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Research Article

Assessing the Importance of Urban Flora Structure and Traits on Carbon Stock Potential in Abomey-Calavi City in Benin (West Africa)

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Abstract

The flora growth stock plays an important role in stabilizing the urban socio-ecological system. This study aims to assess the importance of urban flora structure and traits on carbon stock potential in Abomey-Calavi city. Stratified random sampling approach was adopted to spatially distributing the sample plots. A mixed inventory schema was used to collect floristic and dendrometric data (stem height, DBH, crown diameter) in 173 one-hectare sample plots. These data were graphically and statistically analyzed. A total of 4,390 trees belonging to 105 plant species and 31 identity groups were identified and measured. The city's total plant primary production was evaluated at 5111.651 t of biomass, 2489.374 t of carbon, 9136.004 t of CO_2 sequestered for an ecological value of US$5,816.022. The average carbon stock was estimated at (C_T: 14.389 t/ha; CO_{2T}: 52.809 t/ha; EV: 316.850 $/ha). The stock of carbon estimated in institutional zone was significantly 2.11 – 3.03 times higher than those of two other strata ($p<0.0001$). Stem of DBH < 65 cm concentrated 67.35% of total carbon stock versus 32.65% for those of DBH ≥ 65 cm. The significant interaction between urban strata, diameter category and species origin revealed that native species accumulated 2 times more dry matter than exotic species for the stems of DBH ≥ 65 cm. The average carbon stock of identity groups was evaluated at (C_T: 1.918 ±3.348 t/ha; CO_{2T}: 7.038 ±12.288 t/ha; EV: 11.123 ±19.420 $/ha). The index of contribution was ranged from 0.052 to 1.900 for exotic species groups, compared with 0.056 to 14.441 for native species groups. Native species with single leaves, semi-caducous foliage and disseminated by zoochory stored the most carbon in the city. Strategic forest reserves should be created to conserve species with high carbon stock potential. In this way, the growing effects of heat islands could be effectively mitigated and environmental education reinforced.

Keywords

Stock of Biomass, Life-History Traits, Identity Group, Contribution Index, Urban Strata

1. Introduction

The urbanization process is a complex set of successive filters which affects the ecological integrity of the urban ecosystem [1-3]. This process creates a new dynamic in city flora [4-7]. It leads also to flora homogenization through the

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expansion of exotic species and the decline of native ones [8-10]. In the same way, urbanization has a major influence on the mechanisms linking urban development to carbon stock and its fluxes [11].

Cities are among the primary sources of CO_2 emissions. They emit 40 - 84% of the total greenhouse gases produced by human activities [11-14]. Most of these emissions are captured by urban flora, which convert them into dry matter in stem, roots and branches through photosynthesis [15-17]. This process helps to stabilize the urban socio-ecosystem [18, 19]. Urban flora also provides an important socio-ecological and environmental benefits and services [20-23] that are not mutually exclusive. The architectural, morphological, phenological, functional and structural characteristics of trees are the main parameters that promote the provision of these benefits and services [20-24]. Species abundance and diversity are also an important indicator of the quantity and quality of ecological services provided by trees [25, 26]. These services significantly mitigate the effects of urbanization and climate change [23, 27]. In addition, they improve the living environment of city dwellers [23].

Species carbon accumulation potential is a key urban ecosystem function [18, 19]. Thus, the quality of carbon stock is crucial for assessing the sustainability and efficiency of regulatory function. This capacity of urban forests influences local climate, carbon cycles and energy use [28-30]. Into the city, storage capacity of trees is all the greater as their growth reduces competition for resources (e.g. light, nutrients, etc.). These trees tend to allocate proportionately more resources to diameter and canopy growth than height growth [31]. This significantly favors their architectural and morphological development [32]. Therefore, forest structure is a determining factor of urban trees primary production. Like structure, plants carbon stock is also influenced by the spatial and morphological dynamics of cities, natural environmental features, management policies, land use patterns and social factors [33, 34].

Assessing carbon stock is a relevant exercise for understanding the potential response of cities to curb the carbon dioxide produced. It requires the estimation of biomass and its conversion into carbon and carbon dioxide [35, 36]. Obtaining its ecological value is also an important asset in urban species conservation and management policies. Two methods for estimating biomass are presented in the scientific literature: direct method and indirect method. The non-destructive method (indirect method) is preferred in the present study for its relative ease of use and suitability for rapid assessment of plant primary production in urban areas. In addition, there are major differences between the growth of species in urban environment and natural forests [37]. This gives to the trees an architecture significantly different from those of forest trees [38]. Similarly, management and monitoring practices for urban flora are totally different from those in forested areas. Therefore, it is obvious to develop in situ models or used the models developed for urban trees species in tropical zone in order to better appreciate the contribution of species to total carbon stock in urban area, and to understand its influence on the overall accounting of greenhouse gases produced in cities [39, 40].

The city of Abomey-Calavi is densely populated and has undergone constant spatial expansion over the last ten years. Similarly, the densification of the road network has led to a significant loss of plant species. Yet these species contribute to the primary production potential of urban flora. The flora is also highly homogenized, with more abundance of exotic species. The ratio of exotic to native species is 3.94 (abundance) and 1.76 (species richness) [41]. It should also be highlighted that reliable inventory data on urban trees is almost non-existent or limited to specific sites. Consequently, they are not representative of the characteristics of urban flora on a city scale. Moreover, previous detailed studies on urban plant primary production potential are scarce [41, 42]. In-depth knowledge of plant primary production potential notably the stock of carbon and the groups of species that contribute most to this potential is a major asset for strengthening the urban development plan. This information can serve as the basis for monitoring the stability of the urban ecosystem. In this way, managers will be able to understand urban flora productivity and have a basis for planning the sustainable management of urban forests [43].

The goals of this research were: (1) to analyze the variability of carbon stock between urban strata, diameter categories and species origin, (2) to assess the influence of structure and life-history traits on carbon stock.

2. Materials and Methods

2.1. Study Area

The city of Abomey-Calavi (6°20' - 6°35'30"N and 2°13' - 2°24'30"E) covers an area of 257.11 km^2. It is located in the Guineo-Congolese zone of southern Benin. The climate is sub-tropical with a bimodal precipitation distribution. The mean annual rainfall and temperature recorded were 1277.67 mm and 27.59℃, respectively. Soils are mainly ferralitic on loose clayey sediment of continental terminal, on sandstone and colluvial materials. The urban forests are made up of isolated trees, avenue trees, plantations and sacred groves. Climatic and pedological conditions of the city are favorable for plant species establishment. The average annual growth rate of population is 4.97% [44]. This rapid population growth and urban development intensity are a challenge in preserving and sustaining urban flora.

