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Natural Regeneration of Marker Species of the Tropical Dense Humid Ecosystems in the Loukaya Peri-Urban Forest, Brazzaville-Congo

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Abstract

The study aimed at evaluating the natural regeneration of some characteristic species in the Loukaya peri-urban forest was carried out in Brazzaville, over three surveys of one hectare each. The botanical inventory of the 23 species monitored covers the subjects of $2 \leq d^{0.20} < 10$ cm and $d^{1.30} \geq 10$ cm. The study shows 1255 individuals of which 68.27% are $2 \leq d^{0.20} < 10$ cm. While being tropophilic and mesophilic, this ecosystem is pauciflorous and paucispecific. The phytoecological data show that this formation, which is a link in the African dense humid forest, presents values far below those known elsewhere; while being faithful to the forests of the Cataractes Plateau. As for the rate of natural regeneration, this index is greater than or equal to 100 for 69.56% of the taxa. Sarcochores and heliophytes are the taxa that best support this natural regeneration. This high rate of regeneration would be correlated with the high level of anthropization, whose large canopy gaps are accompanied by a flow of light conducive to the installation of seedlings.

Keywords

Congo, Biodiversity Index, Peri-Urban Forest, Phytoecology, Natural Regeneration

1. Introduction

The management of urban and peri-urban forest ecosystems has always been one of the major problems of municipal authorities in Africa in general and in

Congo in particular [1]. Forests provide communities with several tangible and intangible assets known as ecosystem goods and services [2] [3] [4] [5] [6]. This range of products represents a source of socio-cultural and economic goods (handicrafts, food, water, fuelwood, service and timber, traditional medicine, agricultural land...), and much more subtle ecological and environmental functions that enhance life, such as climate regulation, carbon sequestration, maintenance of air quality... [7]-[12]. The exploitation of goods that are part of supply services (handicrafts, food, fuelwood, timber for services and labor, traditional medicine), which is most often unsustainable, leads to the depletion of resources and the progressive, even irreversible, impoverishment of ecosystems [13].

The expansion of the city of Brazzaville in recent years, under demographic pressure and anarchic urbanization, has resulted in the integration of formerly suburban territories into the urban fabric [14]. This operation leads to the degradation and sometimes disappearance of peri-urban ecosystems, notwithstanding the direct (physiological, socio-cultural, economic, aesthetic, scientific, educational) and indirect (climatic, environmental) benefits resulting from their maintenance [15] [16]. Anthropic action, which is devastating for forest ecosystems, affects the extent of the original area, the floristic composition and impacts the 3 degrees of biodiversity (α, β, γ). The forest islands resulting from the degradation of the Patte d'Oie in Brazzaville, the peri-urban forest of Djoumouna whose area declined by 49.41% between 1998 and 2017 and the disappearance of the Tsiémé, Glaciaire, Corniche and Ravine forests in Chad are a perfect illustration of this [10] [17] [18] [19].

Tropical forest ecosystems are recognized as sufficiently resilient to regenerate after disturbance [8] [9] [20]. Only sustained and/or prolonged logging, causing a break in forest succession, would be likely to divert the dynamics of its trajectory towards the establishment of secondary formations [21]. Their resilience capacity is such that they are capable of recovering an architectural structure very close to the primary forest only a few years after agricultural land is set aside, beyond the fact that the floristic parameters are other than the original ones [9].

In view of the socio-cultural, economic and environmental importance of urban and peri-urban forests, several studies are being carried out on these ecosystems, without delving into the issues of natural regeneration and the dynamics of reconstitution. The themes treated preferentially are ethnobotany [22] [23] [24] and quantitative ecology stricto sensu [1] [10] [16] [18]. The objective of this study is to highlight the state of natural regeneration of urban and peri-urban forests, through the monitoring of some species' characteristic of the Loukaya woody formation.

2. Material and Methods

2.1. Presentation of the Study Area

The peri-urban forest of the Loukaya River is located south-west of Brazzaville

between 4˚21'21.6" - 4˚21'36" south latitude and between 15˚6'21.6" - 15˚6'32.4" east longitude (Figure 1). Evolving in a densely populated area, the Loukaya Forest is bounded to the north by the village Makana 1, to the northeast by Nganga-Lingolo about 4.90 km from the tollgate, to the east by the village Djoumouna, to the south by the village Bissinza, to the southwest by the village Bouanissa, and to the west by the village Makana 2.

The climate of the locality is Bas-Congolese of the Sudano-Guinean type [25] [26] whose specificities are: an average annual temperature of about 25˚C, a low annual thermal amplitude of 5˚C to 6˚C (Figure 2); average annual rainfall of 1200 to 1400 mm [27]. The rains that punctuate the alternation of the seasons begin very weakly at the end of September and settle from October to May, with a very marked slowdown from January to February. The hottest and wettest months are usually March, April and November. On the other hand, the months of June to September are the driest, while July and August are the coolest [26] [28]. Relative humidity, always above 70%, is vital for the flora, especially in the dry season. The annual hygrometric amplitude is low and the daily average varies from 33% in the rainy season to 46% in the dry season [27] [28]. Evaporation varies in the opposite direction of atmospheric humidity (Figure 2) and presents a relative minimum in June and an absolute maximum in August and September [27]. In relation to the seasons, the relative minimum occurs at the turn of the rainy and dry seasons, while the absolute maximum is observed in the last phase of the dry season. In sum, evaporation is moderately low and stable in the rainy season follows the opposite trend of rainfall in January - February; and rises sharply in the dry season.

According to Denis [25], the geological substratum is composed of sedimentary formations of Cenozoic (Tertiary) age, of sandstone nature that form the
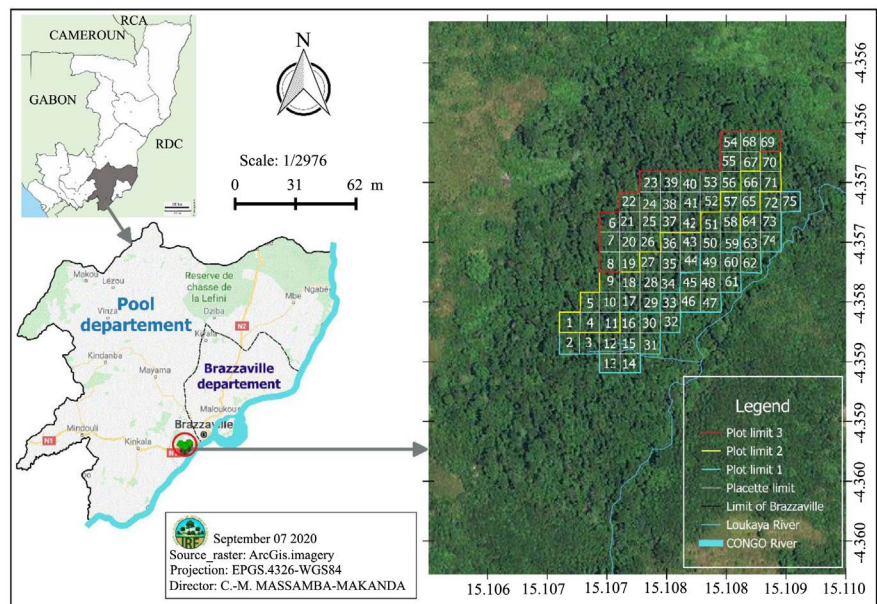

