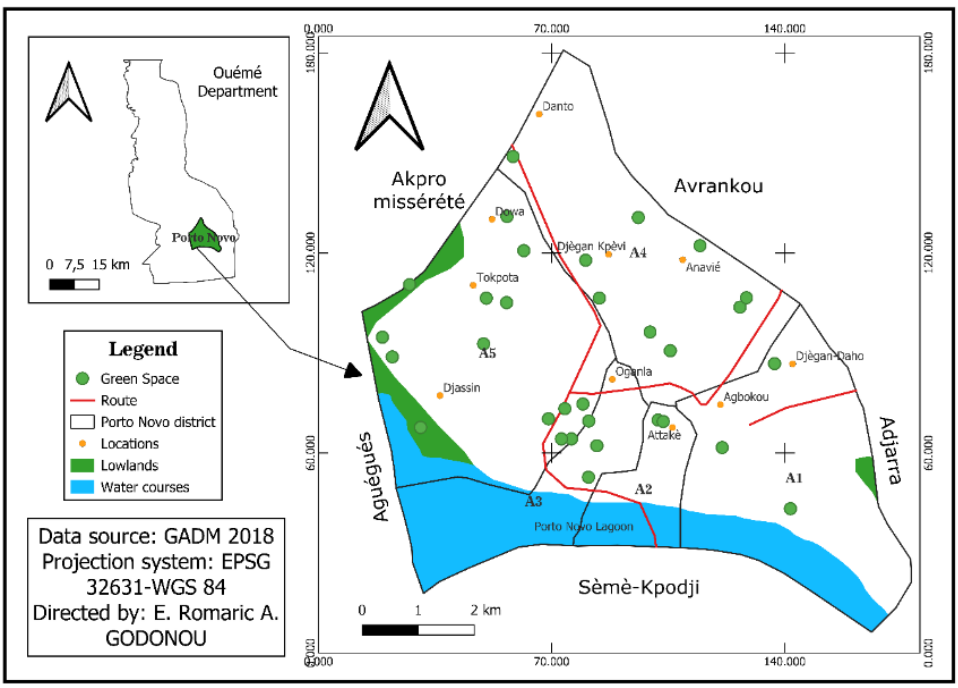

Figure 1. Geographic location of the city of Porto-Novo and location map of the distribution of sampled green spaces

Porto-Novo was selected as the study site due to the diversity and ecological richness of its urban green spaces, the variety of tree species they host, and the significant anthropogenic pressures they face. As an administrative capital with both urban infrastructure and remnants of natural ecosystems, Porto-Novo offers a unique environment to examine tree stand structure, carbon sequestration potential, and human-induced impacts. This setting provides a relevant context for understanding how urban green spaces contribute to climate resilience, biodiversity preservation, and sustainable urban development in a rapidly changing environment.

2.2. Data collection

As part of this study, 39 green spaces were selected in Porto-Novo. This choice was guided by criteria such as availability, accessibility, and representativeness. The selected sites include a variety of settings that accurately reflect the diversity of green spaces in the city. This selection provides a comprehensive and balanced basis for analyzing tree stand structure, evaluating carbon sequestration potential, and assessing the various forms of anthropogenic pressure present. Thus, the 39 chosen sites represent a relevant sample for understanding the role of green spaces in enhancing urban resilience to climate change in Porto-Novo. The study considered seven types of green spaces, each with specific characteristics in terms of management and floristic composition. These spaces include:

1. Green spaces supporting social and educational establishments,
2. Alignment trees along public roads,
3. Cemeteries,
4. The landscaped natural green spaces,
5. Green spaces surrounding public buildings,
6. Public green spaces,
7. Private green spaces.

To quantify their role in carbon sequestration, we estimated the above-ground biomass and carbon stock of trees using a non-destructive method based on allometric equations. This approach, as proposed by Lahoti *et al.* (2020b), allows for biomass estimation without felling trees, thus preserving the vegetation.

Only trees with a diameter at breast height (DBH) greater than 10 cm were included in the analysis, following Nero's (2017) criteria. Tree height was measured using a clinometer by recording the upward and downward sighting angles in combination with the horizontal distance from the tree. DBH was measured using a precision pi tape. For multi-stemmed trees, all stems were considered to obtain an accurate estimate of total biomass.