2.2. Data Collection

The stratified random sampling approach was used for data collection [45, 46]. The urban strata (RZ: residential zone, IZ: institutional zone and RBZ: road buffer zone) considered had already been described in [46]. A mixed inventory schema was used to collect floristic and dendrometric data in 173 one-hectare sample plots. Further information on sample plots can be found in [46]. In each plot, the geographical coordinates of the plots were recorded. All plant species with DBH $\geq$ 5 cm were also identified to species level and counted by species. Their diameters were measured using calipers or a diameter tape. Stem and total heights were also measured an optical clinometer (Brunton Sum 360LA). For a stem with multiple trunks before 1.3 m above-ground, the diameter of each individual was measured and their combined average was calculated as the mean square root to serve as a single value for the stem [7, 47]. All the species inventoried were formally identified by experts of National Herbarium of Abomey-Calavi University (UAC). The nomenclature adopted is that of Angiosperm Phylogeny Group *et al*. [48].

The life-history traits of each species (origin, diaspora dissemination, leaf shape and foliage consistency) were identified from the scientific literature [49-52], and by experts of National Herbarium.

Origin (native and exotic) of species was established based on La Sorte *et al*. [53]. The Guineo-Congolese base element [54] was taken as a reference for native species. However, species introduced after the 1500s are considered exotic (or neophytes). The species description and distribution proposed by [55-57] were also used.

The main diaspora dissemination modes (anemochory, anthropochory, autochory and zoochory) selected correspond to the categories defined by [58] and reviewed by several authors [59-62].

Leaf shape (single leaf and composite leaf) and foliage consistency (deciduous, semi-deciduous and evergreen) were respectively defined following [50] and [63].

2.3. Data Analysis

2.3.1. Estimation of Carbon Stock

Total biomass was calculated by summing above-ground biomass and root biomass. Above-ground biomass is the sum of stem biomass and crown biomass. Stem biomass was obtained using the allometric volume estimation model (Model 2) developed in [64]. Carbon stock and carbon dioxide sequestrated by urban flora were calculated according to conversion factors. Ecological value has an economic or monetary equivalent on the REDD+ or voluntary market. On carbon volume transaction voluntary market, the price per tons of CO_2 sequestered was equivalent to US$5.80 in 2021 for forestry and land use [65]. The biomass expansion factor (BEF) and roof factor (R) were 3.40 [66] and 0.24 [67] respectively. The biomass conversion factor (BCF) used in this study was 0.487 [36]. The carbon conversion factor (CCF) was 3.67 (ratio of molecular mass of CO_2 to atomic mass of carbon) [68].

The equation (1) represents the allometric equation of Model 2 [64], which was used to estimate plant stem volume (V). The equation (2) to (6) were used to calculate total biomass (B_T, t/ha), total carbon (C_T, t/ha), total carbon dioxide (CO_{2T}) and total ecological value (EV). These parameters were estimated by plot and then by urban strata, diameter categories and species life-history traits.

$$V = 3,3338e^{-3} \times DBH^{1,13612} + 3,2977e^{-5} \times \left(DBH^{2,173432} \times h^{0,9307291}\right) \tag{1}$$

(RMSE: 0.054; FI: 0.998; AIC = -3851.324; DBH: 5 – 223 cm)

$$B_T = B_s \times (1 + BEF) \times (1 + R) \tag{2}$$

$$B_s = V \times BD \tag{3}$$

$$C_T = B_T \times BCF \tag{4}$$

$$CO_{2T} = C_T \times CCF \tag{5}$$

$$EV = CO_{2T} \times 5,80 \tag{6}$$

h: stem height; V: stem volume; B_s: stem biomass; BEF: biomass expansion factor; R: roof factor; BD: basic density; RMSE: root-mean-square error; IF: goodness-of-fit index; AIC: Akaike information criterion.

The basic density (BD) of species was deduced from specific density present in digital databases and scientific literature [36, 69-75]. For species with specific density at 12% moisture, the conversion factor of 0.828 [75] was used to convert them to basic density. For specific density of 10 - 18% moisture, the conversion factor of 0.861 was used to obtain the corresponding basic density [76]. The species for which specific density does not exist at species taxonomic rank in these databases, mean value for the genus or family was taken into account [77]. For species whose density does not exist at genus or family level, the mean value of the sample was preferred [77].

2.3.2. Statistical Analysis

The variation in biomass, carbon, carbon dioxide and ecological value of species was graphically analyzed between urban strata (RZ: Residential zone, IZ: Institutional zone, RBZ: Road buffer zone), diameter categories (DBH < 65 and DBH $\geq$ 65) and species origins (Exotic and Native) on the basis of boxplots. The diameter categories used are derived from the results of preliminary analysis of the urban flora structure by diameter classes reported in [41].

To compare parameter values between strata, diameter categories and species origin, 1-2 or 3-factors ANOVA was performed. For this purpose, a Boxcox transformation of the parameters was first performed. Shapiro-Wilk and Levene tests were then performed to ensure normality and equality of samples variance, respectively. In absence of equality of samples variance, Welch's ANOVA test was used. Pairwise comparisons of strata, diameter categories or origin were made using Student's t-test or Games-Howell test as appropriate. The level of significance retained for analysis was 0.05.

Life-history traits of species were combined to form species identity groups "*all species with the same life-history traits*". The contribution of each identity groups to total carbon stock was assessed. To analyze the influence of species identity group to proportional changes in carbon stock, Generalized Linear Model (GLM) with a logarithmic link [78] was used. Pearson Chi^2 test was performed to test the deviance between model obtained and null one.

The contribution of species identity group to carbon stock (SCC, %) was calculated by dividing group's carbon stock to the total carbon stock. The carbon stock contribution index (ICo) was calculated by dividing contribution of identity group's carbon stock to the contribution of identity group's abundance (CA_b, %). This CA_b was calculated by species abundance of identity group to the total species abundance. The ICo is an indication of the relative capacity of identity group to store carbon in urban area [79].

$$ICo = SCC / CA_b \tag{7}$$

$$SCC = \left(\sum_{i=1}^{s} sc_{ig} \Bigg/ \sum_{j=1}^{g} \sum_{i=1}^{s} sc_{ij} \right) \times 100 \tag{8}$$

$$CA_b = \left(\sum_{i=1}^{s} a_{ig} \Bigg/ \sum_{j=1}^{g} \sum_{i=1}^{s} a_{ij} \right) \times 100 \tag{9}$$

sc_{ig} : Carbon stock of species i in group g; sc_{ij} : Carbon stock of species i in any group j; a_{ig} : Abundance of species i in group g; a_{ij} : Abundance of species i in any group j ; g : Number of identity groups ; s : Number of species.