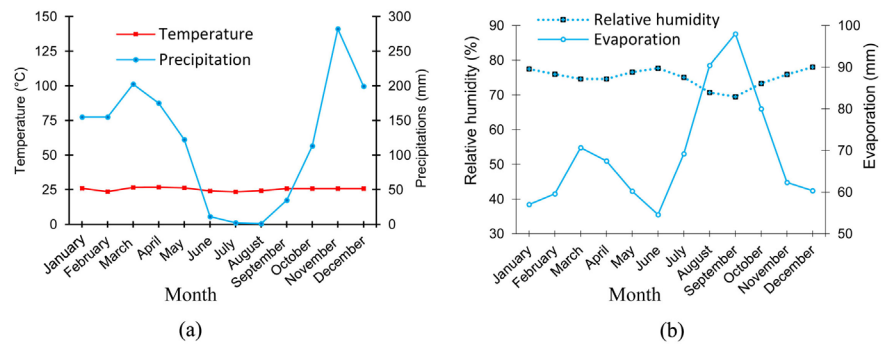Figure 1. Location of the Loukaya peri-urban forest.

Figure 2. Climate parameters of the study area (2000-2018 period, source ANAC). Legend: Ombrothermal curve (a); Relative humidity and evaporation curves (b).

Inkisi sandstone series. According to the authors, this bedrock either is from the Upper Kalahari or is the result of in situ alteration of the schistose sandstone system. This system is composed of two superimposed sets, namely 1) the upper layers known as sandy siltstones, which constitute a large set of ochre-coloured aeolian sandy siltstones that occupy the upper parts of the plateaux. These highly mobile silts have given rise to major reworking, both in situ and by dragging into the valleys; 2) the lower layers known as polymorphic sandstones, which are represented by soft, yellow, white or pink sandstones, with fine and regular grain, without marked stratification.

The soils belong to the class of highly desaturated ferrallitic yellow psamite soils on Batékés sandstones of plateau slopes and hills, as well as hydromorphic soils [25]. From the physical and chemical point of view, highly desaturated ferrallitic soils are acidic soils (pH < 5.5), with a low sum of exchangeable bases (1 meq/100g) and a low saturation rate (less than 20%) of the absorbent complex.

The vegetation in the study area is a forest-savanna mosaic [29] [30]. Forests are established on various topographical positions, hilltops, mainly where there are sandy overburden, slopes, valleys, and often swampy shallows. The forest in the valley bottoms takes the form of narrow galleries and is generally much degraded. In addition to these formations, larger massifs, located along the Congo River, generate ombrophilous *Gilbertiodendron dewevrei* or more often mesophilic semi-caducifolia formations.

2.2. Materials

The plant material consists of the trees of $d^{1.30} \geq 10$ cm of the selected species and their regenerative cohort of diameter between $2 \leq d^{0.20} < 10$ cm, at 20 cm from the ground. The selected individuals in the regenerative cohort are at least 30 cm in height because below this value the survival of individuals is very random [31]. The selection of regeneration species is based on the fact that they are characteristic of the dense tropical rainforests of Central Africa. The taxonomic ordination adopted is APG IV [32] and the nomenclature followed is that of Lebrun and Stork [33]. The parameters monitored are types of diaspora and affinity to light.

The types of diasporas recognized follow the classification of [34] taken up by [10] [16] [23] [24] [35] [36]:

- Ballochores (Ballo): diaspores expelled by the plant itself;
- Barochores (Baro): non-fleshy, heavy diasporas;
- Pterochores (Ptero): diasporas with aliform appendages;
- Sarcochores (Sarco): diasporas totally or partially fleshy.

The type of affinity to light described by Lebrun [35] [37] and taken up by [36] reveals the groups of:

- heliophytes (Heliophytes), plants that enjoy full sunlight. In this group, one finds mainly plants from well-lit grassy groups, trees and lianas from the upper tree dome;
- hemi-heliophytes (Hemi-Helio), plants of the intermediate strata of the forests, trees of the dome which regenerate in undergrowth and can live for a certain time in diffuse light. These plants receive on average 50% to 75% of the total illumination [38];
- hemi-sciaphytes (Hemi-Scia), plants of the forest undergrowth that still receive 5 to 50% of relative illumination [38];
- sciaphytes (Scia), plants of the lower and humigenous strata of forests in general. The illumination received is limited to 1% to 5% of the total light [38].

2.3. Sampling Device

The research system is based on three adjacent surveys of 1 ha, each unit consisting of 25 plots of 400 m^2 (**Figure 3**).
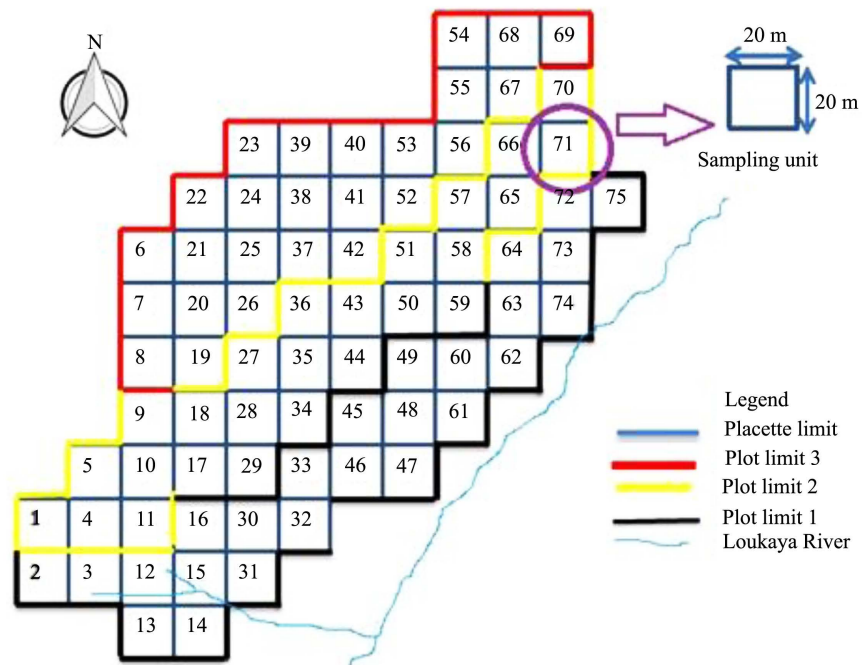

Figure 3. Floristic sampling device.