2.3. Data analysis

2.3.1. Dendrometric characteristics

These characteristics were estimated for each green space. The dendrometric variables used to describe the tree stands included: tree density, diameter, basal area per hectare, and height.

2.3.1.1. Tree height

To estimate the total height (H) of a tree, two angle measurements were taken. The first angle (V_1) was sighted toward the top of the tree, and the second angle (V_2) toward the base. These angles were expressed as percentages of the horizontal distance (L) separating the observer from the tree. The height was then calculated using the formula established by Gomido *et al.* (2019):

$$H = \frac{(V1 - V2) * L}{100}$$

This method, widely used in dendrometry, makes it possible to accurately estimate the height of trees while minimizing measurement errors, particularly in dense forest or urban environments.

2.3.1.2. Diameter of trees

The square diameter (dg_i, in cm) is the measurement of the average diameter of trees that is traditionally used in forestry. It is calculated by the following formula:

$$dg_i = \sqrt{\frac{1}{n}\sum_{i=1}^{n} d_i^2}$$

With di the diameter of a tree i measured within the transects and n the total number of transect trees considered. At the level of each green space, the average diameter (Dg) was estimated by:

$$Dg = \frac{1}{p}\sum_{i=1}^{P} dg_i$$

2.3.2. Carbon storage

In Porto-Novo, we applied urban-specific allometric equations known as Urban General Equations (UGES), which are best suited for estimating tree biomass in urban settings (Nomel *et al.,* 2019). Three different equations were used depending on the tree type:

- Hardwood Biom = $0.16155 \times DBH^{2.310647}$
- Palm trees Biom = $1.282 \times (7.7H + 4.5)$
- Conifers Biom = $0.035702 \times DBH^{2.580671}$

The total biomass for each tree was calculated and summed across all trees in each green space. This allowed the calculation of biomass density (biomass per square meter or hectare). The carbon stock was then estimated by applying a conversion factor of 0.47 (Martin & Thomas, 2011), which represents the proportion of carbon in biomass. Finally, to express the carbon stock in CO_2 equivalent, the value was multiplied by 3.67.

2.3.3. Statistical analysis

After collecting the dendrometric parameters tree density, DBH, and height, an analysis of variance (ANOVA) was performed to determine whether there were statistically significant differences among the different types of green spaces.

In addition, a linear regression was applied to study the distribution of trees by diameter class, examining the relationship between the class midpoints and corresponding tree densities across habitat types. To enhance interpretation and provide a clear visual understanding of the tree structure by diameter and height, bar charts were generated using the ggplot2 package (Wickham, 2016), a widely used tool for flexible and high-quality data visualization.

All statistical analyses were conducted using R software, version 4.0.5 (R Core Team, 2021), selected for its robustness and the wide range of functions it offers for ecological data analysis.

3. Results

3.1. structure of urban green spaces' trees

3.1.1. Spatial distribution of urban green spaces' trees

Table 1 presents 1340 trees found in different types of green spaces in Porto-Novo. The majority of trees are located in green spaces surrounding social and educational institutions, with 480 trees out of 1340, representing 35% of the total, followed by public green spaces with 260 trees, or 19% of the total, and landscaped natural green spaces with 121 trees, or 19%. Cemeteries and private gardens have 14 and 26 trees respectively, with low contributions. The distribution of trees varies across urban areas. This distribution shows the importance of considering vertical zones when calculating and evaluating tree density in gardens such as private gardens and cemeteries.

Table 1: Structural characteristics of green spaces

Line labels	Number of trees	Size (ha)	Density
Trees of alignments	**367**	**03**	**611.65**
Alignment Ouando Tokpota	104	0.6	173.33
Tokpota Alignment at CEG Les Cocotiers	47	0.6	78.33
Carrefour El- Fater to Carrefour Louho	83	0.6	138.33
Fiftieth anniversary Agata	91	0.6	151.66
Lycée Toffa Town Hall	42	0.6	70
Cemeteries	**14**	**2.902**	**10.80**
Danto Cemetery	07	0.976	7.17
Cemeteries Oganla	07	1.926	3.63
Green spaces accompanying public buildings	**72**	**3.981**	**82.91**
National Parliament	10	0.238	7.22
Departmental Directorate of Tourism	08	0.455	17.58

