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# Assessment of Street Tree Diversity, Structure and Protection in Planned and Unplanned Neighborhoods of Lubumbashi City (DR Congo)

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**Citation:** Useni Sikuzani, Y.; Mpibwe Kalenga, A.; Yona Mleci, J.; N'Tambwe Nghonda, D.; Malaisse, F.; Bogaert, J. Assessment of Street Tree Diversity, Structure and Protection in Planned and Unplanned Neighborhoods of Lubumbashi City (DR Congo). *Sustainability* **2022**, *14*, 3830. https://doi.org/10.3390/su14073830

Academic Editors: Paolo Semenzato, Thomas Campagnaro and Luigi Aldieri

Received: 4 February 2022
Accepted: 21 March 2022
Published: 24 March 2022



**Abstract:** Street trees are always considered a vital part of urban green infrastructure in urbanized areas through mitigating the negative effects caused by urbanization taking part in human well-being. However, little is still known about their diversity, structure and protection, mostly in Lubumbashi city in the Democratic Republic of the Congo (DR Congo), where the pace of urbanization is not only rapid but also unplanned. In this study, using an inventory, we have characterized the diversity, structure and protection measures of street trees along a land-use planning gradient in Lubumbashi for both planned and unplanned neighborhoods. From the results, a total of 1596 trees were encountered, comprising 40 species, 33 genera and 17 families, mostly dominated by exotic species (65%). In addition, most of the studied trees (63%) belonged to four species only (*Jacaranda mimosifolia*, *Leucaena leucocephala*, *Mangifera indica*, and *Acacia auriculiformis*) with *Leucaena leucocephala* and *Jacaranda mimosifolia* being highly represented in unplanned and planned neighborhoods, respectively. The most abundant diameter classes in the planned neighborhoods were those with at most 10 cm against the classes larger than 50 cm in the planned neighborhoods. In both neighborhoods, trees with protection equipment represent less than 35%. Furthermore, in planned neighborhoods notably, nearly half of the observed equipment is in a good condition. Despite the benefits associated with street trees, there is a need to reduce the proportion of exotic tree species by planting native utilitarian tree species.

**Keywords:** urbanization; street trees; diversity; alien species; ecosystem services; land use planning

## 1. Introduction

Over decades, increased human needs for energy, food and shelter have drastically led to modified natural ecosystems [1]. According to the global population distribution, the human population was mainly rural at the beginning of the 21st century while most of the global population is living in cities nowadays. Although urban areas cover less than 5% of the earth's surface [2], the expansion of cities has led to the removal of original vegetation cover and its replacement by a diversity of anthropogenic land uses [3–5], which could increase plant diversity [6].

Additionally, urbanization generally causes adverse environmental changes that lead to the overall depletion of native biodiversity [7]. To compensate for this, green spaces are generally introduced and/or managed within cities through urban parks, street trees and other initiatives [8,9]. Street trees especially are a vital part of the urban green infrastructure by providing a set of ecosystem services, including air purification [10], microclimate regulation and noise reduction, thereby improving human well-being [11]. On the other hand, street trees may cause some issues, such as the interruption of views, litter dropping, etc. However, these negative impacts could be avoided by implementing an effective master plan which includes tree variety selection, a program of tree establishment and care, and this with the financial and technical support of the local municipality [10].

Nowadays, little is known about street trees in sub-Saharan Africa [12,13] with most studies being focused on park-like or spacious green spaces [14–16]. Moreover, in northern cities that have previously been studied [17–20], street trees were often uniform and generally comprised only one species, with specialized public services for their setting, maintenance and protection [21]. While these public services exist in most African cities, financial support and human resources are still needed [22]. Consequently, the few existing street trees are generally protected and maintained by common people [23,24].

Uncontrolled access to street tree harvesting increases the interest of the riparian population in their abusive use and diversification [13,25]. Thus, preferred species being introduced into these plantations by local populations has been observed [13]. These practices modify the floristic composition of the plantations, disrupt the viability of the trees and increase the diversity of management approaches [15,26]. Furthermore, Ref. [27] revealed that urban street trees are prone to several types of stress (i.e., pollution) and accidents due to trampling, grazing and vandalism, which hamper their growth and development. To avoid this situation, protective equipment is sometimes installed around street trees during their development. However, this is often performed without assessing the condition of the tree equipment in most developing countries, including the cities of the Democratic Republic of the Congo (DR Congo).