2.4. Methods of Study

For dense tropical rainforests, several methods are used to study natural regeneration. For this study, the full floristic inventory coupling the count of all individuals of selected species from the regenerative cohort ($2 \leq d^{0.20} < 10$ cm) to trees of $d^{1.30} \geq 10$ cm is carried out over the entire study area [10] [39]. This method, which provides a better understanding of the notion of natural regeneration, has the advantage of making data reliable and modelling.

2.4.1. Floristic Inventory

Plot by plot and systematically, all individuals of $2 \leq d^{0.20} < 10$ cm [40] and $d^{1.30} \geq 10$ cm [41] of the monitored species are identified, counted and measured. The diameter of the individuals of the regenerative cohort was measured with the caliper, while the $d^{1.30} \geq 10$ cm were measured with a metric tape measure. The height of the woody trees was measured with 1) a 1.50 m wooden ruler and a 5 m folding tape measure for small trees and 2) at the vertex for large trees. The height data of the individuals allow an appreciation of the vertical structure of the stand, especially of the selected species. The vertical stratification is based on the biological typology of Raunkiaer [42] adapted to tropical forests by Lebrun [37]. The classification adopted for the Loukaya forest is in line with work carried out in the region [43] [44] [45] and whose strata are defined as follows.

Stratum	Limit	Biological forms
I	0.25 - 2 m	Nanophanerophytes
II	2 - 10 m	Microphanerophytes
III	10 - 30 m	Mesophanerophytes
IV	>30 m	Megaphanerophytes

2.4.2. Expression of Results

1) The species scarcity index [46]:

$$Ri = \left[1 - \frac{ni}{N} \right] \times 100 \qquad (1)$$

with ni = the number of plots where the species is encountered and N = the total number of plots inventoried.

Species with a depletion index of less than 80% are considered preferential, very frequent and abundant in the study areas. Those whose rarefaction index is higher than 80% are said to be rare and therefore highly endangered in the locality.

2) The similarity coefficients of Jaccard (*S*) and Sørensen (*K*) [47]. The Jaccard and Sørensen similarity coefficients are distinguished by the fact that Jaccard gives the same value to presence as to absence, while Sørensen gives a double advantage to presence. In the latter case, presence is more informative than absence.

$$S(\%) = \frac{C}{A + B - C} \times 100 \qquad (2)$$

$$K(\%) = \frac{2C}{A+B} \times 100 \tag{3}$$

where "A" is the number of species in the 1st survey; "B" the number of species in the 2nd survey; and "C" the number of species common to both surveys.

3) Diaspora types, light affinity and structural parameters are expressed as raw and weighted spectra, according to the two formulas given as examples:

$$SB(\%) = \frac{A}{B} \times 100 \tag{4}$$

where "A" is the species number by diasporas type; and "B" the total species number

$$SP(\%) = \frac{A}{B} \times 100 \tag{5}$$

where "A" is the trees number by diaporas type; and "B" the total trees number.

4) Density is the number of woody individuals per hectare;

$$D = \frac{A}{B} \tag{6}$$

where "A" is the total trees number (or taxa) per plot; and "B" the total plot area (ha)

5) Woody frequency (F);

$$F = \frac{A}{B} \times 100 \tag{7}$$

where "A" is the plots number where taxon is recorded; and "B" the total plots number

6) The basal area (m²·ha⁻¹) indicates the spatial areas occupied by all trunk sections;

$$S = \sum \frac{\pi Di^2}{4} \tag{8}$$

7) The natural regeneration rate (NR), according to the Rothe scale [48] and taken up by Ramananjatovo [31], is used to judge the regeneration capacity of a species or a habitat.

$$TR = \frac{A}{B} \times 100 \tag{9}$$

where "A" is the regeneration individuals number; and "B" the other individuals' regeneration number. Regeneration is: difficult if $TR < 100\%$; good for $100 \leq TR < 1000\%$; very good when $TR \geq 1000\%$.

8) The dispersion index (I) is the ratio of the variance to the mean of the counts. This index provides information on the type of spatial distribution of the units counted. A dispersion: regular for a value significantly less than 1; random for an index equal or close to 1; and aggregated in other cases [49] [50].

$$I = S^2/\overline{X} \tag{10}$$

The values of the dispersion index (I) were subjected to the chi-square test (χ^2)

for α = 5%, in order to verify if they are significantly different from 1 (random dispersion).

$$\chi^2\left(df = Q-1\right)=\left(Q-1\right)S^2\big/\overline{X} \tag{11}$$

with Q the number of plots, S^2 and $\overline{X}$ respectively the variance and the mean of the number of trees per subplot.

The statistical processing was done with "R, Past and Excel software". The results are subjected to the analysis of variance (ANOVA) using R software. The mean values of the results of the biodiversity indices and structural parameters will be compared and their significant differences will be evaluated at the probability threshold p < 0.05.

3. Results

3.1. Taxonomic and Floristic Data

The inventory shows 23 species corresponding to 21 genera grouped in 13 families (Table 1 and Table 2). As for the number of individuals counted, it should be noted that it amounts to 1255 of which 31.71% are trees of $d^{1.30} \geq 10$ cm. The regenerative cohort $2 \leq d^{0.20} < 10$ cm makes up 1/3 of the count. The mean number of individuals per species is 37.26 ± 6.05 for a range of 2 to 137 plants per species (Table 2 and Figure 4). With more than 100 plants, *Pentaclethra eetveldeana* and *Petersianthus macrocarpus* account for 28.35% of the population. These taxa are followed by *Carapa procera* and *Pentaclethra macrophylla* with a number of plants ranging from 60 to 100, *i.e.* 19.03% of the total. Finally, with at least 20 plants, *Syzygium brazzavillense*, *Synsepalum dulcificum*, *Maranthes glabra*, *Pycnanthus angolensis*, *Millettia laurentii*, *Bosqueiopsis gilletii*, *Millettia eetveldeana*, *Ongokea gore* and *Anisophyllea meniaudi* form the third group, accounting for 43.17% of the population. The least represented group of species, less than 20 plants, covers 9.45% of the inventory and consists of *Xylopia acutiflora*, *Dialium pachyphyllum*, *Allablanckia floribunda*, *Tetraberlinia* sp., *Symphonia globulifera*, *Pterocarpus soyauxii*, *Albizia ferruginea*, *Celtis mildbraedii*, *Anonidium mannii* and *Paramacrolobium coeruleum*.
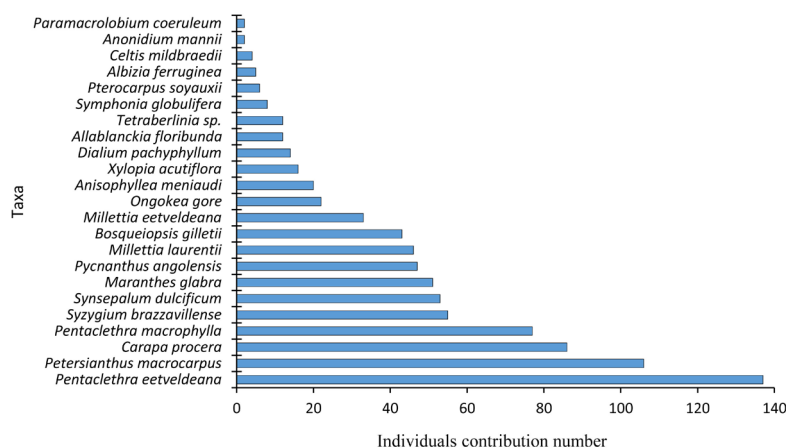

Figure 4. Number of individuals in the regenerative cohort by species.