Holy Mary Catholic Church of Louho	26	0.745	34.89
Protestant Methodist Church	16	1.137	14.07
Municipal swimming pool	12	1.306	9.18
Green spaces supporting social and educational establishments	**480**	**44.778**	**158.59**
EPP Djègan daho	11	1.960	6.56
CEG MALE	08	3.654	2.18
CEG Ananvié	11	2,558	4.30
CEG Djègan Kpevi	58	2.359	24.58
CEG Dowa	81	4.365	18.55
CEG Koutongbé	31	2.635	11.76
CEG coconut trees Tokpota	71	4.850	14.63
CEMAAC	17	1.598	10.63
EPP Attakè	09	1.035	8.69
EPP Danto	07	0.580	12.06
EPP Gbènonkpo	16	1.541	10.38
EPP Hlouenda	26	1.454	17.88
EPP Urban Center	19	2.346	8.09
Behanzin High School	115	13.843	8.30
Natural green spaces fitted out	**121**	**2.006**	**60.31**
JPN Garden	121	2.006	60.31
Private Green Spaces (Private Gardens)	**26**	**0.436**	**166.61**
Akonaboè House	18	0.184	97.82
Akonaboè EF House	04	0.091	43.95
Danto House	04	0.161	24.84
Public green spaces (Parks and Squares)	**260**	**8.200**	**541.39**
Porto Novo Lagoon	18	0.367	49.04
Bayol Square	20	0.635	31.49
Unity Square	96	2.556	37.55
Idi Agbokou Square	55	3.846	14.30
Louho Square	45	0.436	103.21
Houinmè Public Square (Carrefour Fusion)	12	0.079	151.89
Public Square Kandevie	04	0.084	47.61
Public Square Olori Togbe	07	0.144	48.61
Yaya Gendarme Public Square	03	0.052	57.69
Total	**1340**	**65.303**	**1631.76**

3.1.2. Tree diameter in studied green Spaces

Table 2 below presents the average diameters of tree species in different green spaces. These diameters range from 34.11 cm for streetside trees to 79.28 cm for cemeteries. Cemeteries are characterized by diameters reaching up to 143.31 cm and a high standard deviation (38.12 cm), indicating the presence of mature trees. In contrast, private gardens have the smallest minimum diameter (0.11 cm), suggesting a significant presence of young trees or shrubs. These variations reflect specific management practices and planting strategies for each space.

Table 2. Descriptive statistics of tree diameter in the studied green spaces

Line labels	Min Di (cm)	Max Di (cm)	Mean Di (cm)	SD Di (cm)	Dg (cm)

Trees of alignments	9.87	144.27	34.11	30.23	45.39
Cemeteries	12.74	143.31	79.28	38.12	87.97
Green spaces surrounding public buildings	10.83	92.36	39.34	19.15	43.75
Green spaces surrounding social establishments and educational schools	11.46	186.31	47.29	26.62	54.27
Natural green spaces fitted out	10.19	197.45	48.04	38.73	61.71
Private green spaces (Private gardens)	0.11	69.43	42.41	20.32	47.03
Public green spaces (Parks and Squares)	9.55	414.01	43.86	32.46	54.56
Total	0.11	414.01	42.92	30.53	52.61

3.1.3. Tree crown diameter in the studied green spaces

Table 3 shows that cemeteries have the largest average crown diameter (16.93 m), while educational and social spaces reach 11.62 m, reflecting good vegetation cover. However, a maximum value of 480 m in public spaces (parks and squares) seems to be an outlier and requires data verification. Overall, the average crown for all spaces is 11.44 m, with high variability (standard deviation of 13.90 m), highlighting differences in shade management and species diversity.

Table 3. Descriptive statistics of tree crown diameter in the studied green spaces

Line labels	Min Dh (m)	Max Dh (m)	Mean Dh (m)	SD Dh (m)
Trees of alignments	0.75	24.50	8.65	4.44
Cemeteries	10.50	23.79	16.93	3.01
Green spaces surrounding public buildings	2.07	26.10	12.17	5.56
Green spaces surrounding social establishments and educational schools	0.98	35.50	11.62	5.81
Natural green spaces fitted out	1.05	23.00	12.08	4.06
Private green spaces (Private Gardens)	6.75	14.43	9.94	2.34
Public green spaces (Parks and Squares)	2.50	480.00	14.34	29.41
Total	**0.75**	**480.00**	**11.44**	**13.90**

3.1.4. Height of trees in the studied green spaces

Table 4 reveals that the tallest trees are found in green spaces surrounding social and educational institutions, with heights ranging from 16.76 m to 74.10 m. This finding suggests that ecosystem services can be enhanced by mature trees. In Porto-Novo, street trees have heights ranging from 11.41 m to 0.90 m, likely due to pruning to control their growth. Overall, the average height across all green spaces is 15.27 m with a standard deviation of 7.04 m. This result indicates a diversity in tree sizes across the various spaces.