Nowadays, in Lubumbashi city, studies on street trees are still scarce. Lubumbashi city has enjoyed significant economic growth, which has mainly been due to mining activities that have been developed around for more than a century [28–30], but also due to commercial transactions facilitated by its proximity to southern African countries. Additionally, the city has faced a major demographic explosion driven by both the influx of migrants and by nearly 30 years of rapid natural urban growth [31]. On the other hand, the city is experiencing rapid and anarchic urban spatial expansion from post-independence to the present day [32], which could negatively impact the vegetation in and around the city [33].

Indeed, Lubumbashi city presented a set of potentially admirable green spaces [34,35]. Once carefully maintained, these green spaces, including street trees, have been neglected or abandoned (like most of the Eucalyptus plantations) since Lubumbashi does not have a master plan for urban development [29]. Street trees, from which certain plants used in traditional medicine are harvested [36], are not planned in unplanned neighborhoods, the birth of which is accompanied by the systematic destruction of pre-existing vegetation cover [35]. Since public authorities have only limited control over the urban land under their jurisdiction [29], Lubumbashi city is distinguished by the densification of buildings in colonial-era planned neighborhoods. In these areas, it has been difficult to maintain the quality and quantity of green infrastructure, including street trees [35]. On the other hand, many buildings extension areas are appearing in the city's peri-urban zone, contributing to the formation of unplanned neighborhoods with a severe lack of park-like green spaces. For this reason, new organizational patterns for street tree planting by residents are emerging in unplanned neighborhoods.

Thus, many of the city's streets of both planned and unplanned neighborhoods are home to significant flora whose diversity, origin and environmental risks are largely unknown. Only a few recent studies have focused on plant diversity in wooded green spaces [37] and fruit trees in domestic plots [38]. This information, which is crucial for guiding decision-makers in the planning and management of urban flora, is sorely lacking for Lubumbashi city despite their importance for the provision of ecosystem services. Thus, updating the knowledge on the flora of street trees is necessary to complete the little amount of existing floristic data for Lubumbashi city. It is therefore important to analyze street trees by separately considering planned neighborhoods with higher built-up density and unplanned neighborhoods resulting from intensive peri-urbanization.

The present study aimed at analyzing the diversity, structure and protection of street trees along a land-use planning gradient of Lubumbashi city. We hypothesized that the presence of old trees from the colonial period, combined with new plantations, would have increased the diversity of street trees in planned neighborhoods; (ii) regardless of neighborhood type, street tree flora tends to be homogenized by the dominance of a small group of exotic utilitarian and ornamental species; and (iii) in planned neighborhoods, where public services are still concentrated in a few activities, protective equipment around street trees may be in good condition, as opposed to unplanned neighborhoods, where roads are otherwise narrow.

## 2. Materials and Methods

### *2.1. Study Area*

Lubumbashi city (11°27′–11°47′ S and 27°19′–27°40′ E) covers nearly 747 km$^2$ [29] and comprises seven municipalities: Annexe, Katuba, Kampemba, Kamalondo, Kenya, Lubumbashi and Ruashi (Figure 1). Within the city, the altitude varies between 1200 and 1300 m. According to the Köppen classification system, Lubumbashi city has a Cw climate [39] with a dry season (May to September), a rainy season (November to March) and two transition months (April and October). Refs. [40,41] suggested that five seasons are defined from phenological observations of vegetation: the cold dry season (May–July), hot dry season (August–September), early rainy season (October–November), full rainy season (December–February) and the late rainy season (March–April). While this pattern remains valid, recent studies have shown a later onset of rains and lower average annual rainfall [42]. The average annual temperature was around 20.1 °C for the second half of the last century. The dominant soils are ferralsols, mostly represented by yellow and red soils. Oxidation conditions are excellent for red soils and less favorable for yellow soils with a shallow water table [39].

Lubumbashi city and its hinterland were nearly 90% covered by *miombo* woodland at the beginning of the last century [33]. Currently, the city is surrounded by anthropized vegetation resulting from the degradation of *miombo* woodland into tree savannah, then shrub and finally grass [39]. Bare soil is found in areas heavily affected by mining activities and eolian heavy metal deposits, mainly in a conical area northwest of the Gécamines metal processing site [43]. The economic activities that support the survival of almost 2.5 million inhabitants consist of industrial and artisanal mining, general trade, agriculture (subsistence) and informal trade [44].

In Lubumbashi city, there is a clear difference between planned and unplanned neighborhoods. However, over time, orderly city expansion has become the exception and spontaneity is almost the rule. On the one hand, abandoned spaces around the city have been invaded by unplanned neighborhoods [35]. In these neighborhoods, the land is often occupied illegally as inhabitants settle in green spaces, at sewage treatment plants, in areas reserved for facilities and in unhealthy places [29]. In this study, neighborhoods were selected based on the level of planning, leading to their separation into two groups of planned neighborhoods and unplanned neighborhoods. Table 1 summarizes the main biophysical and socio-economic characteristics of each neighborhood and the municipality they belong to. The planned neighborhoods studied date back to the colonial period (before 1960), while the unplanned neighborhoods studied—which are juxtaposed with the planned neighborhoods—are post-colonial. However, they existed as villages during the colonial period.

