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Citizens and urban greening: Do Bobo Dioulasso dwellers participate in greenhouse gas mitigation through urban forestry and greening?

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ABSTRACT

Urban trees and forests play a vital role in maintaining the balance of urban ecosystems and mitigating global warming. However, due to the lack of data and information on the potential of urban forests, their importance remains largely unknown. This study aims to describe citizens' perceptions of trees and assess the forest community's density, diversity, and carbon stock in the residential area of Bobo-Dioulasso, the second-largest city in Burkina Faso.

To carry out the study, tree inventories, and interviews were conducted on 240 selected dwellinghouses using a two-stage stratified sampling approach. The sample was allocated proportionally to three strata based on their population size: the center town (20 %), pericenter (20 %), and periphery (60 %). Trees were found in 86 % ± 0.5 % of dwellings, with an average of four trees per dwellinghouse (4 ± 1). About 63 % of households reported planting trees in their homes, including along roadsides. The main motivations for planting trees were for fruits, shading, and ornamental purposes. However, factors such as discomfort, property ownership, and management costs discouraged some residents from planting more trees.

A total of 934 trees belonging to 69 species and 30 botanic families were counted in the study sample. The most abundant species families were Anacardiaceae, Moraceae, and Moringaceae. *Mangifera indica* (41 %), *Ficus polita* (12 %), and *Moringa oleifera* (8 %) had the highest relative densities of all species found in dwellings.

Using existing allometric equations, the study estimated that the residential area trees stored about 210,000 tons of carbon dioxide equivalent. Based on these findings, it is recommended that city governments implement an action plan to promote urban forestry to strengthen and protect urban forest cover.

1. Introduction

In 2008, for the first time, more than half of the world's population lived in urban areas [1]. This proportion, which was 55.3 % in 2018, is growing and is expected to reach 68.4 % in 2050. Contemporary urbanization was initially a phenomenon in developed countries, as until the 1950s, 60 % of the urban population came from them [2]. However, since the 1950s, the share of the urban population in developing countries has grown steadily to equal and surpass that of developed countries from the 1970s. In 2050, urban

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populations in developing countries will approach 83 % of all cities [2]. Africa and Asia are experiencing particularly strong urbanization dynamics and will have urban populations of 58.9 % and 66.2 % respectively in 2050, whereas in 1950 they represented less than 20 % [1]. In Burkina Faso, for example, the proportion of the population living in cities has increased from 13.2 % in 1985 to 26.3 % in 2019 [3].

These statistics and future projections show that urban landscapes will become the habitat of the majority of human populations [4]. Between 1970 and 2000, the urban extension was estimated worldwide at 58,000 km^2 [5]. By 2030, the projected increase is between 0.30 and 2.3 million square kilometers, i.e., a relative increase of between 56 and 310 % [6] compared to the year 2000, with a growth in the urban population which would be around 70 % [7].

Unfortunately, this population and urban area growth lead to an amplification of land use changes and loss of forest land [8,9]. Indeed, cities dominate the global economy, where more than 90 % of the added value is generated [1]. There is a concentration of populations and economic activities with increasing demands for energy, water, and various infrastructures, sources of pressure on the environment at local, regional, and global scales [10]. In 2006, urban areas accounted for 67–76 % of energy consumption and 71–76 % of CO_2 emissions [6].

However, cities do not only have negative impacts and could be part of the solutions to the urban and global problems of the century in global climate change mitigation [1]. In addition, studies show that in most cases, the per capita ecological footprint of large agglomerations is lower than that of medium-sized towns and neighboring rural areas [5,10–12]. These differences are partly justified by more rationalized consumption and production patterns driven by a greater propensity for innovation in large cities [5,10].

Ignored in the 20th century by ecologists, urban forestry has emerged as one of the alternative strategies for managing the complex problems associated with urbanization in Africa and other tropical regions around the world [13], arousing growing attention and collaboration between ecologists, architects, planners, and other specialists [10]. Although several papers have highlighted the multiple services provided by trees [14–19], the contribution of citizens to urban greening and biodiversity maintenance through it remains little known in many cities, especially those in Africa. Ecological models predict that ecosystem productivity, standing crop, and resource use depend on species diversity [20]. Therefore, some studies have mentioned the close link between the loss in plant diversity and the decline of carbon storage [21,22]. In plantations older than 15 years, high species diversity can be beneficial to 20 % of the increase in standing biomass.

The scarce literature on the subject in West Africa is likely to result in insufficient consideration of urban trees in environmental