Table 4. Descriptive statistics of tree heights in the studied green spaces

Line labels	Min Hi (m)	Max Hi (m)	Mean Hi (m)	SD Hi (m)
Trees of alignments	0.90	42.00	11.41	7.75
Cemeteries	11.00	38.75	19.90	6.80
Green spaces surrounding public buildings	7.00	32.40	15.55	4.18
Green spaces surrounding social establishments and educational schools	2.80	74.10	16.76	6.52
Natural green spaces fitted out	7.50	36.45	19.67	5.74
Private green spaces (Private Gardens)	6.79	22.05	17.16	5.75

Public green spaces (Parks and Squares)	1.10	42.90	15.41	5.53
Total	**0.90**	**74.10**	**15.27**	**7.04**

3.1.5. Distribution of the number of trees by diameter classes for the studied green spaces

The distribution shows that the lowest diameter classes (less than 50 cm) dominate in most green spaces, indicating a significant presence of young or recently planted trees. However, higher diameter classes (up to 414 cm) are notable in some public spaces such as parks, indicating the coexistence of young and mature trees. These quantitative observations reinforce the need for balanced planting programs, promoting both biodiversity and the expansion of large trees to maximize environmental benefits.

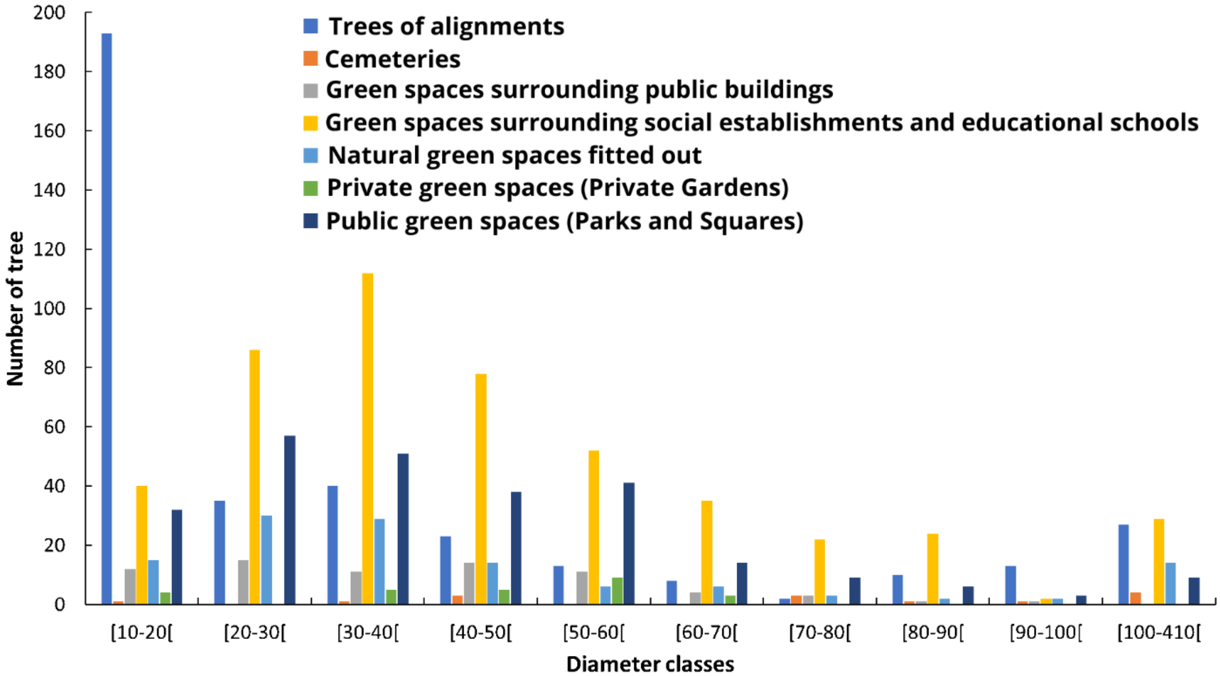

Figure 2. Distribution of the number of trees by diameter class in the studied green spaces