3. Results

3.1. Assessing the Carbon Stock of Urban Strata

The total plant primary production of the city is evaluated at 5111.651 tons (t) of biomass, 2489.374 t of carbon stock and 9136.004 t of CO_2 sequestrated. The ecological value of this potential is estimated at US$54816.022. The range of these parameters is as follows (B_T: 2.121 - 153.092 t/ha; C_T: 1.033 - 74.556 t/ha; CO_{2T}: 3.790 - 273.620 t/ha; EV: 22.740 - 1641.718 $/ha). The average carbon stock of the city is 14.389 t/ha with an accumulation of 52.809 t/ha of carbon dioxide whose ecological value is estimated at US$316.850/ha. The dispersion of this average carbon stock is 100.04%.

Considering urban strata, total carbon stock of institutional zone (IZ) is (C_T = 1081.476 t; CO_{2T} = 3969.019 t; EV = 23814.111 $US). Those for residential zone (RZ) is (C_T = 1180.467 t; CO_{2T} = 4332.313 t; EV = US$25993.880). Total carbon stock of the road buffer zone (RBZ) is (C_T = 227.431 t; CO_{2T} = 834.672 t; EV = US$5008.031). The extent of total carbon stock distribution in urban strata is as follows: institutional zone (C_T: 2.884 - 65.040 t/ha; CO_{2T}: 10.586 - 238.697 t/ha; EV: 63.514 - 1432.180 $/ha), Residential zone ($C_T$: 1.033 - 74.556 t/ha; CO_{2T}: 3.790 - 273.620 t/ha; EV: 22.740 - $1641.718/ha) and Road buffer zone (C_T: 1.077 - 47.765 t/ha; CO_{2T}: 3.954 - 175.297 t/ha; EV: 23.722 - $1051.784/ha).

Species in institutional zone show the highest carbon stock potential (C_T = 24.579 t/ha; CO_{2T} = 90.205 t/ha; EV = 541.230 $/ha). The quantity of carbon stored by species of this stratum is 2.11 times greater than in residential zone (C_T = 11.688 t/ha; CO_{2T} = 42.894 t/ha; EV = $257.365/ha) and 3.03 times greater than in road buffer zone (C_T = 8.123 t/ha; CO_{2T} = 29.810 t/ha; EV = $178.858/ha). Furthermore, the variations observed in IZ (cv = 76.18%) are relatively smaller than those recorded in the RZ (cv = 93.33%) and RBZ (cv = 112.68%).

The variation of carbon stock differs significantly between strata (F = 20.18; p<0.0001) with a correlation ratio of 0.19 (Figure 1). Similarly, paired difference of strata is also significant (RZ - IZ: t = -4.62 and p<0.000; RZ - RBZ: t = 2.61 and p = 0.013; IZ - RBZ: t = 5.47 and p<0.000). The three strata are therefore singular in terms of carbon storage potential. Considering the average carbon stock, we can classify the strata as follows: IZ > RZ > RBZ.

3.2. Importance of Diameter Category on Carbon Stock

The total carbon stock by diameter categories shows that the stems of DBH < 65 cm concentrate 67.35% of carbon (C_T: 1676.682 t) versus 32.65% for the stems of DBH ≥ 65 cm (C_T: 812.692 t).

For the stems of DBH < 65 cm, average amount of carbon stored is 9.692 t/ha of total carbon and 35.569 t/ha of CO_2. The corresponding ecological value is estimated at $213.414/ha. The performance of the stems of DBH ≥ 65 cm in carbon storage is 1.14 times lower than that of previous stems (C_T = 8.466 t/ha; CO_{2T} = 31.069 t/ha; EV = $186.411/ha).

The distribution of carbon stock by diameter categories shows wide variations within each stratum (Figure 2). The contribution of the stems of DBH < 65 cm to carbon stock is ranged from 58.23% (RBZ) to 72.42% (IZ), compared with 27.58% (IZ) to 41.77% (RBZ) for stems of DBH ≥ 65.

The IZ stratum has the highest carbon production, with relatively low variations whatever the diameter category considered (Figure 2). In this zone, average carbon stock of the stems of DBH < 65 cm is (C_T = 17.801 t/ha; CO_{2T} = 65.329 t/ha; EV = $391.975/ha). This production is respectively 2.36 times and 3.76 times higher than that recorded for the same diameter category in residential and road buffer zones.

The amount of carbon accumulated by the stems of DBH ≥ 65 cm is estimated at (C_T = 9.038 t/ha; CO_{2T} = 33.168 t/ha; EV = $199.007/ha). It is respectively 1.19 times and 0.76 times higher than that recorded for the same diameter category in residential and road buffer zones.

The effect of the interaction between urban strata and diameter categories is statistically significant at 5% level (F = 7.520; p<0.0001) (Figure 2). A significant difference in carbon stock was noted between diameter categories in institutional zone (t = 3.650; p = 0.0003). However, carbon stock between diameter categories was not statistically significant in residential zone (t = 1.770; p = 0.0776) and road buffer zone (t = -1.680; p = 0.0941).