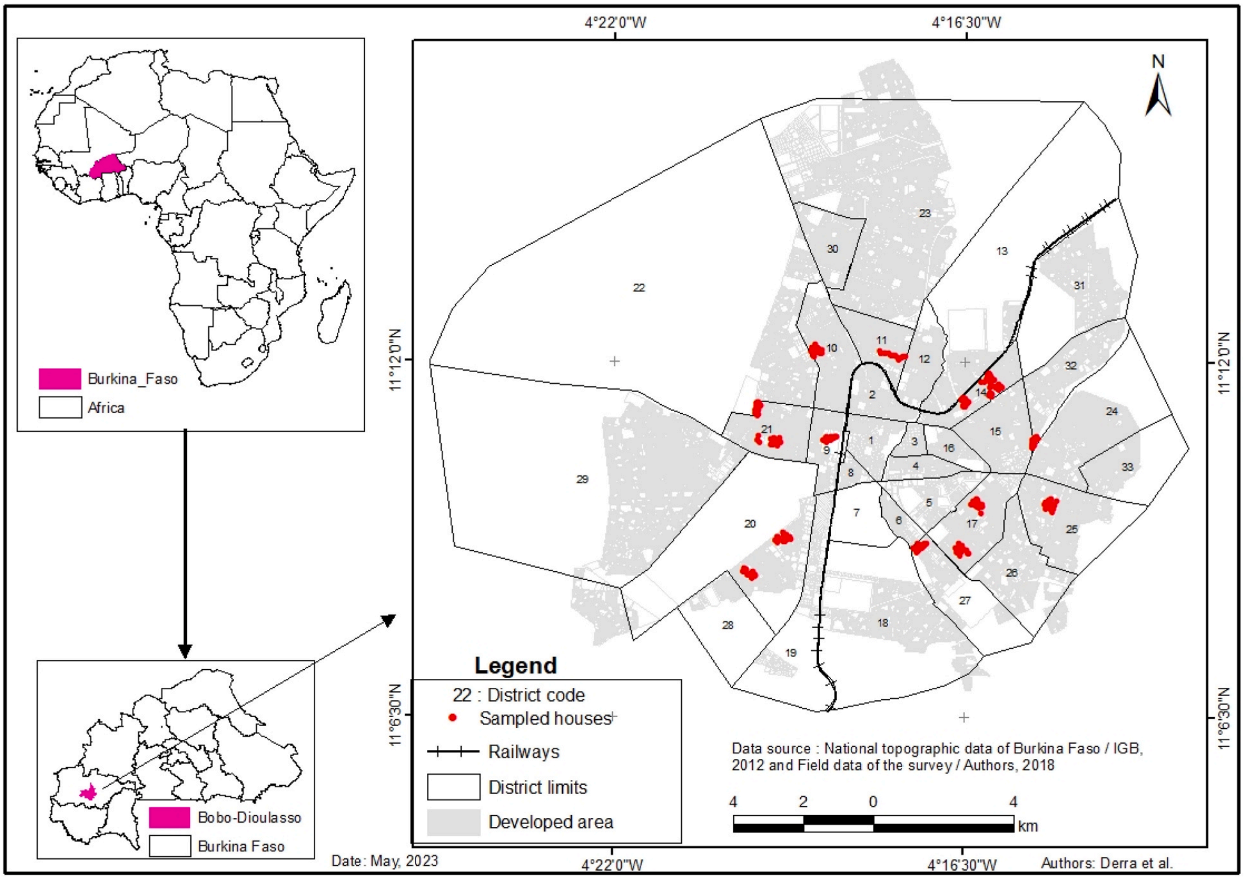

Fig. 1. Distribution of sampled dwellinghouses in the study area.

policies. While trees in cities can provide solutions to many urban problems, they are also threatened by climate change [18,23] and other environmental pressures, which require specific actions.

It is natural for the present study to focus on evaluating the diversity, structure, and carbon storage potential of trees to enhance the perception of the role of residential trees in mitigating the effects of climate change. Specifically, the study aims to highlight citizens' motivations and demotivation for trees, analyze the density, diversity, and community structure of trees in houses, and assess their carbon storage capacity. The choice of Bobo-Dioulasso, the second-largest city in Burkina Faso, aims to showcase the efforts of city dwellers in planting and maintaining trees, which, in the context of sustained urban expansion, constitute an important pool of sequestered carbon from city greenhouse gases. The efforts of city dwellers, supervised, supported, and promoted, can mitigate the negative effects of urbanization and make urban forestry an important tool in strategies for building green and safe cities.

2. Material and methods

2.1. Study area

Bobo-Dioulasso is a city located in the west of Burkina Faso at 350 km from the capital Ouagadougou (Fig. 1). It is the capital of Houet province and the Hauts Bassins region. The urban agglomeration is divided into seven (07) districts, subdivided into 33 sectors.

Bobo-Dioulasso is located in the southern Sudanian or pre-Guinean zone where the average annual rainfall varies between 900 and 1200 mm with an average water height of 1051 mm recorded over the period 2006 to 2016. In this time frame, the minimum and maximum monthly mean temperatures were 28 °C and 34 °C respectively [24].

The population of Bobo-Dioulasso increased from 489,967 in 2006 to 903,887 in 2019, with an average annual growth of 4.8 % [3]. If this rate is maintained, the city will have nearly 1.5 million inhabitants by 2030.

This population growth leads to an extension that increased the area of the agglomeration from 7904 ha in 1992 to 14,676 ha in 2018 [25], i.e., an increase of around 86 % and an average annual growth rate of 2.4 %. Although the rate of urban expansion remains lower than the rate of demographic growth, some periods such as that from 2002 to 2012 are marked by an average annual rate of urban expansion of 4.3 % before falling back to 1.2 % between 2012 and 2018.

Bobo-Dioulasso, the second economic hub after Ouagadougou, is home to 18 % of the country's formal businesses, these are divided into (04) sectors of activity, namely trade (64 %), state services (27 %), handicrafts (6 %) and industry (4 %) [25]. Industrial development is at an embryonic stage but is not without consequences for the urban environment, as evidenced by the overruns of Burkinabè standards and industrial wastewater evacuation standards [26].

2.2. Data collection

2.2.1. Sampling technique

The biological material refers to all trees present in the dwellinghouses, representing forest plots, which are the basic statistical units. The definition of optimal sample size and sampling approaches are important considerations for data collection.

In the absence of reference data, we start with the theoretical assumption that the proportion (P) of households with at least one tree planted in their compound is 0.5. Based on this assumption, we have determined that a sample size of 240 plots and respondents is optimal by solving equation (1) [27].

$$n^{*} = \frac{N * t_{\alpha}{}^{2} P(1-P)}{\left[N * k^{2} + t_{\alpha}{}^{2} P(1-P)\right]} \tag{1}$$

where n* represents the optimal sample, N is the size of the population (i.e., the total number of households in the city in 2006), k is the relative margin of error set at 5 % to account for budget constraints, and tα is the fractal of order α, read from the normal distribution table. For 95 % accuracy, tα is approximately 1.96.

For sampling, we conducted a two-stage stratified survey. The city was divided into three strata: the central stratum (the old and administrative core), the pericenter stratum, and the peripheral stratum. In the first stage of drawing, we randomly selected 15 enumeration zones, proportional to their size in terms of the number of inhabitants, out of the 507 that constitute the city. Enumeration zones (primary sampling units, PSU) are subdivisions of the population into geographical blocks, made by the National Institute of Statistics and Demography of Burkina Faso for statistical surveys.

The stratification was based on the hypothesis of a correlation between wood density and a gradient of city development, starting from a central, old core towards the periphery. We assumed that the planted area or density of trees is positively correlated with the age and area of the dwellinghouse [28,29], and these are potentially higher in older, developed areas. For example, its average size declines as one moves away from the center. Based on the city's cadastral data we estimated the average dwellinghouse area to be about 539 ± 354 m^2 in the center, 489 ± 122 m^2 in the pericenter, and 390 ± 127 m^2 in the periphery.

In the second stage of sampling, we randomly selected 16 plots for each primary sampling unit making a sample study with 240 plots.

Finally, the study sample was allocated proportionally to the population size of each stratum. Thus, the central and pericenter strata each received 48 plots, while the remaining 144 were allocated to the peripheral stratum.

2.2.2. Data collection

The tree inventory and respondent interviews took place from May 1st to May 10th, 2018 and involved a multidisciplinary team that was divided into two units: the forest inventory unit and the population perception survey unit.