3.2. Carbon sequestration potential and tree carbon sequestration

Table 5 below presents statistics on carbon storage by trees in Porto Novo's green spaces in terms of aboveground biomass (AGB), belowground biomass (BGB), total biomass (Tot B), and total carbon (Tot C). The total biomass reaches 2838.41 Mg, corresponding to 1299.53 Mg of sequestered carbon. Social and educational spaces contribute the most to storage, with 484.60 Mg of carbon, or about 37% of the total. Public and developed natural green spaces follow with 236.57 Mg (18%) and 179.82 Mg (14%), respectively. In contrast, private gardens, despite their number, show the lowest storage (15.83 Mg, or only 1.2%). It is important to preserve and expand green spaces to increase the rate of carbon sequestration in Porto Novo.

Table 5. Carbon sequestration and tree sequestration potential

Line labels	AGB	BGB	Tot B (Mg)	Tot_C (Mg)
Trees of alignments	521034.85	130258.71	651293.56	298.23
Cemeteries	73676.73	18419.18	92095.91	42.17
Green spaces surrounding public buildings	73930.75	18482.69	92413.43	42.32
Green spaces surrounding social establishments and educational schools	846640.47	211660.12	1058300.59	484.60
Natural green spaces fitted out	314168.44	78542.11	392710.55	179.82
Private green spaces (Private Gardens)	27660.31	6915.08	34575.38	15.83
Public green spaces (Parks and Squares)	413309.59	103327.40	516636.99	236.57

Total	2270421.13	567605.28	2838026.41	1299.53

3.3. Anthropogenic pressures on trees in green spaces

This table analyzes the types and frequencies of human-induced pressures on trees in green spaces, such as bark stripping, pruning, pollarding, and topping. Out of a total of 1,340 surveyed trees, 22 were affected among the pressures, 154 cases of bark stripping were observed, representing approximately 53.8%, indicating that this practice is the most prevalent. Combined pressures, such as bark stripping coupled with pollarding or topping, are much rarer (1 case for topping combined with bark stripping). The most affected species are *Khaya senegalensis* (95 cases), *Terminalia mantaly* (49 cases), and *Mangifera indica* (31 cases), which account for nearly 61.2% of the total pressures. These species, widely present in green spaces, are primarily subjected to bark stripping. Species like *Khaya senegalensis* and *Mangifera indica* show a high level of exposure, often linked to their economic or medicinal uses. Practices such as pruning (75 cases) or pollarding (44 cases) are less frequent but remain significant, particularly for species like *Terminalia mantaly* (37 cases) for both and *Terminalia catappa* (19 cases) as well as *Corymbia torelliana* (13 cases) for pruning only. This table highlights the impact of human activities on tree health and the need for interventions to limit these pressures in the context of sustainable green space management.

4. Discussion

4.1. Carbon sequestration and anthropogenic pressure on tree species in green spaces

Urban green spaces in Porto-Novo play a significant role, offering both ecological services and well-being for residents. The study results indicate a decline in plant species density in the city's green spaces compared to findings by Osseni *et al.,* (2020). This could be attributed to the rapid urbanization of African cities (Fousseni et al. 2019), often developed without adequate planning and disregard for vegetation cover (Konijnendijk *et al.,* 2005). The loss of urban biodiversity is a direct result of development projects (such as road construction) undertaken in cities, particularly in Porto-Novo (Amontcha *et al.,* 2015). Our study affirms these findings, showing that the urbanization process has led to a significant reduction in the density of trees, which we attribute to the expansion of infrastructure at the cost of green spaces.

The uneven distribution of trees across different green space types (Table 1) highlights the influence of land use and management practices. The concentration of trees in social and educational institutions (35%) suggests that these areas prioritize green spaces, reflecting their importance for community well-being and educational environments. However, the relatively lower numbers in public green spaces (19%) and landscaped natural green spaces (19%) warrant further investigation to understand the factors limiting tree establishment and growth in these areas. This discrepancy reinforces the hypothesis that urban green spaces are fragmented and influenced by surrounding land uses, as observed by Ahern *et al.,* (2014), suggesting that management strategies may need to be tailored to specific green space types to enhance their ecological function.