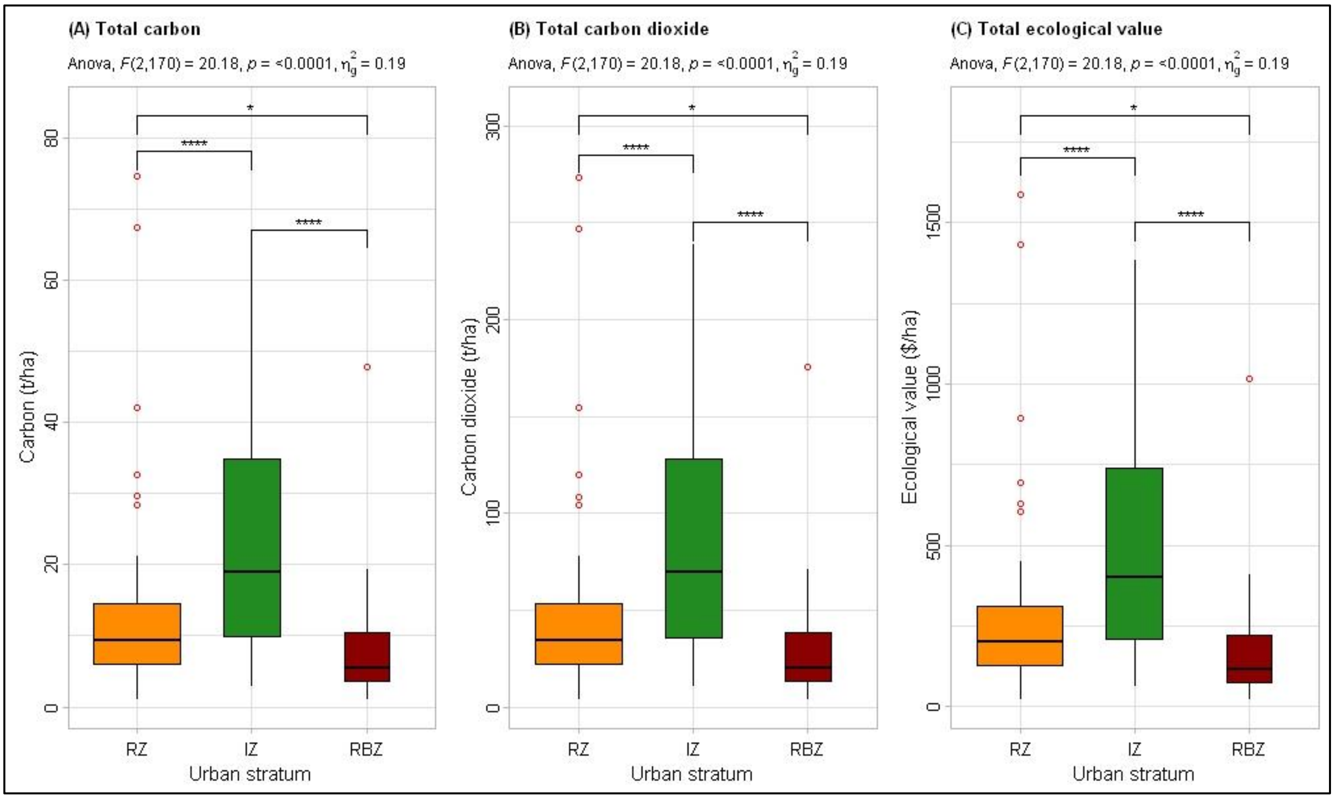

*Figure 1. Total carbon stock in urban strata. RZ – Residential zone; IZ – Institutional zone; RBZ – Road buffer zone; level of significance ("****": p<0.0001, "*": p<0.05, ns: Non-significant at 0.05).*

3.3. Influence of Life-history Traits on Carbon Stock

3.3.1. Variation of Carbon Stock by Origin

According to diameter categories, the carbon stored by native species shows greater variation (cv: 93.43% (RBZ) to 148.02% (IZ)) than for exotic ones (cv: 60.02% (RZ) to 102.11% (IZ)) in urban strata (Figure 3).

Exotic species with DBH < 65 cm accumulate the most carbon stock in institutional zone (C_T = 15.326 t/ha; CO_{2T} = 56.248 t/ha; EV = 88.893 $/ha) than in residential zone (C_T = 5.772 t/ha; CO_{2T} = 21.185 t/ha; EV = 33.480 $/ha) and road buffer zone (C_T = 3.359 t/ha; CO_{2T} = 12.328 t/ha; EV = 19.483 $/ha). For this diameter category, the ratio of carbon stock between exotic and native species is ranged from 1.85 (RBZ) to 5.21 (IZ). Exotic species produce 2 to 6 times more carbon than native ones.

The situation described above is reversed between these two categories of species origins when considering the stems of DBH ≥ 65 cm. Native species produce, on average, 1.67 (IZ) to 1.78 (RBZ) times more carbon than exotic species. This production is higher in road buffer zone (C_T = 13.943 t/ha; CO_{2T} = 51.172 t/ha; EV = $80.872/ha) than residential zone (C_T = 8.152 t/ha; CO_{2T} = 29.917 t/ha; EV = $47.281/ha) and institutional zone (C_T = 9.451 t/ha; CO_{2T} = 34.685 t/ha; EV = $54.816/ha).

The interaction between urban strata, diameter categories and species origin have a significant positive effect on carbon sock (F: 10.40; p<0.0001) (Figure 3). With regard to the stems of DBH < 65 cm, the quantity of carbon stored by exotic species differed significantly from that of native species in each stratum at 5% (ZH: t = -7.170 and p<0.0001; ZI: t = -7.150 and p<0.0001; ZDV: t = -2.190 and p = 0.029). In contrast, the difference in carbon stock between species origin for the stems of DBH ≥ 65 cm was not statistically significant at 5% (ZH: t = 0.894 and p = 0.372; ZI: t = 0.429 and p = 0.668; ZDV: t = 0.726 and p = 0.468).

3.3.2. Contribution of Life-history Traits to Carbon Stock

Species were grouped into 31 identity groups, of which 16 were exotic species groups and 15 native species groups. The exotic species identity group contributes to 69.14% of total carbon stock, compared with 30.86% of native species identity group (Table 1). Within these different species identity groups, species with single leaves (exotic: 47.64%; native: 15.31% of carbon stock) or composite leaves (native species: 15.55%), evergreen foliage (exotic: 52.59%; native: 22.66%) and disseminated by anthropochory (exotic: 53.12%; native: 23.31%) contribute most to the total carbon stock of the city.

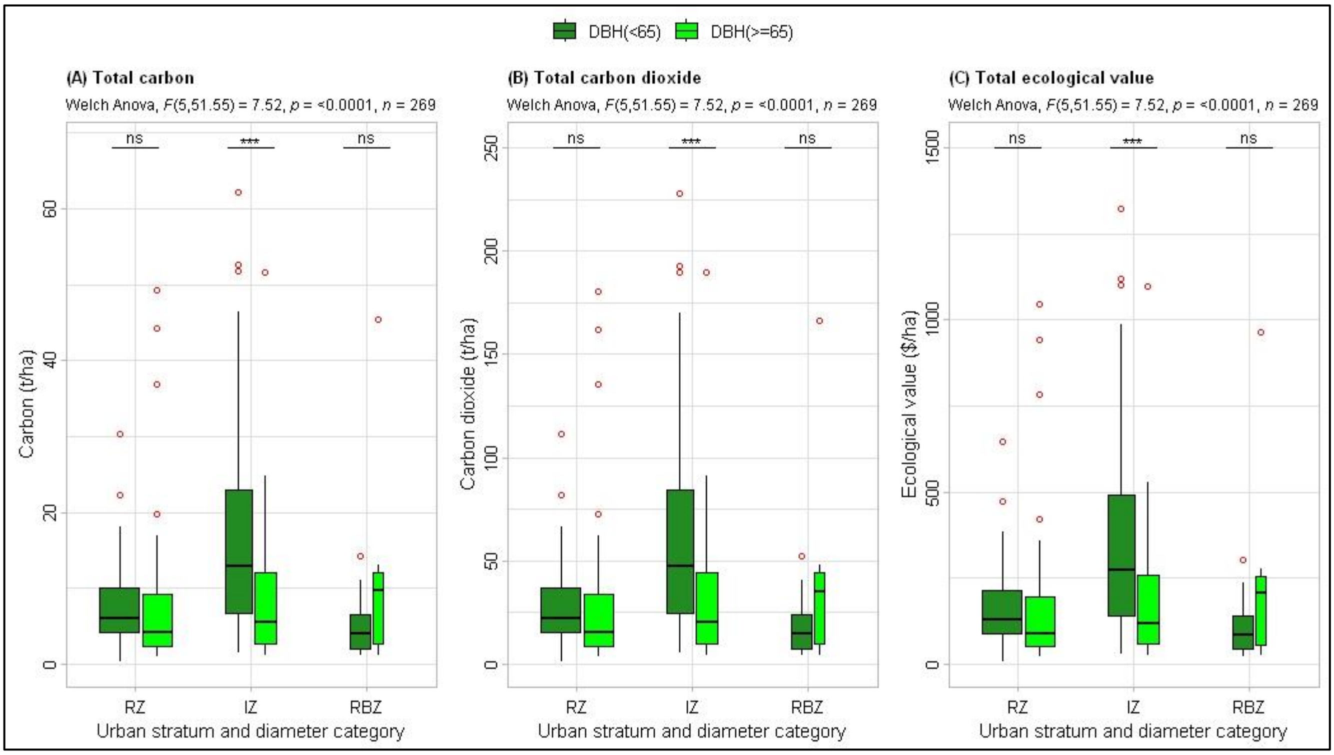

Figure 2. *Total carbon stock by diameter category in urban strata. RZ – Residential zone; IZ – Institutional zone; RBZ – Road buffer zone; level of significance ("***": p<0.001, ns: Non-significant at 0.05).*