The forest inventory unit surveyors were equipped with smartphones for mobile data collection, Pi tape, decameters, GPS, and forest inventory manuals (dendrometry and flora measurement techniques). They were instructed to count any tree located in the sampled dwellinghouse, whether indoors or outdoors in line plantations, with a diameter at breast height (DBH) of 3 cm or greater, taken at 1.30 m from the ground level. For branched trees below 1.30 m, all stems were measured. However, climbers were not included due to difficulties in measuring diameter.

Of the 240 sampled plots, the inventory finally covered 239, resulting in a response rate of 99.58 %. The one un-surveyed plot was unavailable due to the prolonged absence of its inhabitants.

In addition to the tree inventory, we interviewed one respondent from each sampled house about tree plantation, maintenance, motivations, and demotivation for urban trees. The response rate for the interviews was 95.88 % indicating good participation rate.

2.3. Data treatment

2.3.1. Statistical inference method

Statistical inference aims to extend sample information to the entire study area by considering the mean and total of selected variables of interest. The estimation method for these indicators is the one applied to the self-weighted two-stage design [30,30]. Thus, equations (2) and (3) were used to respectively estimate the total of any variable y and its mean $\bar{y}$.

$$t_y = \sum_{h=1}^{H} \sum_{i \in S_h}^{N_h} \sum_{j \in S_{hi}}^{M_{hi}} \omega_{hij} y_{hij} \tag{2}$$

$$\bar{y} = \frac{\sum_{h=1}^{H} \sum_{i \in S_h}^{N_h} \sum_{j \in S_{hi}}^{M_{hi}} \omega'_{hij} y_{hij}}{\mathrm{M}} \tag{3}$$

where $\omega_{hij} = \frac{1}{\pi_{hij}} = \frac{\sum_{i=1}^{N_h} M_{hi}}{n_h * m_{hi}}$ is the sampling weight of a sampled plot is represented by $\mathrm{w_{hij}}$, while π_{hij} denotes the inclusion probability in a stratum h (h = 1, 2, 3), each of which has a number of primary sampling units (enumeration zones named ZD) $\mathrm{N_h}$, from which only $\mathrm{n_h}$ is sampled. In each primary unit sampled in a stratum, a fixed number of plots ($\mathrm{m_{hi}}$) at 16 is drawn from the $\mathrm{M_{hi}}$ houses counted, according to the sampling design. The quantity M in equation (2) is an estimation of the size of the population of the study site, i.e., the total number of dwellinghouses in Bobo-Dioulasso.

We used the Jackknife resampling method to measure the accuracy of the mean and total indicators, as it leads to asymptotic consistency of the variance estimators [31,32]. Additionally, to compare the statistics of the three strata, we employed the Kruskall-Wallis rank tests, which offer better robustness because they are free of assumptions on the data distribution [33].

2.3.2. Density and horizontal structure

The density of trees in each sampled plot was determined by counting all trees with DBH $\geq$3 cm, whether they were located inside the compound or outside and bordering the roads. Using statistical inference as described above, we calculated the average number of trees per sample unit and the total stock of the forest community in the residential zone. Due to technical constraints, we were unable to directly measure the area of each plot. Therefore, we used the municipality cadastral database to derive the average density per hectare. However, due to restrictions on the cadastral database, we could only calculate the average area of the sample plots to be used for tree density per hectare at each stratum level. As a result, we could not compute standard errors for per-hectare density indicators.

Regarding the assessment of the horizontal structure of the forest community, the literature review led us to focus on a few statistical distributions. It was found that the Weibull [34–37], log-normal [37,38], and Johnson SB [39] distributions are commonly used to fit the shape of forest community structure in order to monitor their growth. While none of these distributions are universally applicable, the use of Weibull's fit is recurrent in the literature. Therefore, we fitted the stand structure with three parameters of the Weibull distribution, namely shape, scale, and location, and compared it with competing gamma and lognormal models.

In the case of Weibull distribution, the value of the shape indicator (c) determines the overall shape of the tree diameter distribution [34,40] and implies a given ecological interpretation [41].

Thus, for:

- $c < 1$, the distribution is in the form of an inverted J, characteristic of a multi-species stand with high regeneration potential,
- $c = 1$, exponentially decreasing distribution characterizing a stand with high regeneration potential but facing a survival problem,
- $1 < c < 3.6$, mound-shaped positive skewness highlighting an artificial multispecies stand with a predominance of young, small-diameter individuals,
- $c = 3.6$, the distribution is that of a normal distribution, characteristic of populations of species with low regeneration potential due to exogenous actions or characteristics of the species,
- $c > 3.6$, distribution progressively tending towards negative skewness and illustrating an aging multispecies stand dominated by large-diameter trees.

2.3.3. Calculation of diversity indices

In ecology, different statistical descriptors are used to characterize the diversity of a community. In this study, species diversity was assessed based on stand richness (S), Shannon-Weaver (H′), Simpson (SDI), and Pielou (J) diversity indices. Some of these indices and those of the dendrometric parameters were used to calculate indices of different species importance values (IVI).

The richness of the stand is measured by the number of species inventoried (S).

The Shannon-Weaver index, H′ was calculated through equation (4) for the whole stand and disaggregated according to the three strata:

$$H' = -\sum_{i=1}^{S} p_i \, ln(p_i) \tag{4}$$

Where p_i is the proportional abundance of a found specie $\left(p_i = \frac{n_i}{N}\right)$; $ln(p_i)$ the natural logarithm of this proportion. n_i is the number of individuals counted for a specie, N is the number of individuals in the stand whose species cardinal is S.

The Shannon-Weaver index varies from zero to a maximum value given by $H'_{max} = ln(S)$ [42]

The Simpson diversity index (SDI) was calculated according to the system of equation (5) and varies from zero to one:

$$SDI = 1 - D, où \; D = \sum_{i=1}^{S} \frac{n_i(n_i - 1)}{N(N-1)} \tag{5}$$

The Pielou equitability index (J) in equation (6) is defined as the ratio of the Shannon-Weaver index (H′) to its maximum value (H'max) and varies from zero to one:

$$J = \frac{H'}{H'_{max}} = \frac{H'}{ln(S)} \tag{6}$$

Each of the above-mentioned indices has limitations in terms of its ability to capture the species diversity of a stand on its own. Therefore, interpreting a large number of indices is generally accepted to improve the understanding of the diversity of a stand.

The species diversity indices were calculated using the vegan package, version 2.5–7 [43], while the comparison tests for the Shannon-Weaver index were performed using the ecolTest package, version 0.0.1 of the R program [44].