Table 1. Structural parameters of taxa involved in the regenerative study.

Taxa	Plants of $2 \le d^{0.20} < 10$ cm							Trees of $d^{1.30} \ge 10$ cm			TR (%)	RI (%)	Dispersion index				TD	Light affinity
	Plot 1	Plot 2	Plot 3	Total	Density (ind. ha⁻¹)	Freq. (%)	ST (m²·ha⁻¹)	Trees number	Density (ind. ha⁻¹)	ST (m²·ha⁻¹)			I	χ^2	P value	Eff. (%)		
Anisophylleaceae	8	4	8	20				5										
Anisophyllea meniaudi Aubrév. & Pellegr.	8	4	8	20	6.67	0.21	0.06	5	1.67	0.35	400	78.67	0.390	28.860	0.995	57	Sarco	Hemi-Hélio
Annonaceae	9	3	6	18				5										
Anonidium mannii (Oliv.) Engl. & Diels	2	0	0	2	0.67	0.03	0.01	0	0.00	0.00	-	97.33	0.000	0.000	0.995	57	Sarco	Hemi-Helio
Xylopia acutiflora (Dunal) A. Rich.	7	3	6	16	5.33	0.13	0.02	5	1.67	0.08	320	86.67	0.527	39.033	0.995	57	Sarco	Hemi-Helio
Cannabaceae	3	0	1	4				26										
Celtis mildbraedii Engl.	3	0	1	4	1.33	0.05	0.02	26	8.67	1.39	15	94.67	0.354	26.225	0.995	57	Sarco	Helio
Chrysobalanaceae	35	10	6	51				10										
Maranthes glabra (Oliv.) Prance	35	10	6	51	17.00	0.35	0.06	10	3.33	0.28	510	65.33	0.868	64.256	0.500	17	Sarco	Helio
Clusiaceae	11	7	2	20				19										
Allanblackia floribunda Oliv.	7	4	1	12	4.00	0.11	0.04	19	6.33	0.57	63	89.33	0.353	26.109	0.995	57	Sarco	Helio
Symphonia globulifera L. f.	4	3	1	8	2.67	0.08	0.01	0	0.00	0.00	-	92.00	0.167	12.333	0.995	57	Sarco	Helio
Fabaceae	75	141	116	332				231										
Albizia ferruginea (Guill. & Perr.) Benth.	1	2	2	5	1.67	0.07	0.01	1	0.33	0.03	500	93.33	0.000	0.000	0.995	57	Baro	Helio
Dialium pachyphyllum Harms	12	1	1	14	4.67	0.09	0.03	6	2.00	0.19	233	90.67	0.733	54.267	0.900	57	Sarco	Helio
Millettia eetveldeana (Micheli) Hauman	7	22	4	33	11.00	0.20	0.07	39	13.00	2.25	85	80.00	3.322	245.844	0.005	22	Ballo	Helio
Millettia laurentii De Wild.	12	17	17	46	15.33	0.33	0.09	22	7.33	1.10	209	66.67	0.822	60.809	0.750	17	Ballo	Helio
Paramacrolobium coeruleum (Taub.) J. Léonard	0	2	0	2	0.67	0.01	0.00	6	2.00	0.66	33	98.67	0.107	7.929	0.995	57	Ballo	Helio
Pentaclethra eetveldeana De Wild. & T. Durand	23	64	50	137	45.67	0.71	0.18	119	39.67	5.21	115	29.33	1.652	122.282	0.005	22	Ballo	Helio
Pentaclethra macrophylla Benth.	19	27	31	77	25.67	0.56	0.11	40	13.33	1.74	193	44.00	1.167	86.367	0.100	4	Ballo	Helio
Pterocarpus soyauxii Taub.	0	0	6	6	2.00	0.03	0.02	3	1.00	0.04	200	97.33	0.528	39.056	0.995	57	Ptero	Helio

Continued

Tetraberlinia sp	1	6	5	12	4.00	0.09	0.05	0	0.00	0.00	-	90.67	0.452	33.476	0.995	57	Ballo	Helio
Lecythidaceae	41	44	21	106				34										
Petersianthus macrocarpus (P. Beauv.) Liben	41	44	21	106	35.33	0.59	0.23	34	11.33	1.49	312	41.33	1.469	108.720	0.005	22	Ptero	Helio
Meliaceae	33	45	8	86				15										
Carapa procera DC.	33	45	8	86	28.67	0.56	0.12	15	5.00	0.30	573	44.00	1.454	107.568	0.005	22	Sarco	Helio
Moraceae	16	14	13	43				27										
Bosqueiopsis gilletii De Wild. & T. Durand	16	14	13	43	14.33	0.39	0.08	27	9.00	0.72	159	61.33	0.466	34.501	0.995	57	Sarco	Helio
Myristicaceae	20	19	8	47				12										
Pycnanthus angolensis (Welw.) Warb.	20	19	8	47	15.67	0.37	0.09	12	4.00	0.95	392	62.67	0.999	73.957	0.250	17	Sarco	Helio
Myrtaceae	12	17	26	55				5										
Syzygium brazzavillense Aubrév. & Pellegr.	12	17	26	55	18.33	0.39	0.07	5	1.67	0.37	1100	61.33	0.967	71.533	0.250	17	Sarco	Helio
Olacaceae	12	5	5	22				1										
Ongokea gore (Hua) Pierre	12	5	5	22	7.33	0.21	0.05	1	0.33	0.02	2200	78.67	0.343	25.361	0.995	57	Sarco	Helio
Sapotaceae	20	14	19	53				3										
Synsepalum dulcificum (Schumach. & Thonn.) Daniell	20	14	19	53	17.67	0.35	0.08	3	1.00	0.12	1767	65.33	1.497	110.804	0.005	22	Sarco	Hemi-Scia
Total	295	323	239	857	285.67	-	1.48	398	132.67	17.89	-	-	-	-	-	-	-	-
Moyenne ± ES	-	-	-	285.67 ± 24.69	-	0.49 ± 0.06	132.67 ± 8.97	5.96 ± 0.67	-	-	-	-	-	-	-	-	-	-

Table 2. Summary of taxonomic and floristic data.