Ten of the 31 species identity groups obtained contribute more than 2% of carbon stock. Thus, 7 exotic species identity groups (66.10%) and 3 native species identity groups (26.27%) account for 92.37% of the total carbon stock. In contrast, average carbon stock per native species identity group (C_T: 2.490 ± 4.628 t/ha; CO_{2T}: 9.140 ± 16.984 t/ha; EV: 14.444 ± 26.841 $/ha) is 1.80 times greater than that of exotic species identity group (C_T: 1.381 ± 1.341 t/ha; CO_{2T}: 5.067 ± 4.920 t/ha; EV: 8.008 ± 7.775 $/ha), but with very wide variation (cv = 185.82%).

Among the exotic species identity groups, species with single leaves, evergreen foliage and disseminated by anthropochory accumulate the most carbon stock (C_T: 4.152 ± 5.921 t/ha; CO_{2T}: 15.237 ± 21.728 t/ha; EV: 24.080 ± 34.339 $/ha). In contrast, they are the native species with single leaves, semi-caducous foliage and disseminated by zoochory, which store the most carbon stock (C_T: 18.425 ± 23.756 t/ha; CO_{2T}: 67.619 ± 87.186 t/ha; EV: 106.865 ± 137.788 $/ha) in native species identity groups.

In terms of contribution to total carbon stock, the group of exotic species with single leaves, evergreen foliage and disseminated by anthropochory (SCC = 36.525%) is the best contributor. In contrast, the group of native species with composite leaves, evergreen foliage and disseminated by anthropochory (SCC = 14.046%) contributes the most to carbon stock in native species identity groups (Table 1).

The carbon contribution index ranges from 0.052 to 1.900 for exotic species groups and from 0.056 to 14.441 for native species groups. In the exotic species identity group, species with composite leaves, evergreen foliage and disseminated by zoochory (ICo = 1.900) contribute most to carbon stock. On the other hand, native species with single leaves, semi-caducous foliage and disseminated by zoochory (ICo = 14.441) accumulate the greatest amount of carbon stock in the native identity groups.

The GLM results (Table 1) reveal a statistically significant likelihood ratio (χ^2 = 1598.5; p<0.0001). The adjusted model is better than the null or constant-only model at 5%. A species identity group taken at random cannot explain the variation in carbon stock recorded on its own. The effect of identity groups on carbon stock is also significant (F = 21.01; p < 0.0001). Therefore, the effect of each group on carbon stock is discernible.

Average carbon stock for all species identity groups is estimated at (C_T: 1.918 ±3.348 t/ha; CO_{2T}: 7.038 ±12.288 t/ha; EV: 11.123 ±19.420 $/ha). The reference group chosen is that whose average carbon stock is less than or equal to the average of all groups.

There was a significant difference in carbon stock between the majority of species identity groups (Table 1). The carbon stock of seven species identity groups highlighted in Table 1 shows a positive and significant difference in contrast (p < 0.05) with the reference group. They carbon stock is 2.66 to 5.01 times higher than that of reference group, with little dispersion. Thus, they have a major impact on carbon storage, with effect sizes ranging from 0.744 to 1.325 for exotic species groups, and from 0.927 to 1.397 for native species groups.