Finally, we calculated the importance value index (IVI) to assess the ecological importance of each species α [42,45], following equation (7):

$$IVI_\alpha = (RD_\alpha + DOM_\alpha + RF_\alpha) * 100 \tag{7}$$

RD_α is the relative abundance of species α, calculated by relating the number of individuals of the species to the total stand size.

DOM_α is the relative dominance of the species α, calculated by relating the total basal area of the species, measured at 1.30 m from the ground, to that of the total stand studied.

RF_α is the relative frequency of occurrence of the species in the plot, calculated by dividing the frequencies of occurrence of the species by the sum of all frequencies of occurrence.

2.3.4. Method for predicting biomass and stored carbon

Allometry is used to establish equations or relationships between different parts of a living organism, specifically plants [46]. For trees, allometry enables the prediction of a measurement (e.g., biomass) from another easily obtainable measurement (dendrometry parameters).

While the theoretical foundations of allometry are clear, the selection of relevant variables to explain the parameters of interest leads to divergences, each supported by empirical results. In the elaboration of allometric equations for above-ground biomass, the use of DBH is most frequent in the literature, appearing in 63 % of biomass equations in Sub-Saharan Africa, compared to 15 % for height, 8.6 % for girth ($c_{1.30}$), and 6 % for basal area, with a diversity of functional forms [47].

Due to a lack of allometric equations for some ecological zones, notably in Sub-Saharan Africa [47], the pantropical model [48,49] has long been an alternative [50]. Although it has proven to be accurate at times [51,52], the generic pantropical model tends to lose the comparative predictive advantage over local models and small geographic areas [50,53–56].

To avoid destruction of city trees, we preferred the use of existing allometric equations adapted to our study site climate. In this regard, the allometric equations developed for settlement land categories on Sudanian savanna zones [45] which are similar to our study area caught our attention. They revealed to provide practical equations for assessing the carbon stock of a sufficiently diversified taxonomic stand. These equations only use one predictor, which is diameter (DBH). Based on a sample of 63 trees for the land use category considered, the empirical allometric equation found is given in equation (8):

LnBA = 2.454958 + 0.091898*DBH [45]

$$(0.011445) \; (0.003292) \tag{8}$$

The numbers in parentheses are the standard errors of the estimates. However, these allometric equations are valid for trees with diameters lying between 9.2 cm and 57.9 cm, i.e., 80 % of our trees sample. Therefore, the prediction of the biomass of DBH trees outside the validity range was made by using the generic pantropical model in a situation where tree height was not measured, as given by equation (9).

$$\text{AGB} = \exp\left[-1.803 - 0.976 * E + 0.976 * \ln(\rho) + 2.673 * \ln(DBH) - 0.0299 * [\ln(DBH)]^2\right] \tag{9}$$

Where AGB is the above-ground biomass, BGB is the below-ground biomass, and ρ is wood-specific gravity. The stress factor E is a function of fluctuations in ambient temperature (TS), maximum water deficit (CWD), and variations in monthly rainfall (PS) over a year, as mentioned earlier [49].

For the pantropical approach, the biomass estimation was performed using the BIOMASS package, version 2.1.4, of the R program [57]. The estimation was done for trees with diameters between 5 and 9.2 cm and above 57.9 cm. The wood-specific densities database, ρ [58], was used for this purpose. Trees with diameters smaller than 5 cm were excluded as their biomass was considered negligible [59].

To account for belowground biomass, the root/shoot ratio was used, despite the limitations of this approach [60–62].

Finally, the total biomass of a single tree was estimated using equation (10):

$$Total\ biomass\ (tonne) = AGB_{est} * (1 + RSR) \tag{10}$$

Where AGB is the above-ground biomass and RSR is the below-ground biomass ratio with a default value of 0.28 in dry tropics [63].

Finally, the conversion of total biomass to carbon is done by multiplying with the fraction of carbon in biomass, which has a default value of 0.5 [64].

3. Results

3.1. Motivations and demotivation for trees in dwellinghouses

The tree inventory revealed that 86.1 % ± 0.5 % of houses had at least one tree. Additionally, 63.1 % of residents, including 93 % of homeowners and 12 % of tenants, have planted trees in their residence or the alignment of their homes and have taken care of them. Maintenance practices include watering, pruning of young plants, and protecting them from breakage and wind. For mature trees, common maintenance practices involve pruning branches that pose safety challenges to humans and infrastructure.

Three main motivations for planting trees were identified during interviews (Fig. 2a). The need for edible fruits was the first motivation and was cited by 38 % of respondents. The next most important motivation was the need for shade, expressed by 34 % of the respondents. Finally, the beauty of the houses ranked as the third motivation with 12 % of the opinions recorded.

In addition, residents revealed factors that discourage them from having trees in their yards. In order of importance, these factors include discomfort related to the presence of trees, property rights to housing, and the cost of maintenance (Fig. 2b). The cost of maintenance, mentioned in 4 % of opinions, includes both the financial resources required for trees and the time invested in them.

Discomfort, expressed in 68 % of opinions, includes all the dissuasive factors reported by the interviewees, such as cluttered space, darkness caused by the foliage, management of residues (branches and dead leaves), and attraction of animals (especially insects). Property rights to housing represent 25 % of the demotivation factors cited by respondents, with tenants being less motivated than owners.

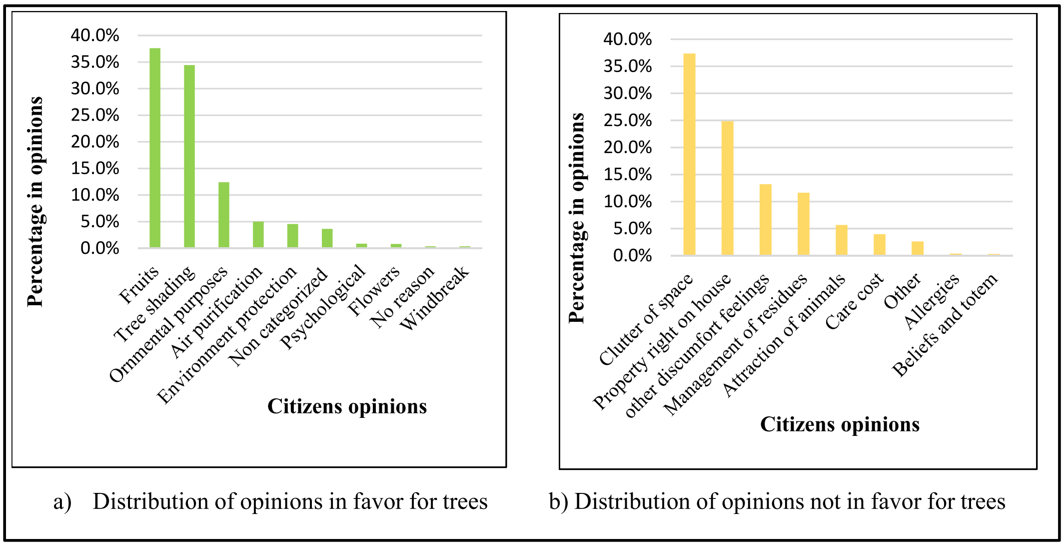

Fig. 2. Bobo-Dioulasso inhabitants' motivations and demotivation for dwellinghouse trees