The analysis of diameter classes underscores the early life stages of tree populations in many green spaces, revealing that a younger demographic predominates in most areas. This result aligns with Godonou *et al.,* (2024), who found similar patterns in other African cities. Our findings emphasize the necessity for balanced planting strategies to ensure both the longevity and the effective functioning of these green spaces. We affirm the need to incorporate species that offer both rapid growth and long-term carbon storage potential in future urban greening projects.

Crown diameter and tree height further support the observed variations in tree age and structure. Cemeteries exhibit the largest average crown diameter, consistent with the presence of mature trees. The high maximum crown diameter observed in public spaces, while potentially an outlier, highlights the importance of these spaces in preserving mature individuals. We support the view that public green spaces, particularly parks and squares, serve as essential refuges for large, mature trees that provide critical ecosystem services, including shade and carbon sequestration (Nowak and Crane, 2002). The wide range of tree heights across green spaces confirms that variations in management practices contribute significantly to the diversity of tree structures, with social and educational institutions showing the tallest trees due to well-planned management.

Pruning and pollarding, although less frequent, can also impact tree growth and ecological function. These practices, which are often employed to control tree size in urban environments, may limit the development of full canopy cover, reducing the tree's ability to perform vital functions such as carbon sequestration and air quality improvement (McKinney, 2008). We agree with Sinsin *et al.,* (2003) that urban tree management must be balanced, and propose that tree management strategies in Porto-Novo should integrate professional pruning techniques to support the overall health of urban trees.

Table 6: Anthropogenic Pressures on Trees in Green Spaces

Line labels	Bark stripping	Bark stripping and pollarding	Bark stripping and Topping	Pruning	Pollarding	Topping	Total
***Acacia auriculiformis* A.Cunn. ex Benth.**	10			3	1	4	18
***Adansonia digitata* L.**						2	2
***Albizia lebbeck* (L.) Benth.**	1						1
***Azadirachta indica* A.Juss.**	8	1	1			4	14
***Citrus sinensis* (L.) Osbeck**	1						1
***Corymbia torelliana* (F.Muell.) K.D.Hill & L.A.S.Johnson**	3			13			16
***Delonix regia* (Hook.) Raf.**						1	1
***Eucalyptus globulus* Labill.**	3						3
***Ficus spp*.**	1					5	6
***Gmelina arborea* Roxb.**	1		1			2	4
***Haematoxylum campechianum* L.**				3		1	4
***Khaya senegalensis* (Desr.) A.Juss.**	91		4				95
***Mangifera indica* L.**	21		3			7	31
***Morinda lucida* Benth.**			1			1	2
***Parkia biglobosa* (Jacq.) R.Br. ex G.Don**	1						1
***Persea americana* Mill.**	1					1	2
***Pterocarpus santalinoides* L'Hér. ex DC.**						1	1
***Salix babylonica* L.**	1					3	4
***Tectona grandis* L.f.**	2						2
***Terminalia catappa* L.**	4			19	1	1	25
***Terminalia mantaly* H.Perrier**	1			37		11	49
***Terminalia superba* Engl. & Diels**	4						4
Total	154	1	10	75	2	44	286

The analysis of carbon sequestration reveals the significant contribution of Porto-Novo's green spaces to carbon storage. Our findings affirm the importance of tree size and age in carbon sequestration, as the total biomass and carbon storage figures underscore the role of urban trees in mitigating climate change (McPherson *et al.,* 1997). The disproportionately high contribution of social and educational spaces to carbon storage, despite not having the highest number of trees, emphasizes the importance of promoting the growth and longevity of mature trees. The lower carbon storage in private gardens, despite their relatively high number of trees, reiterates the observation that younger trees, although numerous, do not yet contribute significantly to carbon sequestration (Nowak *et al.,* 2006). These findings underline the necessity to focus on the growth and preservation of mature trees in urban areas to maximize carbon storage (Folega et al. 2017).
Despite the importance of trees, they face significant anthropogenic pressures, mainly in the form of bark stripping for medicinal and artisanal uses. Bark stripping accounts for 53.8% of recorded cases, affecting species such as *Terminalia superba* and *Khaya senegalensis*. Pruning and pollarding, though less frequent, remain significant and are often poorly executed, weakening the trees. Certain species, such as *Terminalia mantaly* and *Mangifera indica*, are particularly affected due to their popularity and utility. These results validate the concern that anthropogenic pressures, if left unchecked, will undermine the ecological function of urban trees, particularly their ability to sequester carbon.
The results obtained in this study are consistent with those of Cissé *et al.,* (2024) in Senegal, who highlighted that urbanization and landscape degradation significantly compromise forest ecosystem services. Furthermore, the work of Gnonyi *et al.,* (2024) shows that well-structured agroforestry systems can partially compensate for these losses through better ecological and social resilience, particularly through carbon storage.
The findings of this study emphasize the need for methods to reduce the impact of human activities, preserve trees, and increase ecosystem services, especially carbon sequestration in green spaces. Sustainable solutions must be implemented to ensure the resilience of green spaces in the face of numerous urban challenges. Our study confirms the importance of sustainable urban management practices and underscores the need for policies that protect trees from anthropogenic pressures while maximizing their ecological benefits.