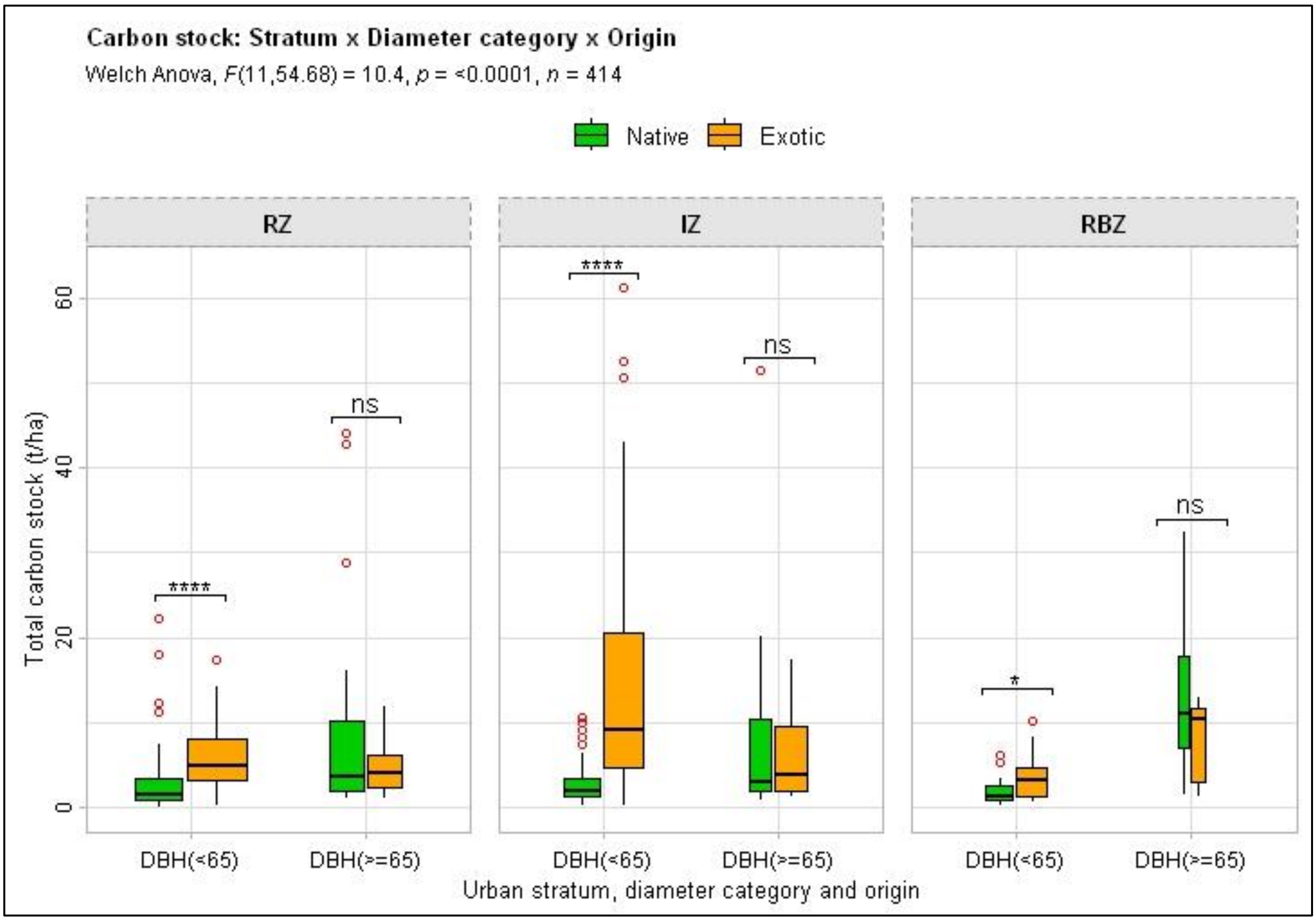

Figure 3. *Total carbon stock by origin and diameter category in urban strata. RZ – Residential zone; IZ – Institutional zone; RBZ – Road buffer zone; level of significance ("****": p<0.0001, "*": p<0.05, ns: Non-significant at 0.05).*

Thirteen species identity groups show a negative and significant difference in contrast (p<0.05) with the reference group. These groups are relatively modest importance to the carbon stock potential of the city. Their effect sizes ranging from -2.832 to -0.867 for exotic species groups, and from -2.071 to -0.831 for native species groups. The most illustrative group is that of exotic species with single leaves, semi-caducous foliage and disseminated by anemochory (Table 1).

As for the species identity groups showing non-significant contrast differences (p>0.05) in carbon stock with the reference group, their contribution to the total carbon storage is intermediate and centered around that of the reference group. Their effect size in carbon accumulation ranges from -1.709 to 0.306 for exotic species groups and from -2.321 to 0.990 for native species groups, but with a greater dispersion (Table 1).

4. Discussion

4.1. Assessing the Carbon Stock of Urban Strata

Plant primary production (biomass and its derived values) differs significantly between urban strata. The average of carbon stock is 14.389 t/ha, with an accumulation of 52.809 t/ha of carbon dioxide (CO_2), whose ecological value is estimated at $316.850/ha. These data show very wide variations (cv =100.042%) in carbon accumulation across urban strata. This dispersion greatly dilutes the potential of carbon storage on the city-wide scale. The quantity of carbon stored by trees in the city of Abomey-Calavi is much higher than that reported by [42] for the city of Cotonou. This difference is linked to the intensity of urbanization and tree architecture [80].

In terms of urban strata, institutional zone has the highest carbon stock, compared with the other two strata (RZ and RBZ). Ranking the strata on basis of their carbon stock potential yields the following IZ > RZ > RBZ. This ranking schema is relatively different from those reported for the cities of Cotonou [42] and Niamey [47], where it is the road buffer zone which accumulate, on average, more carbon than the institutional and residential zones. Major cities with an economic or business function of south Sahara are more urbanized than other cities in the same country. Cotonou and Niamey are two such cities. This special status, combined with absence of any real policy for selection and conservation of species with high carbon storage potential, has led the managers to focus solely on street trees for aesthetic reasons. Thus, reforestation efforts were mainly concentrated in this stratum, which explains the high contribution of road buffer zone compared with the other strata of these cities. Furthermore, the difference between RBZ and (IZ & RZ) is also linked to their carrying capacity. Species are less abundant in RBZ due to environmental constraints, especially the spatial constraints. Although there are several large-diameter trees, the density is not sufficient to increase overall carbon stock potential. The difference between strata (IZ & RBZ) and RZ is linked to the management method. As most RZ species are freely accessible or self-managed by their owners, they are constantly under the control of local population. Only sacralization still prevents the exploitation of some of them, including forest relics [81]. However, carbon storage capacity of the RZ species is necessary to maintain the essential functions of the urban ecosystem. In view of the densification of urban landscape, RZ must have a higher carbon productivity than the agrosystems they replace in order to maintain ecosystem balance [82, 83]. In addition, the carbon productivity of the urban flora shows that it is possible to obtain US$54,816.022 on the carbon market. The knowledge of the growth dynamics of species with high carbon accumulation potential and the forms of pressure exerted on them is needed to conserve this potential.

Table 1. *Descriptive characteristics (m ± σ) of carbon stock and statistical parameters of the GLM model as a function of species life-history traits. m ± σ: Mean ± Standard deviation of carbon stock by group; C_T: Total carbon; CO_{2T}: Carbon dioxide; EV: Ecological value; SCC: Contribution to carbon stock; ICo: Contribution index; β: Effect size; se: Standard error; origin: Exot – Exotic, Nati – Native; leaf form: SL – Single leaf, CoL – Composite leaf; foliage consistency: EF – Evergreen, SDF – Semi-caducous, DF – Deciduous; Mechanism of dissemination: AnChor – Anthropochory, ZoChor – Zoochory, AuChor – Autochory, NeChor – Anemochory; level of significance ("***": p<0.001, "**": p<0.01, "*": p<0.05, ns: Non-significant ar 0.05); p: p-value.*

N°	Identity group	C_T(t/ha)	CO_{2T}(t/ha)	EV ($/ha)	SCC (%)	ICo	β(se)	t-value	p-value	Signification
1	Exot + CoL + DF + AnChor	3.192 ± 4.10	11.716 ± 15.05	18.516 ± 23.78	2,821	1,032	1.008 (0.33)	3.044	0.0024	**
2	Exot + CoL + DF + NeChor	0.663 ± 2.43	2.432 ± 8.92	3.844 ± 14.10	1,331	0,352	-1.601 (0.26)	-6.177	0.0000	***
3	Exot + CoL + DF + ZoChor	0.693 ± 1.28	2.543 ± 4.68	4.019 ± 7.40	0,612	0,472	-0.867 (0.33)	-2.618	0.0090	**
4	Exot + CoL + EF + AnChor	1.753 ± 3.76	6.434 ± 13.81	10.168 ± 21.82	5,070	0,863	0.306 (0.24)	1.283	0.1998	ns
5	Exot + CoL + EF + AuChor	0.240 ± 0.30	0.880 ± 1.09	1.390 ± 1.72	0,019	0,423	-1.709 (0.93)	-1.837	0.0665	ns
6	Exot + CoL + EF + ZoChor	2.928 ± 3.62	10.747 ± 13.29	16.984 ± 21.01	10,822	1,900	0.744 (0.23)	3.262	0.0011	**
7	Exot + CoL + SDF + AuChor	0.825 ± 1.31	3.027 ± 4.81	4.783 ± 7.60	0,828	0,343	-0.512 (0.32)	-1.617	0.1063	ns
8	Exot + SL + DF + AnChor	2.047 ± 2.86	7.512 ± 10.49	11.872 ± 16.58	5,016	1,034	0.113 (0.25)	0.455	0.6492	ns
9	Exot + SL + DF + AuChor	2.983 ± 4.35	10.946 ± 15.96	17.299 ± 25.22	2,157	0,853	0.796 (0.36)	2.239	0.0254	*
10	Exot + SL + DF + ZoChor	0.274 ± 0.32	1.006 ± 1.17	1.589 ± 1.85	0,055	0,242	-1.522 (0.61)	-2.514	0.0121	*