Survey	Taxa			Individuals number	
	Families	Genera	Species	$2 \le d^{0.20} < 10$ cm	$d^{1.30} \ge 10$ cm
Plot$_1$	13	19	21	295	120
Plot$_2$	12	18	20	323	150
Plot$_3$	13	19	21	239	128
Total	13	21	23	857	398
Average ± ES	12.67 ± 0.33	18.67 ± 0.33	20.67 ± 0.33	285.67 ± 24.69	132.67 ± 8.97

3.2. Structure Parameters

3.2.1. Floral Density

Floral density Trees of $d^{1.30} \ge 10$ cm have an average density of 132.67 ± 8.97 individuals ha^{-1}. This density is supported by 4 taxa (*Pentaclethra eetveldeaena*, *Pentaclethra macrophylla*, *Petersianthus macrocarpus*, *Millettia eetveldeana*) whose number of trees per unit area is in the range 11 - 39. As for the regenera-

tive cohort ($2 \leq d^{0.20} < 10$ cm) the mean density is 285.67 ± 24.69 individuals ha^{-1}. Notwithstanding the variations observed in the surveys, the dominant taxa in this category are *Pentaclethra eetveldeaena*, *Petersianthus macrocarpus*, *Carapa procera*, *Pentaclethra macrophylla*. *Maranthes glabra*, *Millettia eetveldeana*, *Millettia laurentii*, *Bosqueiopsis gilletii*, *Pycnanthus angolensis*, *Syzygium brazzavillensis*, *Synsepalum dulcificum*. These species have an average of 11 to 45 individuals ha^{-1} (Table 1). The mean number of individuals does not vary significantly (p-value = 0.1818 for the ANOVA test) between surveys. The mean absolute densities of the surveys, for all diameter classes (regenerative cohort and large-diameter trees combined), do not vary significantly (p-value = 0.1706 for the ANOVA test). This observation is synonymous with a random distribution of individuals within the woody formation.

3.2.2. Frequency of Taxa
Considering the sampling units, the frequency of the regenerative cohort ($2 \leq d^{0.20} < 10$ cm) varies from 0.01 to 0.71%, or an average of 0.26 ± 0.04 (Table 1). 82.61% of the species are present in all 3 surveys; 13.04% restricted to 1/3 of the surveys; and finally 4.35% restricted to 2/3 of the surveys. The distribution of taxa shows floristic heterogeneity.

3.2.3. Basal Surface Area of Taxa
The average basal area of the trees of $d^{1.30} \geq 10$ cm is 5.96 ± 0.67 m²·ha⁻¹, for a range between 4.63 and 6.79 m²·ha⁻¹. The regenerative cohort ($2 \leq d^{0.20} < 10$ cm) has a mean basal area of 0.49 ± 0.06 m²·ha⁻¹, for a range of values from 0.39 to 0.61 m²·ha⁻¹ (Table 1). Mean basal area values showed a significant difference for regeneration individuals (p-value = 0.04299 for the ANOVA test) between surveys 2 and 3 for which the Student test gave a p-value = 0.044. However, the differences are not significant between the mean basal area values for large diameter individuals (p-value = 0.4835 for the ANOVA test) within the surveys. The mean basal area values do not differ significantly (p-value = 0.2357 for the ANOVA test) within the surveys for all diameter classes.

3.2.4. Vertical Stratification of the Regenerative Cohort
Most of the individuals surveyed belong to stratum II, regardless of the survey (Figure 5). This observation is also valid for the ecosystem as a whole, with 59.76% of the individuals surveyed. The Kruskal-Wallis test does not reveal any significant differences between the median height values of the three surveys (p-value = 0.9853). However, highly significant differences were observed between the height values in the different strata (p-value $< 2.2 \times 10^{-16}$). This observation is supported by the Wilcoxon and Mann-Whitney test with p-value < 0.05 (Megaphanerophytes - Mesophanerophytes = 3.1×10^{-13}; Megaphanerophytes - Microphanerophytes = 2.7×10^{-13}; Megaphanerophytes - Nanophanerophytes = 2.3×10^{-10}; Mesophanerophytes - Microphanerophytes $< 2 \times 10^{-16}$; Mesophanerophytes - Nanophanerophytes $< 2 \times 10^{-16}$; Microphanerophytes - Nanophanerophytes $< 2 \times 10^{-16}$).
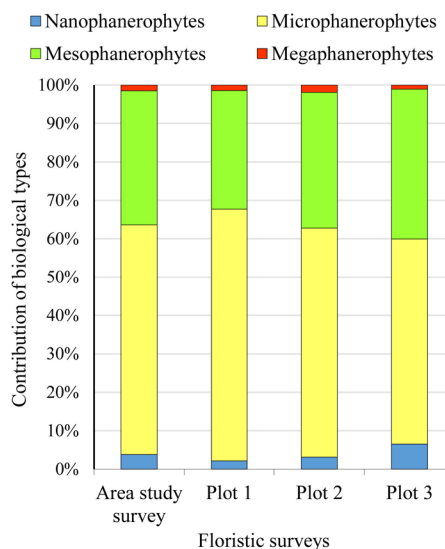
Figure 5. Vertical stratification of taxa in the Loukaya peri-urban Forest.

3.2.5. Diameter Structure of Taxa

Dendrometric data from trees of $d^{1.30} \geq 10$ cm show an inverted "L" or "J" shaped curve, indicating consistent recruitment between diameter classes (**Figure 6(a)** and **Figure 6(b)**). Notwithstanding this overall effect, specific monitoring of the taxa in the study revealed erratic curves (**Figure 6**). This observation is evidence of their poor natural regeneration. The mean values of the diameters of regeneration individuals within the surveys do not show significant differences (p-value = 0.09187 for the ANOVA test). The median values of the diameters of the individuals within the surveys do not show significant differences from one survey to another (p-value = 0.4545 for the Kruskal-Wallis test). This data would reflect a similar evolution of the flower-bulb considered within the three surveys constituting the study area.

3.3. Regenerative Cohort Height-Diameter Relationship

A positive correlation was noted between the height and diameter of individuals monitored in the Loukaya peri-urban forest, regardless of the inventory level (**Figure 7**). The Spearman's coefficient ("rho") being, in all cases, higher than the Pearson's coefficient ("r"), reflects a monotonous and non-linear relationship. This observation reveals that the diameter of individuals increases concomitantly with height, but not proportionally. This phenomenon could be a consequence of accidents occurring during their growth stages. These include 1) anthropogenic actions and natural accidents such as windfalls; 2) the diversity of growth rates of the species considered, as well as their distribution pattern within the study area.
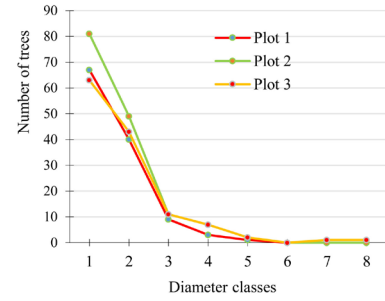
3.4. Phytodiversity Index
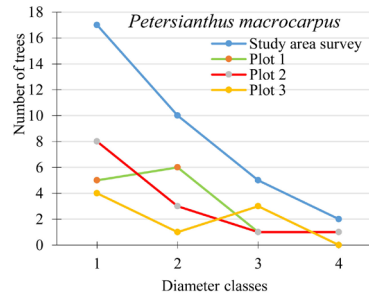
3.4.1. Species Depletion Index