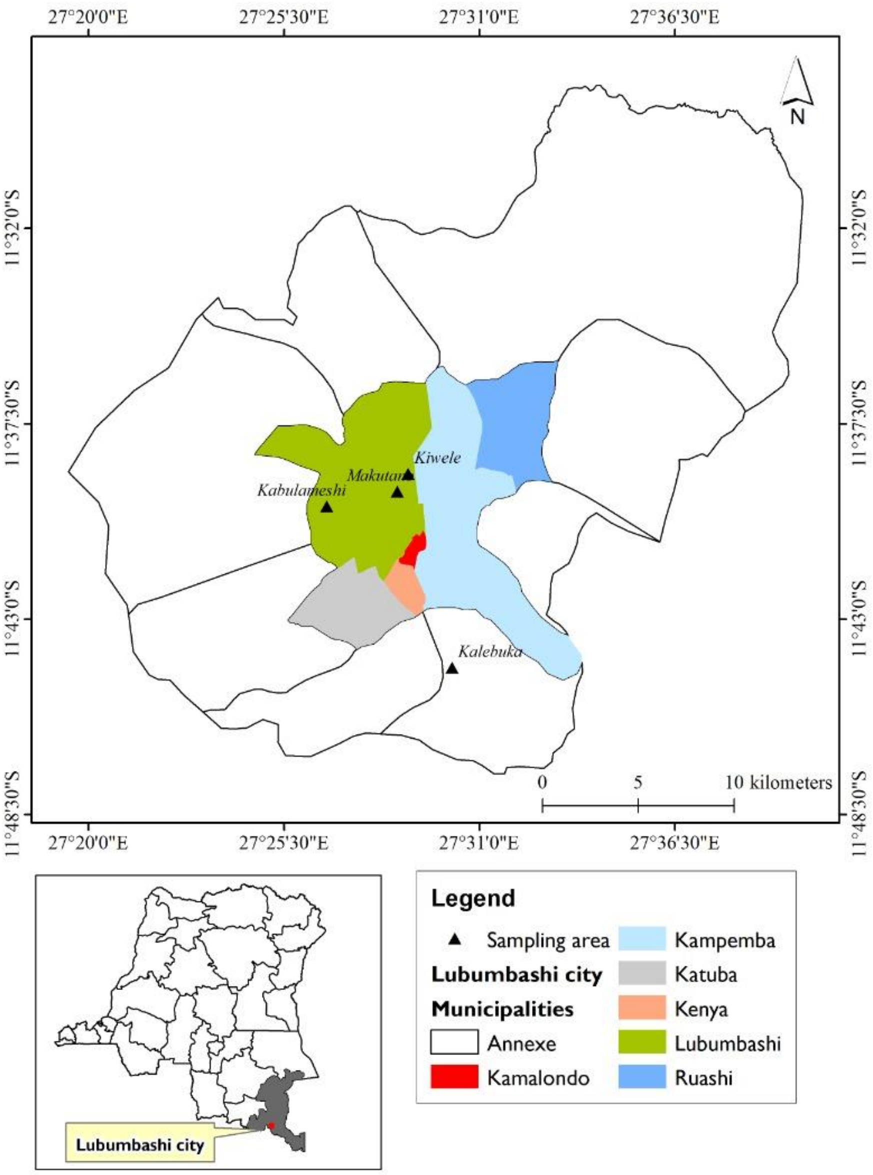


**Figure 1.** Geographic location of Lubumbashi city in the Upper Katanga province, south-eastern DRC. The neighborhoods studied within the two municipalities of Lubumbashi city are marked by the black points.

**Table 1.** Main characteristics of unplanned and planned neighborhoods studied in Lubumbashi city.

| Neighborhood Type | Neighborhood (Municipality) | Location | Area (km$^2$) | Vegetation Status |
|---|---|---|---|---|
| Planned | Kiwele (Lubumbashi) | 11°38′54.43″ S 27°28′59.70″ E | 0.75 | Composed of paved roads with old street trees. There are also some parks with small acreage. Vegetation is managed by the public services although this management is limited |
| | Makutano (Lubumbashi) | 11°39′24.86″ S 27°28′41.34″ E | 4.34 | Composed of a planned part with the presence of some paved roads with easy accessibility. There are public and private green spaces, mainly managed parks. A lot of old street trees have been recently cut in this neighborhood without replacement, in order to prevent accidents. |