3.2. Density and horizontal structure of compound trees

Based on the statistical inferences from the study sample, the average number of trees per dwelling unit was found to be 3.9 ± 0.04. When this is related to the average area of dwellinghouses estimated from a secondary data source (416 ± 182 m^2), the density of residential trees is estimated to be approximately 94 trees per hectare. Similarly, the density of trees per hectare was estimated to be 102 in the central stratum, 61 in the pericenter, and 76 in the periphery.

A Kruskal-Wallis test was conducted to compare the distribution of trees in the three strata, and significant differences ($p < 0.05$) were observed (Fig. 3). Post-hoc Steel-Dwass test [63] showed that the density distribution in the central stratum, with a mean of 5.52 ± 0.14, was significantly different from that of the other two strata, namely the pericenter ($p = 0.006$) and the periphery ($p = 0.04$), which had means of 3.0 ± 0.08 and 3.7 ± 0.05 respectively.

The diameters of the trees in the sample ranged from 3.0 to 101 cm, with an average of 26.3 ± 0.3 cm. Their distribution (Fig. 3) also varied significantly between the three strata ($p < 0.05$). Post-hoc Steel-Dwass test indicated that the tree diameter distribution in the peripheral stratum, with a mean of 27.3 ± 0.4 cm, was significantly different from that of the pericentral stratum ($p = 0.01$), with a mean of 25.4 ± 0.5 cm, and the central stratum ($p = 0.06$), with a mean of 24.4 ± 0.4 cm.

Fitting our observations through the R packages forestfit [64] and fitdistrplus [65] by Weibull distribution provided a shape parameter equal to 1.22 and a mound-shaped, straight asymmetric curve (Fig. 4). According to the Akaike Information Criteria (AIC) and the Bayesian Information Criteria (BIC), the Weibull model has a better fit (AIC = 7805.5, BIC, 7815.17) than the Gamma (AIC = 7814.98, BIC = 7824.659) and the Logistic-Normal (AIC = 7901.517, BIC = 7911.196).

The shape of tree diameter distribution is similar to that of an uneven-aged or multi-species artificial forest with a predominance of small to medium-diameter individuals.

3.3. Floristic richness and diversity

The inventory of the forest revealed a specific richness of 69 species belonging to 60 genera and 30 families. The relative densities of Anacardiaceae (44 %), Moraceae (16 %), and Moringaceae (9 %) are the highest in the community. Regarding species, 44 of them, or 64 %, are exotic species. *Mangifera indica*, found in 72 % of the city's dwellinghouses, has a predominant place in the stand with an importance value index (IVI) of 132 (see annex).

The specific diversity indices (alpha diversity) are summarized in Table 1. The measurements of the Shannon-Weaver index are above 50 % of the entropy values (H'max), illustrating the heterogeneity of the stand. The Shannon-Weaver diversity index at the city level is 2.65, or 62.7 % of the maximum entropy value, with the index closest to the maximum value in the pericentral area.

The Simpson diversity index (SDI) has values above 0.7 for the city and all strata. Thus, at the city level, the probability that a pair of randomly selected plants are of different species is 0.81, with the probability being higher in the pericentral stratum where it reaches 0.84.

Lastly, the Piélou equitability index (J) reaches 0.63 over the whole city and has its highest value (0.72) in the pericentral stratum.

3.4. Carbon storage capacity

The results indicate that the average carbon stock in trees per dwellinghouse is 0.97 ± 0.03 tons (Table 2). When this value is

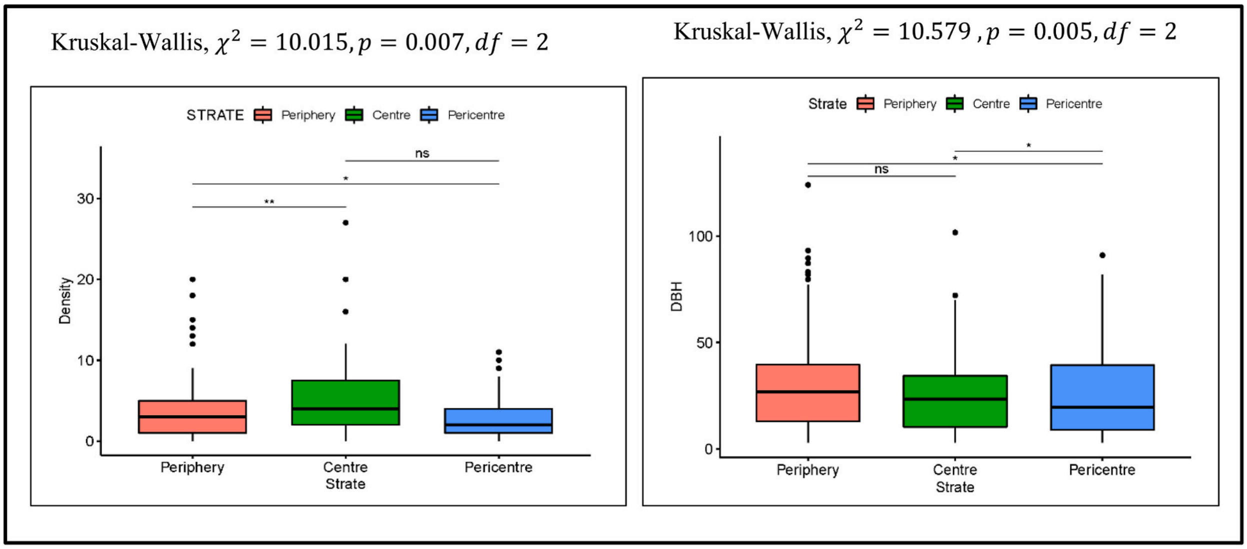

Fig. 3. Tree density and DBH distribution along city stratum.