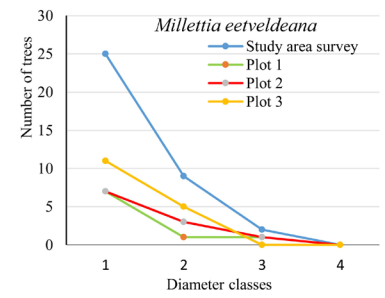Of the 23 species monitored for regeneration ($2 \leq d^{0.20} < 10$ cm), 52.17% have a
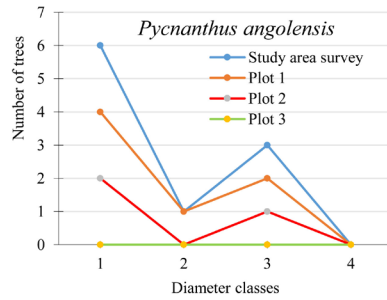
(a)

(b)

(c) *Petersianthus macrocarpus*

(d) *Millettia eetveldeana*

(e) *Pycnanthus angolensis*

(f) *Maranthes glabra*

(g) *Synsepalum dulcificum*

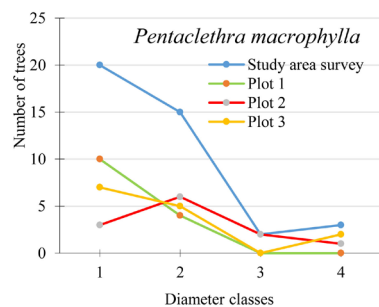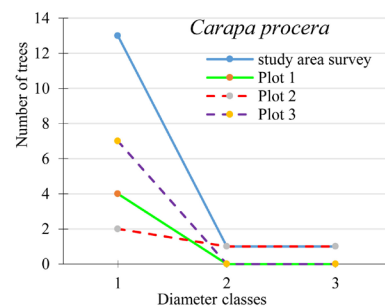(h) *Syzygium brazzavillense*

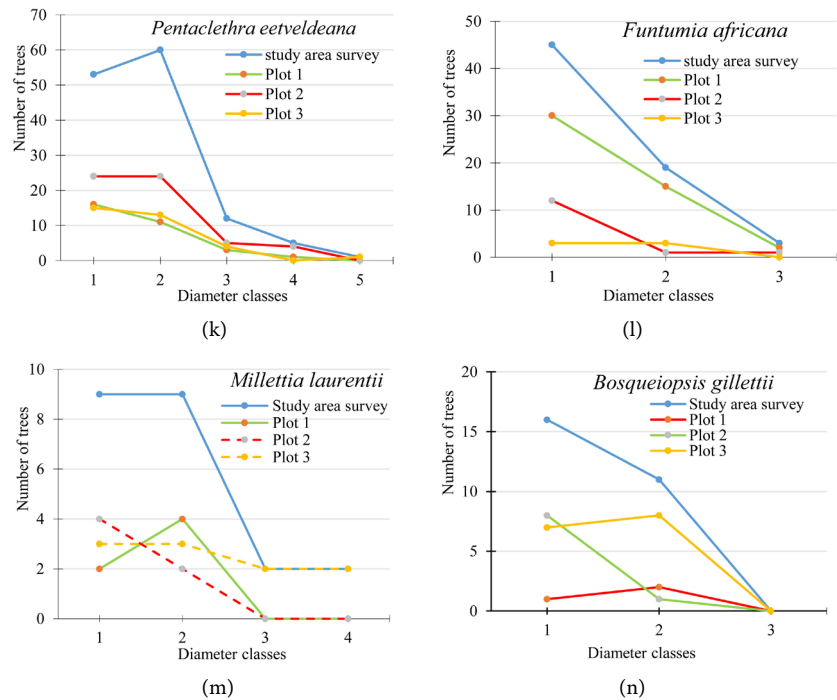(i) *Pentaclethra macrophylla*

(j) *Carapa procera*
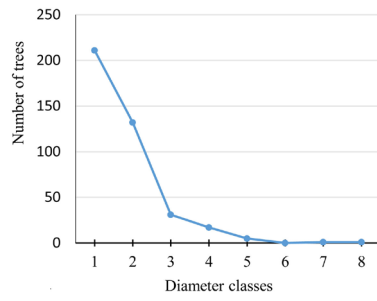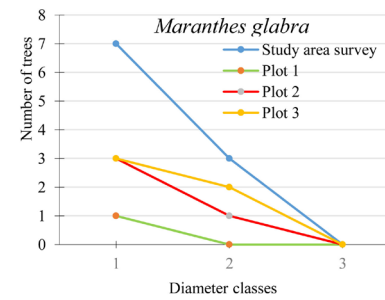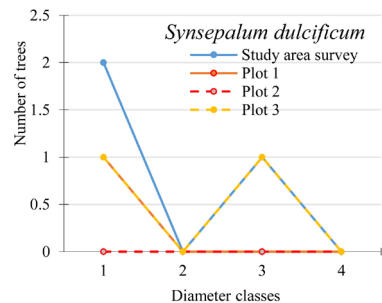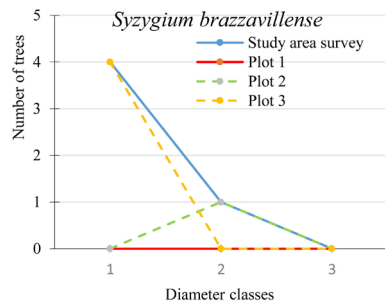
Figure 6. Diameter structure of the predominant species of the regenerative cohort. Legend: entire study area survey (a); per survey (b); species per plot and study area survey ((c)-(n)).
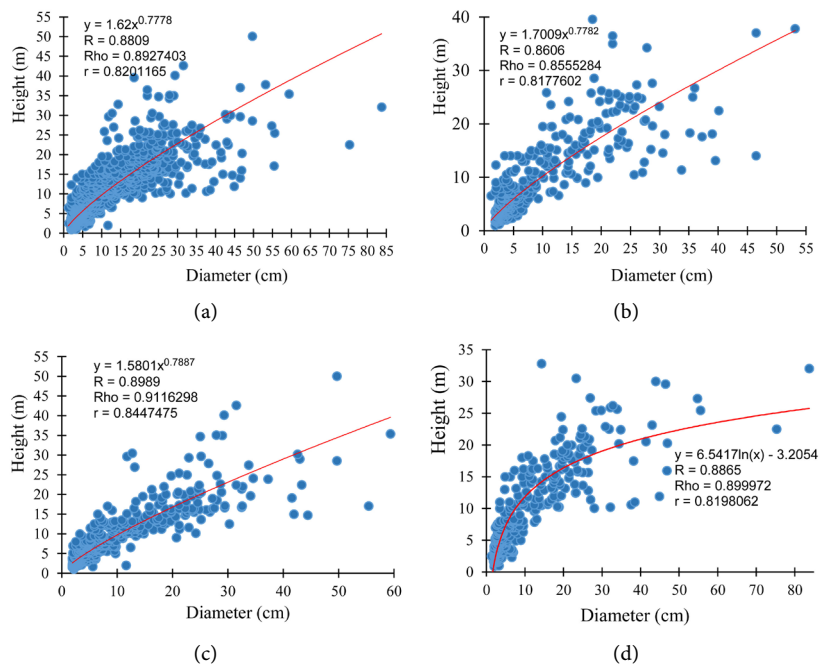