4.2. Implications for green space planning

The results of this study highlight the importance of urban green spaces in carbon sequestration and biodiversity conservation, while also underscoring the challenges posed by anthropogenic pressures and rapid urbanization. These findings have significant implications for the planning and management of green spaces in Porto-Novo and other African cities facing similar urban dynamics.
First, the results show that certain tree species, such as those found in green spaces associated with social and educational institutions, contribute significantly to carbon sequestration due to their size and maturity. This suggests that the planning of green spaces should prioritize the planting and conservation of species with high carbon sequestration potential, such as *Terminalia superba* and *Khaya senegalensis*, which are also resilient to urban conditions (Nowak *et al.,* 2013; McPherson, 2006). Sustainable urban planning should incorporate floristic inventories to identify and promote these species in reforestation and green space management projects (Dossa & Miassi, 2024). For example, fast-growing and long-lived species should be prioritized to maximize their long-term contribution to urban carbon stocks.
Next, the study reveals an uneven distribution of trees across different types of green spaces, with a concentration in social and educational institutions and low density in cemeteries and private gardens. This underscores the need for diversification of green spaces to maximize their ecological benefits. Cemeteries, although sparsely populated, host mature trees with large diameters, making them potential areas for biodiversity conservation and carbon sequestration (Konijnendijk *et al.,* 2005). Adaptive management, taking into account the specificities of each type of green space, is essential to optimize their ecological functions. For example, public spaces such as parks and squares could be designed to accommodate both young and mature trees (Folega et al. 2020), promoting continuity in the provision of ecosystem services (Ahern *et al.,* 2014).
Anthropogenic pressures, particularly bark stripping and improper pruning, severely affect tree health and their ability to sequester carbon. Measures must be taken to limit these practices, including awareness campaigns and stricter regulations. For instance, educational programs could be implemented to inform local communities about the ecological importance of trees and sustainable management practices (Sinsin *et al.,* 2003). Additionally, professional pruning techniques should be promoted to minimize damage to trees while ensuring public safety (McKinney, 2008). The protection of vulnerable species, such as *Terminalia mantaly* and *Mangifera indica*, which are often targeted for their medicinal or economic uses, should be a priority in green space management policies.
Moreover, green spaces should not be seen merely as decorative elements but as essential ecological infrastructure for urban resilience to climate change. An integrated approach to urban planning, which includes the creation and preservation of green

spaces, is necessary to maximize their ecosystem services, such as climate regulation, air quality improvement, and urban heat island mitigation (Gómez-Baggethun *et al.,* 2014). Urban policies should also encourage the creation of green corridors to connect fragmented green spaces, thereby promoting biodiversity and wildlife mobility. This approach would help create a more resilient and functional urban ecological network.

Finally, the study highlights the limitations of traditional allometric methods for estimating biomass and proposes the use of advanced technologies, such as Sentinel-2 data and machine learning, to improve the accuracy of aboveground biomass estimates (Liu *et al.,* 2024; Netsianda & Mhangara, 2025). These tools could be integrated into green space management systems to monitor tree health in real time and assess their contribution to carbon sequestration. This would enable more proactive and data-driven management, essential for addressing climate and urban challenges. For example, predictive models could be developed to anticipate the impacts of climate change on green spaces and adapt management strategies accordingly.