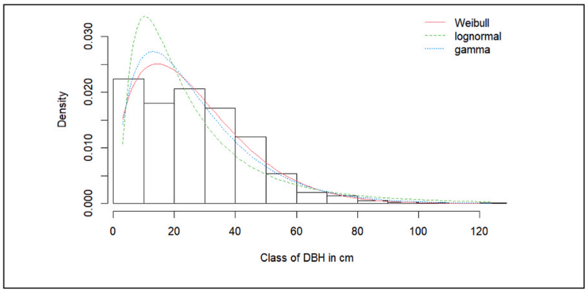

Fig. 4. Histogram and theoretical probability densities of trees community.

Table 1
Summary of alpha diversity indices.

Specific diversity index	Global	City centre	Pericenter	Periphery
Shannon-Weaver (H′)	2.65	2.47	2.39	2.61
H'max	4.23	3.66	3.30	4.13
H' as % of H'max	62.7 %	67.5 %	72.5 %	63.3 %
Simpson's Index (SDI)	0.81	0.82	0.84	0.79
Simpson's inverse (1/D)	5.14	5.41	6.19	4.8
Pielou equitability index (J)	0.63	0.68	0.72	0.63

Table 2
Carbon storage capacity.

Stratification unit	*Average carbon stock (t) and standard error*	*Total carbon stock (t) and standard error*
City centre	1.04 ± 0.01	11 822 ± 194
Pericenter	0.88 ± 0.05	5853 ± 380
Periphery	0.96 ± 0.04	39 766 ± 1248
Whole city	0.97 ± 0.03	57 441 ± 1319
Kruskal-Wallis chi-squared and significancy (in parenthesis) at df = 2	1.207 (0.5469)	Not estimated

related to the average surface of the houses parcels, the carbon stock is 22.41 per hectare. A non-parametric Kruskal Wallis test did not show a significant difference in carbon stock mean between the three strata ($P > 0.1$). At the residential area level, the total carbon stock of the trees studied in 2018 is estimated at 57,441 ± 1319 tons or 210,618 tons of CO_2.

Furthermore, when considering all species, a single tree has an average carbon stock estimated at 263.25 ± 6.8 kg. Moreover, 55 % of the carbon stock is held by trees with a diameter at breast height (DBH) greater than 45 cm, even though these trees only make up 9 % of the stand.

4. Discussion

4.1. Contribution of households to urban greening and the supply of ecosystem services provided by trees

We found that more than six out of ten households have planted trees in their plots. For homeowners, this proportion is nearly nine out of ten households. Several factors were important in the decision to plant or not to plant trees. Among the motivating factors for having trees in the yard, we noted that the need for fruit, shade, and yard beauty is preponderant. There is consistency between the motivations of urban residents and the composition of trees in the houses, dominated by fruit trees such as *Mangifera indica* (the most abundant), those with strong shade such as *Ficus polita* (the second most abundant species), and beautiful trees such as *Cascabela thevetia* (the fourth most abundant species). Moreover, the motivations are quite similar to the literature on the benefits of urban trees [13–16,66]. The reasons expressed for limiting the planting of trees, such as discomfort and maintenance costs, are also similar to those found in the literature [14,66,67].

However, given the high proportions of households advocating the "fruit, shade, and beauty" trio, it is quite likely that city dwellers only understand the concrete services provided by trees, ignoring other major ecosystem services recognized at the environmental, social, and economic levels [19,67,68].

The proportion of dwellinghouses with at least one tree is 86.1 % with an average number of about 4 plants per house. A similar study in three South African towns known as Tzannee, Bela Bela, and Zeerrust, found that 90 % of the dwellinghouses had trees with an estimated average number of trees evaluated to 7.7 ± 6.1 [69]. While there are several reasons for these differences, the divergence in tree selection criteria between the two studies should be noted. In the south African three cities study cited above, all trees were recorded in each plot, whereas in our case, only individuals with a DBH of at least 3 cm were included.

The density of 94 trees per hectare found in this study remains similar to or higher than the tree cover in 55 % of the country's rural communes [70].

The high proportion of homeowners who have planted trees in their plots highlights their contribution to the greening of the city and the supply of tree ecosystem services.

These findings suggest that urban dwellers who are ecologically aware can help mitigate the negative effects of urbanization on forest potential. Therefore, the notion that urban dwellers only contribute to deforestation needs to be qualified [69], rather, it is the complete clearing of trees during the construction of residences that causes landscape degradation and loss of diversity [69].

The average density of trees is higher in the central core than in the other two strata. This result is not due to a cultural difference in planting but rather reflects differences in the size of the housing plots. The central stratum includes the oldest developed areas with the largest housing plots. As urbanization increases, the high demand for housing combines with shrinking land areas, leading to severe space constraints in dwellinghouses developed in pericentral and peripheral zones, limiting planting efforts. This finding is consistent with the idea of positive relationship between the canopy index and available planting space [29].

Furthermore, the stand structure is similar to that of an uneven-aged forest, with a significant presence of juvenile and young growing trees (DBH≤25 cm), medium-diameter trees (DBH between 25 and 50 cm), and a low proportion (9 %) of large-diameter trees. This structure indicates good plantation dynamics, although the low proportion of large-diameter trees is a concern. Natural mortality or management methods that involve removing old trees for various reasons, including housing security, may explain the under-representation of large-diameter trees, as suggested by some households interviewed about their tree management practices.

4.2. Trees diversity and ecosystem resilience

The richness and diversity of the forest stands in dwellinghouses were assessed in this study. Indeed, a richness of 69 species belonging to 60 genera and 30 families was observed. Our results are similar to the city of Parakou and Kpalimé where *Mangifera indica* and the Anacardiaceae family were found to be predominant in dwellinghouses [71,72]. According to the Shannon-Weaver and Simpson's inverse indices, our site recorded values of 2.65 and 5.14, respectively, compared to 1.27 and 4.11, respectively, measured by the second national forest inventory in the rural area of Bobo Dioulasso [70]. This suggests that the urban area is more diversified in ligneous species. Heterogeneity is specifically higher in urban ecosystems, highlighted by Pielou's index (0.63–0.72). This situation is due to a greater presence of exotic species [73,74], which may be the result of socioeconomic and cultural factors [75,76] that are more diverse in cosmopolitan environments such as cities [77]. Our results on diversity are similar to those found for the city of Accra, where 70 species belonging to 30 families were recorded [78]. However, the richness of the residential environment in Bobo-Dioulasso remains higher than that for the city of Lokossa [42] but lower than the statistics for Niamey and Maradi cities [77].

This diversity is important for the urban ecosystem as it increases its resilience by making it more capable of suppressing diseases and epidemics while significantly reducing pathogen transmission [76,79]. Forests, including those in urban areas, dominated by a few species are prone to the potentially devastating effects of insect pests, plagues, and epidemics [76].