Figure 7. Height-diameter relationship of monitored regenerative taxa. (a): Study area; (b): Survey 1; (c): Survey 2; (d): Survey 3.

species rarity index (RI) of less than 80%. These taxa with RI values ranging from 29.33% to 78.67% are abundant and include *Maranthes glabra*, *Millettia laurentii*, *Pentaclethra eetveldeana*, *Pentaclethra macrophylla*, *Pycnanthus an-*

golensis, *Petersianthus macrocarpum*, *Carapa procera*. However, the remaining 47.83% have an IR between 80% and 98.67% (Table 1). Rare taxa in this category include *Paramacrolobium coeruleum*, *Anonidium mannii*, *Pterocarpus soyauxii*, *Tetraberlinia* sp., *Allablanckia floribunda*, *Celtis mildbraedii*, *Dialium pachyphyllum*, *Symphonia globulifera*.

3.4.2. Coefficients of Floristic Similarity

Regardless of the similarity coefficient (Jaccard or Sørensen), the floristic composition is very homogeneous between the surveys. Jaccard's similarity coefficient is on average 87.67 ± 1.67, compared to 93.67 ± 0.67 for Sørensen. The differences are not significant between surveys (p-value = 0.6853 for the ANOVA test).

3.4.3. Natural Regeneration Rate

At the scale of the study, the natural regeneration rate is 215.33%. In contrast, in surveys 1, 2 and 3, the respective rates are 245.83%; 215.33% and 178.36%, from the specific level (Table 1). The observation of the rate of natural regeneration declines for 3 taxa groups. The first group, with TR > 1000%, consists of 13.04% of species with very good natural regeneration (*Ongokea gore*, *Synsepalum dulcificum* and *Syzygium brazzavillense*); the second, with 56.52% of the inventory and a rate of 100 ≤ TR < 1000%, consists of species with good natural regeneration (*Carapa procera*, *Maranthes glabra*, *Albizia ferruginea*, *Anisophyllea meniaudi*, *Pycnanthus angolensis*, *Xylopia acutiflora*, *Petersianthus macrocarpus*, *Dialium pachyphyllum*, *Millettia laurentii*, *Pterocarpus soyauxii*, *Pentaclethra macrophylla*, *Bosqueiopsis gilletii* and *Pentaclethra eetveldeana*); and finally, the last group, with 30.44% of taxa and a TR rate < 100%, includes all species with poor natural regeneration (*Millettia eetveldeana*, *Allablanckia floribunda*, *Paramacrolobium coeruleum*, *Celtis mildbraedii*, *Tetraberlinia* sp., *Symphonia globulifera* and *Anonidium mannii*).

3.4.4. Taxa Dispersion Index

The dispersion index (I) applied to the 23 species (*i.e.* 1255 individuals) in the study area reveals that 22% of species corresponding to 625 trees show significant gregarious dispersion (χ^2; p value < 0.05) (Table 1). *Pentaclethra macrophylla* alone gathering 117 individuals, or 4% of the floristic richness of the phytocenosis, presents a non-significant gregarious dispersion (χ^2; p-value > 0.05). Uniform dispersal is found in 57% of species (265 individuals) of the phytocenosis. However, this hyperdispersion remains non-significant in view of the results of the Chi-square test (χ^2; p value > 0.05). This study area covers 17% of species with a non-significant random dispersion (χ^2; p value > 0.05) whose density is evaluated at 248 (Table 1).

3.5. Diaspora Types and Affinity in the Light of Taxa

Sarcochores are preponderant with 60.87% of the species, corresponding to a proportion of 50.53% of individuals (Figure 8(a) and Figure 8(b)). Ballochores
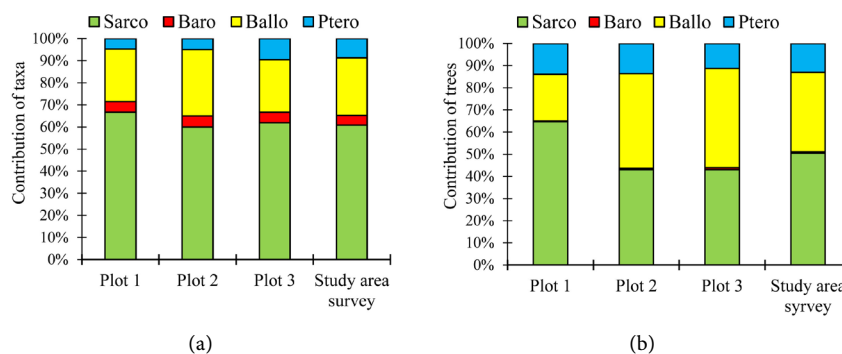
Figure 8. Spectrum of diaspora types. Legend: Raw spectrum (a); Weighted spectrum (b), Sarcochores (Sarco), Barochores (Baro), Ballochores (Ball), Pterochores (Ptero).

come in the second position with 26.09% of the species and 35.82% of the individuals. This observation made at the scale of the study is also valid when considering the surveys, where sarcochores remain dominant ahead of horehounds.

In relation to light affinity, 82.61% of the species surveyed are heliophilic, *i.e.* 89.39% of individuals (**Figure 9(a)**). The hemi-heliophilic plants have a specific proportion of 13.04%, while hemi-sciaphiles are ahead of them in terms of individuals with 6.18% of the individuals recorded (**Figure 9(b)**).

4. Discussion

4.1. Analysis of Phytodiversity

Like all the intra-urban and peri-urban forests in Brazzaville (Patte d'Oie and Djoumouna Forests) whose phytodiversity data are almost under control, the Loukaya woodland formation is no exception. Mesophilic and tropophilic in type, the Loukaya forest is a very diverse and concomitantly tree-poor formation [10] [16] [51] [52] [53] [54] [55]. This state is the tangible result of anthropogenic effects that severely impact all levels of biodiversity (*α, β, γ*). These woody formations, although they are part of the dense tropical rainforests, without being compared to the neotropical and palaeotropical forest ecosystems of South-East Asia, are very atypical in terms of specific and floristic richness [52]. These structural parameters would be dependent on pedoclimatic determinism, in general. These indices establish the link of their belonging to the physiographic area of the Cataractes district [10] [16] [51] [52] [53] [54] [56].