4.3. Limitations of the study

While this study provides valuable insights into the carbon sequestration potential and anthropogenic pressures on urban green spaces in Porto-Novo, it is not without limitations. One major limitation is the reliance on traditional allometric equations for biomass estimation, which may not fully capture the variability in tree growth forms and species-specific characteristics in urban environments. Recent studies have shown that allometric models developed for natural forests may not be directly applicable to urban trees due to differences in growth conditions, such as soil quality, water availability, and microclimatic factors (McHale *et al.,* 2022). This could lead to inaccuracies in carbon stock estimates, particularly for species that are underrepresented in existing allometric databases. Therefore, future research should consider developing or adapting allometric equations that better reflect the unique conditions of urban green spaces, to provide more accurate carbon sequestration estimates.

Another limitation is the spatial scope of the study, which was confined to specific green spaces within Porto-Novo. This restricts the generalizability of the findings to other urban areas in Benin or similar contexts. Urban green spaces are highly heterogeneous, and their ecological functions can vary significantly depending on local environmental conditions, management practices, and socio-economic factors (Dobbs *et al.,* 2021). Future research should expand the geographical scope to include a wider range of urban green spaces across different regions, allowing for a more comprehensive understanding of carbon sequestration potential and biodiversity patterns in African cities. This would offer valuable insights into the spatial variability of urban carbon stocks and help refine global urban greening strategies.

Additionally, the study did not fully account for the belowground biomass (BGB) of trees, which is a critical component of carbon storage in urban ecosystems. Recent research has emphasized the importance of including BGB in carbon stock assessments, as it can account for a significant proportion of total biomass, particularly in mature trees (Smith *et al.,* 2023). The exclusion of BGB in this study may have led to an underestimation of the total carbon sequestration potential of Porto-Novo's green spaces. Future studies should incorporate methods for estimating BGB, such as root-to-shoot ratios or direct measurements, to provide a more accurate and holistic assessment of carbon stocks in urban environments. Including BGB would ensure that the full capacity of urban trees to store carbon is properly accounted for, leading to more reliable management recommendations.

The study also faced challenges in quantifying the full extent of anthropogenic pressures on urban trees. While bark stripping and improper pruning were identified as major threats, other factors such as pollution, soil compaction, and invasive species were not thoroughly examined. These stressors can have cumulative effects on tree health and their ability to sequester carbon (Gregg *et al.,* 2023). A more holistic approach to assessing anthropogenic pressures, including the use of remote sensing and citizen science data, could provide a more comprehensive understanding of the challenges facing urban green spaces. Future studies should consider integrating these additional stressors to offer a more complete picture of the challenges facing urban tree populations.

Finally, the study's reliance on field measurements for dendrometric data, such as tree height and diameter, may have introduced measurement errors, particularly in densely vegetated or hard-to-access areas. Advances in remote sensing technologies, such as LiDAR and drone-based imaging, offer promising alternatives for accurate and efficient data collection in urban environments (Alonzo *et al.,* 2024). These technologies can provide high-resolution data on tree structure and biomass, reducing the reliance on manual measurements and improving the accuracy of carbon stock assessments. Incorporating these technologies into future studies could lead to more precise and scalable data collection, enabling the monitoring of urban trees on a broader scale and enhancing the overall quality of carbon sequestration assessments.

5. Conclusion

Urban green spaces in Porto-Novo play a fundamental role in carbon sequestration, climate regulation, and improving the quality of life for residents. This study highlights the importance of these spaces as biodiversity reservoirs and carbon storage zones while emphasizing the challenges related to their management. The analysis of tree diversity reveals significant heterogeneity among different types of green spaces, influenced by management practices and increasing urbanization. While some categories, particularly those associated with social and educational institutions, demonstrate high carbon sequestration potential, others remain underutilized and vulnerable to anthropogenic pressures. The findings indicate that urban trees face considerable threats, mainly in the form of bark stripping, improper pruning, and topping, compromising their growth and ability to perform essential ecological functions. These pressures call for urgent measures to ensure sustainable green space management, prioritizing the conservation of high-carbon sequestration species and the adoption of proper maintenance practices. A better integration of green spaces into urban planning, supported by protection policies and awareness campaigns, is crucial to enhance their resilience against human pressures and climate change. These actions will contribute to preserving urban biodiversity and improving the ecosystem services provided by these spaces, ensuring a more sustainable living environment for future generations.

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