4.3. Contribution of residential trees to greenhouse gas reduction

Urban trees offer a solution for adapting to global warming in urban environments, but their impact on GHG mitigation is limited due to space constraints in cities [80]. However, with an increased emphasis on urban greening, along with adequate maintenance, urban trees can become significant carbon sinks while improving the living environment. As urbanization increases rapidly in some parts of the world, making cities sites for carbon sequestration and storage through greening becomes a necessity. In our study area, the residential area alone has an estimated carbon stock in trees of nearly 57,000 tons or 210,000 t of CO_2 equivalent. Based on the carbon footprint of a Burkinabè estimated at 0.22 tons per year [81], we calculated that the amount of CO_2 removed from the atmosphere by plants in our study area is equivalent to the annual emissions of a Burkinabè city of about 1 million inhabitants, which is approximately Bobo-Dioulasso.

When related to the average surface area of dwellinghouses, our study's carbon stock is 22.41 t C ha^{-1}, which is similar to that of aboveground biomass in rural environment trees of Burkina Faso (22.76 t C ha^{-1}), as calculated by the second national forest inventory [70].

4.4. Implications for urban forestry policy

The study revealed the presence of a diverse and important forest stand in the residential area of Bobo-Dioulasso, offering potential ecosystem services that benefit the local and global environment as well as city dwellers. However, the urban trees are vulnerable to various environmental stress factors, including climate change, air pollution, low humidity, and extreme weather events. Moreover, urban trees are often threatened by destruction and mutilation due to development purposes. To address this issue, promoting urban forestry practices is crucial to provide information and guidance for tree-planting populations to make appropriate choices and maintenance techniques in line with climatic challenges and opportunities.

The study also found that carbon storage is strongly dependent on a few species, namely *Mangifera indica* and *Ficus polita*, as well as large-diameter trees. This indicates that the objective of high carbon sequestration potential can be achieved through tree maintenance and improving growth, especially in open spaces and urban environments. However, the urban environment is marked by heavy transport traffic and high demographic pressure, generating significant pollution and stress that can affect trees and reduce the quality of the services they provide. Therefore, low-carbon urban development policies are needed to achieve a green city.

While changing individual attitudes towards trees may be difficult, channeling reforestation efforts into public urban areas can increase the city's reforestation potential.

5. Conclusion

This study presents data on urban trees in the city of Bobo-Dioulasso, aimed at policymakers, urban planners, and urban ecology researchers, and contributes to reducing the inadequate knowledge of urban forests and trees in Burkina Faso and West Africa. The study shows that trees are present in almost all housing dwellinghouses in appreciable densities, similar to the surrounding natural vegetation, and exhibit better diversity due to exotic species such as *Mangifera indica* being dominant. However, the services provided by urban trees go beyond their edible or shade-providing attributes.

The study also assesses the potential of these trees to contribute to the reduction of greenhouse gas emissions and found that they have the capacity to reduce the equivalent annual emissions of a Burkinabè city of one million inhabitants. This contribution could have been even greater if all land-use categories in the city (parks and gardens, services and institutions, administrative reserves, wetlands, etc.) were considered. However, urban trees face various stress factors related to the urban environment, climate change, and uncertainty. Therefore, it is crucial to implement actions that preserve and consolidate urban forests as a whole.

It is important to consider the inclusion of urban forests and trees in climate change response plans at national and local levels. Rapid urbanization makes it necessary to turn cities into carbon sequestration sites by promoting natural sinks such as trees.

At the level of the urban commune of Bobo-Dioulasso, this study calls for the development and implementation of an action plan focused on the management of the city's forest stand in general and trees in dwellinghouses more specifically. Such an action plan should popularize good urban forestry practices for the benefit of households and implement incentive mechanisms to increase the planted areas in household residences.

To go further, developing countries could include future urban forestry developments and trees in dwellinghouses in the clean development mechanism. This would create a strong impetus for tree planting in urban areas, contribute to the stabilization of greenhouse gases, and help meet their quantified emission limitation and reduction commitments.

However, three main limitations of this study should be made explicit for future investigations. Firstly, the tree inventory, due to financial constraints, only covered dwellings, excluding other categories of land with high tree potential (urban parks and gardens, institutions and services, administrative and land reserves). Also, the collection only concerned woody plants with DBH$\geq$3 cm; even woody vines were not inventoried to limit errors in measuring DBH.

Secondly, the study did not rely on a quantitative assessment of the ecosystem services of yard trees, except for stored carbon, to inform the extent of the functions they play in the urban environment. For some functions, such as carbon sequestration, long-term monitoring of yard trees is needed to assess forest dynamics.

Finally, it is important to note that the calculation of stocks per hectare (number of trees and quantity) was carried out using secondary data that do not allow for an appreciation of the magnitude of estimation errors. Additionally, the inclusion of trees in line plantations belonging to the sampled plots is likely to overestimate the densities per hectare to some extent.

Author contributions statement

Dr. Sidnoma Abdoul Aziz Traoré: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Dr. Gouwidida Elice Kaboré: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Harouna Derra: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Data availability statement

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e21181.

Annex.