The passage from one diameter class to another induces a decrease in density following the conquest of space, which is not extensible [20] [57] [58]. Thus, high mortality of juvenile individuals ($2 \leq d^{0.20} < 10$ cm) is observed under the influence of intrinsic and extrinsic factors (descent of peaks, trampling, irregularity of rainfall, grazing) as mentioned in several works [10] [13] [17] [59] [60] [61]. As a result of the high mortality rate among the regenerative cohort, Baraloto [57] points out that barely 1% of seedlings (germinated seeds) reach adulthood in tropical forests. Notwithstanding the natural events that affect natural regeneration in the forest, the share associated with humans would be preponderant in this ecosystem. The disturbance in the recruitment of taxa within
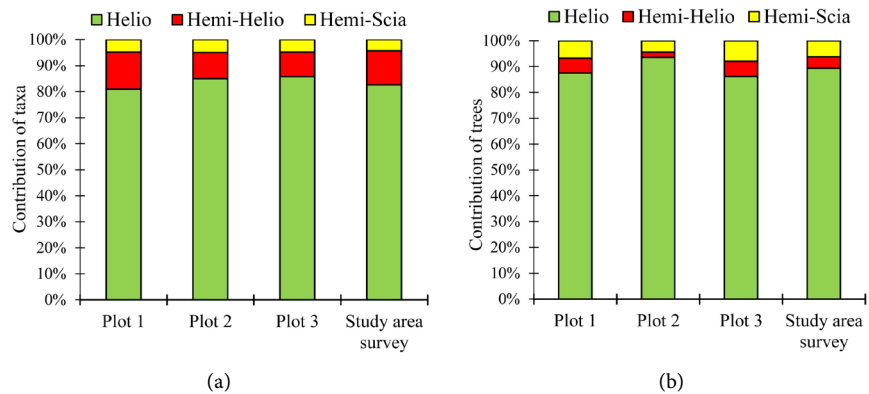
Figure 9. Spectrum of light affinity types. Legend: Raw Spectrum (a), Weighted Spectrum (b), Heliophile (Heli), Hemi-heliophile (Hemi-Helio), Hemi-Sciaphile (Hemi-Scia).

diameter classes ($d^{1.30} \geq 10$ cm), which is at the origin of the erratic curves for each of the species monitored, is irrefutable proof of recurrent anthropogenic interventions [10] [16] [20] [51] [52] [53] [54] [55] [62]. The corollaries of this ever-increasing and continuous anthropogenic pressure have a lasting impact on the natural regeneration of these taxa and concomitantly that of the entire ecosystem.

4.2. Status of Natural Regeneration

The natural regeneration of a forest is supported by the ratio of seedlings to large trees in the stand [63] [64] [65]. As such, natural regeneration is the basis for understanding the dynamics of woody vegetation, integrating the process of diametric recruitment, juvenile mortality, developmental stages and ecosystem survival [62] [66]. Under the dependence of several factors (light intensity, humidity, nature of the substrate, biological characteristics), natural regeneration would be a phenomenon sensitive to the variation of environmental parameters [67]. Correlatively, the modification of the parameters of the Loukaya ecosystem, following the various anthropic actions of the local residents, would explain some of the results of this study, particularly the mortality of young plants [1].

The Loukaya forest, which is much secondarised, looks like an ecosystem in full recovery, taking into account the high rate of young plants of heliophilic species (*Ongokea gore* and *Syzygium brazzavillense*). These stages of forest recovery are generally marked by a massive presence of pioneer heliophilic species [68]. A high level of anthropisation affects the physiognomy of the forest facies through the opening of the gaps. The corollaries are a variation in the flow of light reaching the ground, directly or through the heat, it brings generally considered as a determining factor in the renewal of forest stands [69] [70] [71]. This parameter would explain the high rate of seedlings in the study area; confirmed by a regeneration index greater than 100%; synonymous with good regeneration on the Rothe scale [48].

Also, it should be noted that the type of diaspora and the mode of dissemination effectively intervene in the process of densification of regenerants. The do-

minance of sarcochores in the Lukaya forest induces high densities of regenerants subject to predation and high mortality due to intraspecific competition at the base of the productive trees [57] [59] [72] who reports that in tropical forests confirms this hypothesis, only 1% of the individuals at the base of the productive trees reach maturity.

Although the natural regeneration index is satisfactory, the absence of individuals in certain diameter classes indicates that the process is subject to disturbances whose primary origin is human activity. Peri-urban forests are excellent places for supplying the surrounding populations with daily basic needs [73] [74] [75].

4.3. Spatial Structure and Dispersion of Diasporas

The spatial distribution of a species results from the interaction of biotic and abiotic factors, and as long as resources are not too limiting [76] [77]. Under these conditions, dissemination becomes the main spatial limitation and therefore determines the probability of recruitment [78] [79] [80]. As the Loukaya peri-urban forest is dominated by sarcochorous species, endozoochory is the main mode of spread. Human practices in peri-urban ecosystems, including hunting, are factors limiting spread, due to pressure on wildlife. Thus, the observed aggregate distribution of individuals of $2 \leq d^{0.20} < 10$ cm would be the result of the limitation of dispersal [76] [80] [81] [82].

Anthropogenic activities in this ecosystem (hunting and cutting of trees and small woods) have a direct impact on biodiversity in general and indirectly on the dispersion of diasporas, especially sarcochores. These diasporas, which cannot ensure long-distance dispersal without animal involvement, give an aggregated spatial structure to the taxa of the regenerative cohort. Gaps or even windfalls are appropriate environments for the development of this phenomenon, as they provide optimal conditions for germination and growth of individuals [20] [83] [84]. Windfalls and open gaps resulting from natural and/or artificial events are important niches for regeneration [85].

Finally, it should be noted that the aggregate structure of the regenerative cohort evolves towards a random structure over time. Since the vital area is not extensible, recruitment within diameter classes affects densities, in the sense of regression. Indeed, the larger the trees, the lower their density [20] [62]. This evolution of structure would be the result of the mortality dependence mechanism of the individuals, which often corresponds to the transition from the young to the adult stage following intraspecific competition and that of water and mineral resources [86].

5. Conclusion

The peri-urban forest of Loukaya is subject to an exceptional level of anthropic pressure, which negatively affects biodiversity in all three dimensions. In this tropophilic and mesophilic ecosystem, anthropic activities would be the cause of

the poor generation of the woody population, especially sarcochorous taxa. The flora-fauna association in tropical forests is fundamental to their dynamics. In the peri-urban forest of Loukaya, as everywhere else, natural regeneration is strongly influenced by several parameters, notably the mode of dispersal and the various biotic and abiotic factors. The distribution of the regenerative cohort is dependent on the dispersal power of the taxa. These dispersal mechanisms determine the structure and fate of the stands. The absence of the agents of dissemination is at the origin of the aggregative structure of the regenerants, the corollaries of which are a high level of inter- and intra-species competition for available soil resources. The high frequency of regenerants coupled with their exceptionally high rate in windfalls and gaps are clear indications of the intensity and quantity of light reaching the undergrowth. Thus, light remains one of the essential elements in the development of the regenerating cohort.

Acknowledgements

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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