N°	Identity group	C_T(t/ha)	CO_{2T}(t/ha)	EV ($/ha)	SCC (%)	ICo	β(se)	t-value	p-value	Signification
11	Exot + SL + EF + AnChor	4.152 ± 5.92	15.237 ± 21.73	24.08 ± 34.34	36,525	0,793	1.325 (0.20)	6.501	0.0000	***
12	Exot + SL + EF + AuChor	0.138 ± 0.11	0.505 ± 0.41	0.798 ± 0.65	0,039	0,212	-1.833 (0.52)	-3.517	0.0005	***
13	Exot + SL + EF + ZoChor	0.167 ± 0.16	0.613 ± 0.57	0.968 ± 0.91	0,114	0,156	-1.760 (0.36)	-4.848	0.0000	***
14	Exot + SL + SDF + AnChor(R)	1.872 ± 2.22	6.872 ± 8.14	10.86 ± 12.86	3,686	1,458	-0.440 (0.18)	-2.390	0.0170	*
15	Exot + SL + SDF + AuChor	0.106 ± 0.09	0.389 ± 0.32	0.615 ± 0.51	0,013	0,140	-2.028 (0.77)	-2.643	0.0083	**
16	Exot + SL + SDF + NeChor	0.060 ± 0.09	0.222 ± 0.34	0.350 ± 0.55	0,036	0,052	-2.832 (0.38)	-7.441	0.0000	***
17	Nati + CoL + DF + AuChor	0.946 ± 0.65	3.471 ± 2.39	5.485 ± 3.78	0,266	0,778	0.005 (0.52)	0.010	0.9919	ns
18	Nati + CoL + DF + NeChor	0.565 ± 0.73	2.075 ± 2.66	3.279 ± 4.21	0,091	0,665	-1.348 (0.67)	-2.010	0.0447	*
19	Nati + CoL + DF + ZoChor	0.310 ± 0.30	1.138 ± 1.12	1.799 ± 1.76	0,112	0,547	-1.138 (0.47)	-2.434	0.0151	*
20	Nati + CoL + EF + AnChor	3.642 ± 6.02	13.367 ± 22.09	21.125 ± 34.91	14,046	1,835	0.927 (0.23)	4.093	0.0000	***
21	Nati + CoL + EF + NeChor	0.574 ± 1.10	2.107 ± 4.04	3.330 ± 6.38	0,692	0,249	-0.831 (0.30)	-2.781	0.0055	**
22	Nati + CoL + EF + ZoChor	1.803 ± 0.71	6.616 ± 2.59	10.456 ± 4.09	0,145	3,179	0.990 (0.93)	1.064	0.2877	ns
23	Nati + CoL + SDF + AuChor	0.483 ± 0.64	1.772 ± 2.34	2.801 ± 3.70	0,194	0,532	-0.867 (0.45)	-1.937	0.0531	ns
24	Nati + SL + DF + AnChor	1.962 ± 2.41	7.199 ± 8.85	11.377 ± 13.99	3,073	0,843	0.317 (0.28)	1.145	0.2524	ns
25	Nati + SL + DF + AuChor	0.111 ± 0.11	0.406 ± 0.39	0.641 ± 0.62	0,013	0,195	-2.071 (0.77)	-2.700	0.0071	**
26	Nati + SL + DF + ZoChor	2.688 ± 4.20	9.867 ± 15.41	15.593 ± 24.36	1,404	3,625	-0.118 (0.40)	-0.293	0.7693	ns
27	Nati + SL + EF + AnChor	4.814 ± 8.56	17.668 ± 31.4	27.923 ± 49.62	6,189	3,671	1.254 (0.29)	4.279	0.0000	***
28	Nati + SL + EF + ZoChor	0.839 ± 0.77	3.080 ± 2.81	4.867 ± 4.45	1,584	0,695	-0.163 (0.26)	-0.621	0.5351	ns
29	Nati + SL + SDF + AuChor	0.131 ± 0.08	0.480 ± 0.28	0.759 ± 0.44	0,084	0,205	-1.784 (0.37)	-4.803	0.0000	***
30	Nati + SL + SDF + NeChor	0.063 ± 0.00	0.232 ± 0.00	0.366 ± 0.00	0,003	0,056	-2.321 (1.30)	-1.782	0.0751	ns
31	Nati + SL + SDF + ZoChor	18.425 ± 23.76	67.619 ± 87.19	106.865 ± 137.79	2,961	14,441	1.397 (0.67)	2.082	0.0376	*

(R) Reference identity group.

4.2. Importance of Diameter Category

Carbon stock increases with tree diameter. Individually, large trees make a greater contribution to carbon production than small-diameter stems. Large stems (DBH ≥ 65 cm) recorded in the city are less abundant (5.65% of total abundances), but accumulate 32.65% total carbon stock. The average carbon stock between the two diameter categories is relatively close (e.g. C_T = 9.692 ±10.030 t/ha for DBH < 65 and C_T = 8.466 ± 10.227 t/ha for DBH ≥ 65). This confirms the importance of large-diameter trees in carbon stock on the city-scale [32] and the need to take their growth dynamics into account in urban flora management policies [42, 80].

In the urban strata, average carbon stock of the stems DBH ≥ 65 cm is 1.01 - 2.51 times greater than that of stems DBH < 65 cm in the RZ and RBZ respectively. But it is 0.51 times lower than that of stems DBH < 65 cm in the IZ. This difference in trend between the diameter categories in (RZ & RBZ) and IZ can be explained by difference in abundance of large-diameter trees between these strata. In addition, these strata are not managed in the same way. In institutional zone, species are frequently maintained and renewed. They are mostly exotic and primarily selected for aesthetics or planting, unlike species in residential zone. Jaman *et al.* [84] have also shown the positive and significant effect of large-diameter trees on carbon stock.

Furthermore, the absence of strong inter- and intra-specific competition due to the isolation of the majority of trees in cities favors their mensuration. Trees are often low and branched, with canopy lengths exceeding 2/3 of their total height [41]. So, urban landscape favors the establishment of large-diameter trees with well-developed canopies. However, diameter growth and canopy development are essential for biomass accumulation. On this, large-diameter play an important role in urban ecosystem functioning and contribute significantly to primary production of urban forests [32, 85].