A: Important Value Index of species in the study area

Species	Family	Origin	Density in the sample	Frequency (%)	Relative frequency (%)	Relative density (%)	Relative dominance (%)	Importance Value Index
Mangifera indica	Anacardiaceae	Exotic	381	71.5	29.4	40.8	61.9	132.1
Ficus polita	Moraceae	Native	109	31	12.7	11.7	9.7	34.1
Moringa oleifera	Moringaceae	Exotic	80	14.2	5.9	8.6	0.8	15.2
Gmelina Arborea	Lamiaceae	Exotic	15	4.6	1.9	1.6	3.2	6.7
Delonix regia	Fabaceae	Exotic	18	2.5	1	1.9	3	6
Adansonia digitata	Malvaceae	Native	17	5.9	2.4	1.8	1.4	5.7
Ficus benjamina	Moraceae	Native	14	4.2	1.7	1.5	1.7	4.9
Ficus platyphylla	Moraceae	Native	9	2.5	1	1	2.9	4.9
Cascabela thevetia	Apocynaceae	Exotic	25	4.6	1.9	2.7	0.2	4.8
Azadirachta indica	Meliaceae	Exotic	12	4.2	1.7	1.3	1.6	4.6
Senna siamea	Fabaceae	Exotic	12	4.2	1.7	1.3	1.3	4.3
Citrus auranthium	Rutaceae	Exotic	16	4.6	1.9	1.7	0.2	3.8
Ficus umbellata	Moraceae	Native	6	2.5	1	0.6	2	3.7
Bougainvillea spectabilis	Nyctaginaceae	Exotic	19	3.8	1.5	2	0.1	3.7
Spondias purpurea	Anacardiaceae	Exotic	12	3.3	1.4	1.3	0.4	3.1
Citrus limon	Rutaceae	Exotic	11	4.2	1.7	1.2	0.1	3
Polyalthia oblongifolia	Annonaceae	Exotic	15	2.9	1.2	1.6	0.2	3
Annona squamosa	Annonaceae	Exotic	13	3.8	1.5	1.4	0	3
Artocarpus heterophyllus	Moraceae	Exotic	8	3.3	1.4	0.9	0.4	2.6
Vernonia colorata	Compositae	Native	8	3.3	1.4	0.9	0.1	2.3
Lannea microcarpa	Anacardiaceae	Native	6	2.5	1	0.6	0.5	2.1
Unidentified species[3]	unknown		8	2.5	1	0.9	0.1	2
Newbouldia laevis	Bignoniaceae	Native	8	2.1	0.9	0.9	0.2	1.9
Calotropis procera	Apocynaceae	Native	6	2.5	1	0.6	0.2	1.9
Ziziphus mauritiana	Rhamnaceae	Native	5	2.1	0.9	0.5	0.4	1.8
Eucalyptus camaldulensis	Myrtaceae	Exotic	4	1.7	0.7	0.4	0.6	1.7
Psidium guajava	Myrtaceae	Exotic	6	2.5	1	0.6	0	1.7
Casuarina equisetifolia	Casuarinaceae	Exotic	6	2.1	0.9	0.6	0.1	1.6
Anacardium occidentale	Anacardiaceae	Exotic	5	2.1	0.9	0.5	0.2	1.6
Phoenix dactylifera	Arecaceae	Exotic	3	1.3	0.5	0.3	0.7	1.6
Borassus aethiopum	Arecaceae	Native	3	1.3	0.5	0.3	0.7	1.6
Parkia biglobosa	Fabaceae	Native	2	0.4	0.2	0.2	1.1	1.4
Terminalia mantaly	Combretaceae	Exotic	3	0.8	0.3	0.3	0.7	1.4
Vitellaria paradoxa	Sapotaceae	Native	3	1.3	0.5	0.3	0.4	1.2
Albizia lebbeck	Fabaceae	Exotic	3	1.3	0.5	0.3	0.4	1.2
Jatropha curcas	Euphorbiaceae	Exotic	4	1.7	0.7	0.4	0	1.1
Lawsonia inermis	Lythraceae	Exotic	4	1.7	0.7	0.4	0	1.1
Hura crepitans	Euphorbiaceae	Exotic	3	1.3	0.5	0.3	0.2	1.1
Roystonea regia	Arecaceae	Exotic	3	0.8	0.3	0.3	0.3	0.9
Saba senegalensis	Apocynaceae	Native	3	1.3	0.5	0.3	0	0.9
Ficus thonningii	Moraceae	Exotic	3	0.8	0.3	0.3	0.2	0.8
Duranta erecta	Verbenaceae	Exotic	6	0.4	0.2	0.6	0	0.8
Balanites aegyptiaca	Zygophyllaceae	Native	2	0.8	0.3	0.2	0.2	0.8
Acalypha amentacea	Euphorbiaceae	Exotic	2	0.8	0.3	0.2	0.2	0.7
Cordia myxa	Boraginaceae	Exotic	2	0.8	0.3	0.2	0.1	0.7
Clerodendrum inermis	Lamiaceae	Exotic	3	0.8	0.3	0.3	0	0.7
Tamarindus indica	Fabaceae	Native	2	0.8	0.3	0.2	0.1	0.6

(*continued on next page*)

(*continued*)

Species	Family	Origin	Density in the sample	Frequency (%)	Relative frequency (%)	Relative density (%)	Relative dominance (%)	Importance Value Index
Leucaena leucocephala	Fabaceae	Exotic	2	0.8	0.3	0.2	0	0.6
Bauhinia rufescens	Fabaceae	Native	2	0.8	0.3	0.2	0	0.6
Theobroma cacao	Malvaceae	Exotic	2	0.8	0.3	0.2	0	0.6
Elaeis guineensis	Arecaceae	Native	1	0.4	0.2	0.1	0.3	0.6
Ligustrum vulgare	Oleaceae	Exotic	2	0.8	0.3	0.2	0	0.6
Cocos nucifera	Arecaceae	Exotic	1	0.4	0.2	0.1	0.2	0.5
Borassus akeassii	Arecaceae	Native	1	0.4	0.2	0.1	0.2	0.4
Blighia sapida	Sapindaceae	Native	1	0.4	0.2	0.1	0.2	0.4
Artocarpus altilis	Moraceae	Exotic	1	0.4	0.2	0.1	0.1	0.4
Pterocarpus erinaceus	Fabaceae	Native	1	0.4	0.2	0.1	0.1	0.3
Erythrina senegalensis	Fabaceae	Native	1	0.4	0.2	0.1	0.1	0.3
Acacia nilotica	Fabaceae	Native	1	0.4	0.2	0.1	0	0.3
Sarcocephalus latifolius	Rubiaceae	Native	1	0.4	0.2	0.1	0	0.3
Thuja occidentalis	Cupressaceae	Exotic	1	0.4	0.2	0.1	0	0.3
Gardenia jasminoides	Rubiaceae	Exotic	1	0.4	0.2	0.1	0	0.3
Cola nitida	Malvaceae	Exotic	1	0.4	0.2	0.1	0	0.3
Bixa orellana	Bixaceae	Exotic	1	0.4	0.2	0.1	0	0.3
Punica granatum	Lythraceae	Exotic	1	0.4	0.2	0.1	0	0.3
Euphorbia loricata	Euphorbiaceae	Exotic	1	0.4	0.2	0.1	0	0.3
Combretum indicum	Combretaceae	Exotic	1	0.4	0.2	0.1	0	0.3
Persea Americana	Lauraceae	Exotic	1	0.4	0.2	0.1	0	0.3
Euphorbia tirucalli	Euphorbiaceae	Exotic	1	0.4	0.2	0.1	0	0.3

NB: The importance value index is calculated by summing the scores of the relative frequency, the relative density, and the relative dominance. The frequency column gives estimate of the percentage of dwellinghouse where a specific specie is found.

[3] Data collection team failed to name clearly a tree species found in the study and reported it as "unidentified species".

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