4.3. Influence of Life-historical Traits

The cumulative carbon stock of exotic identity groups (69.14%) is higher than that of native ones (30.86%). However, the average carbon stock of native identity groups is 1.80 times higher than that of exotic ones. The contribution index provides more precise idea of the individual contribution of each identity group. It averages 0.645 for exotic groups and 2.101 for native groups. Therefore, native species groups contribute 3.26 times more to carbon stock than exotic species groups.

The combination of structure and origin in the analysis highlights the importance of native species in carbon stock capacity of the city. The carbon production per species or group is very useful, as it enables to fine-tune the selection of species or groups which have a high carbon storage potential in order to achieve urban heat island mitigation. Although these species grow under the same environmental conditions, they differ significantly in their contribution to the city's carbon stock potential. Some of them contribute by abundance (number of individuals), others by section size.

The difference observed between species identity group can be explained by a combination of factors. It may be due to selection pressure, particularly in residential zone. It may also be explained by the species' strategy or temperament under environmental constraints. The primogeniture rules that native species seem to adopt, because of they belonged to the original environment long time before peri-urbanization, reflects their mobilization of resources for diametric growth. However, exotic species behave like species using "r" strategy as a mode of establishment, in order to persist in such a constraining environment as the city. They mainly use abundance as means of conquering this host environment. This is facilitated by forest management practices inherited from colonization and the preference of populations. Two important ecological processes (growth dynamics and colonization strategy) can explain the contribution of species to the total carbon stock potential of the city. Moreover, as exotic species are mostly fast-growing, they store more biomass in the first phase of their life cycle, but not throughout. In contrast, slow-growing native species, for the most part, store biomass throughout their cycle due to their high specific gravity [86].

Ten of the 31 species identity groups obtained account for 92.37% of total carbon stock. Among the exotic identity groups, species with composite leaves, evergreen foliage and disseminated by zoochory (e.g.: *Azadirachta indica* A. Juss. (ICo = 1.717)), and those with single leaves, evergreen foliage and disseminated by anthropochory (e.g.: *Eucalyptus camaldulensis* Dehnh. (ICo = 2.665)), accumulate the most carbon stock. Among the native identity groups, species with single leaves, semi-caducous foliage and disseminated by zoochory (e.g.: *Cola gigantea* A. Chev. var. *gigantea* (ICo = 21.501)), and those with single leaves, evergreen foliage, disseminated by anthropochory (e.g.: *Chrysophyllum albidum* G. Don (ICo = 3.944)) store the most carbon. These results reveal the importance of leaf type and foliage consistency in production and accumulation of carbon for the urban flora. Particular attention must be paid to these identity groups when planning flora or forests in urban environment. Their growth dynamics, spatial distribution and the services they provide should be monitored to conserve relevant traits. The carbon stock potential of these species despite environmental constraints underlines their resilience. Monitoring their populations would guarantee the effectiveness of the services they provide, as well as the proper functioning of the urban ecosystem in its current state. Species from these groups can be used to create urban reserves and botanical garden in order to ensure the conservation of native species and maximize city's carbon stock.

5. Conclusions

The potential of carbon stock of the city is 2489.374 t with ecological value of US$54816.022. The average carbon stock of the city is (C_T = 14.389 t/ha; CO_{2T} = 52.809 t/ha; EV = US$316.850/ha) with a very wide dispersion (cv = 100.04%). The institutional zone has higher carbon stock than the residential and road buffer zones. The mean carbon production differs significantly between urban strata (IZ > RZ > RBZ). The production of carbon is dominated by the stems DBH ≥ 65 cm in the strata RZ and RBZ. In contrast, it is the stems DBH < 65 cm that control the amount of carbon stored in ZI. The very wide dispersion of carbon stock in the strata, diameter categories or species origin is due to the nature of species contribution (number of individuals or size) to carbon stock. The exotic species produce 2 to 6 times more carbon stock than native species in DBH < 65 cm category. However, native species accumulate 2 times more carbon stock than exotic species in DBH ≥ 65 cm category. Thirty-one (31) species identity groups were identified (16 exotic and 15 native groups). Ten of these groups contribute more than 2% each to total carbon stock (92.37% of carbon potential). The group contribution index ranges from 0.052 to 1.900 for exotic species and from 0.056 to 14.441 for native species. In the exotic identity groups, species with composite leaves, evergreen foliage and disseminated by zoochory, and those with single leaves, evergreen foliage and disseminated by anthropochory, accumulate the most carbon stock. Among the native identity groups, they are species with single leaves, semi-caducous foliage and disseminated by zoochory, and those with single leaves, evergreen foliage and disseminated by anthropochory, which store the most carbon. The activities integrating ecological sustainability of cities will need to take into account the contribution of species historical life traits to maximize urban flora carbon stock potential. Managers need to select and promote species according to the dynamics of carbon accumulation in order to have long-term leverage to curb urban microclimate variability. In order to mitigate the effect of variation in overall carbon stock assessment at city scale, separate regressions of carbon stock could be developed according to diameter categories or species origin. Protocols for selecting, testing, adopting and raising public awareness of species with high carbon storage potential can be developed to facilitate the gradual integration of these species into people's habits and preferences, as well as into the standard of urban environment managers. Strategic forest reserves and botanical garden should be created to conserve species with high carbon stock potential. In this way, the growing effects of heat islands could be effectively mitigated and environmental education reinforced.

Abbreviations

RZ	Residential Zone
IZ	Institutional Zone
RBZ	Road Buffer Zone
h	Stem Height
V	Stem Volume
Bs	Stem Biomass
BEF	Biomass Expansion Factor
R	Roof Factor
BD	Basic Density
RMSE	Root-Mean-Square Error
IF	Goodness-of-fit Index
AIC	Akaike Information Criterion
BEF	Biomass Expansion Factor
BCF	Biomass Conversion Factor
CCF	Carbon Conversion Factor
B_T	Total Biomass
C_T	Total Carbon
CO_{2T}	Total Carbon Dioxide
EV	Ecological Value
t	Tons
GLM	Generalized Linear Model
SCC	Contribution of species or species identity group to carbon stock
ICo	Index of Contribution
CA_b	Relative Abundance of Species
sc_{ig}	Carbon Stock of Species i in Group g
sc_{ij}	Carbon Stock of Species i in any Group j
a_{ig}	Abundance of Species i in Group g
a_{ij}	Abundance of Species i in any Group j
g	Number of Groups
s	Number of Species
se	Standard Error
Exot	Exotic
Nati	Native
SL	Single Leaf
CoL	Composite Leaf
EF	Evergreen
SDF	Semi-caducous
DF	Deciduous
AnChor	Anthropochory
ZoChor	Zoochory
AuChor	Autochory
NeChor	Anemochory
p	p-value

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Conflicts of Interest

The authors declare no conflicts of interest.

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