**Table 1.** *Cont.*

| Neighborhood Type | Neighborhood (Municipality) | Location | Area (km$^2$) | Vegetation Status |
|---|---|---|---|---|
| Unplanned | Kalebuka (Annexe) | 11°44′22.26″ S 27°30′13.96″ E | 8.80 | Generally informal districts and dilapidated streets. Only the main road is paved and difficult to access. The presence of dust during the dry season. Private properties planted with fruit trees, including Mango tree. Street trees are planted and managed by local populations and some NGO. There are no public services activities in terms of street tree management. |
| | Kabulameshi (Lubumbashi) | 11°39′49.90″ S 27°26′42.20″ E | 4.26 | Generally informal districts and dilapidated streets. Only the main road is paved. The presence of dust during the dry season. Public green spaces are absent. Street trees are planted and managed by local populations. Private properties planted with fruit trees, including Mango tree. |

## *2.2. Methods*

### 2.2.1. Sampling and Data Collection

A complete observation of street trees in the seven municipalities of Lubumbashi city was realized using Google Earth software. Neighborhoods with street trees (more than one) were selected and visited between June and July 2019. The inventory of trees was performed in two planned neighborhoods (Kiwele and Makutano) and two unplanned neighborhoods (Kabulameshi and Kalebuka) where street trees are present on at least two streets. This inventory included all streets with trees in these four neighborhoods, including 39 avenues in the planned neighborhoods (18 streets in Kiwele and 21 streets in Makutano) and 27 streets in the unplanned neighborhoods (11 streets in Kabulameshi and 16 streets in Kalebuka). Since the streets were not fully planted with trees, all trees along the streets were measured. To verify that anarchic urbanization in unplanned neighborhoods has led to a reduction in the width and length of streets, and consequently the density of trees, the length and width of each road were measured using the view route tool from Google Earth. From the collected values, we determined the length as well as the minimum and maximum width. The ratio of the total length of roads or their total width by their number within each type of neighborhood was used to calculate the average length and width of each road. Additionally, the length of each street that was covered by trees was determined via Google Earth.

In order to verify that the preservation of old tree species and the planting of new tree species would increase the species richness and plant diversity in the planned neighborhoods, all species found along each street (in both unplanned and planned neighborhoods) were identified using available flora guides [45] and the specialized literature [46,47], and the number of individuals per species was determined. Species origin was determined following [48]. Briefly, exotic species were considered those species that are not indigenous to a specific geographic area (in the *miombo* ecoregion). According to [46], the identified plant species were classified as ornamental, utilitarian (human or animal nutrition, shade provision, hydrological flow regulation, medical benefits, etc.), or mixed (ornamental and utilitarian). To check that the street trees in unplanned neighborhoods are relatively young, heights were measured using a Suunto clinometer, while the diameter at breast height (DBH) was measured using a DBH meter. Indeed, height and DBH provide information on the age of trees (seedling or adult). Thus, a tree is considered a juvenile when its DBH is between 0 and 10 cm and an adult when it has a DBH greater than 10 cm [49,50]. However, the crown diameter of each tree was measured by projecting the spread of the tree to the ground. Two perpendicular measurements were taken, and an average was calculated.

For each type of neighborhood, the density of street trees was determined by the ratio of the total number of trees surveyed to the total length of the street surveyed. Throughout the region, vehicle tires, as well as metal, wooden or bamboo structures, are sometimes placed/constructed around the bases of trees to protect them from trampling. For this reason, we checked their presence and condition. For protected trees, this equipment could either be in good condition (intact) or poor condition (partially or entirely damaged). Due to the high concentration of utilitarian human activities in the planned neighborhoods, it is expected that the trees along their will be further protected by devices in good condition.

#### 2.2.2. Data Analysis

Diversity indices, including Shannon's, Simpson's and Pielou's equitability, were calculated using PAST software version 4.05. Simpson's index describes the probability that a second individual from a stand is of the same species as the previous one, whereas Shannon's index indicates the species heterogeneity of a plant community and the distribution pattern of individuals among these species [18]. Pielou's equitability is the ratio of the observed diversity to the maximum possible diversity based on the total number of species surveyed. It indicates whether a stand is dominated by individuals belonging to a particular species [51]. These indices are increasingly used by biologists to understand community structure. Furthermore, they provide more information on community composition than only species richness and give insights into species rarity [52]. The similarity of the two neighborhood types was determined using Jaccard's similarity index [53]. To verify that certain botanical families would be abundant and characteristic of neighborhood types, a chi-square test was applied to compare the proportions of botanical families in planned neighborhoods and unplanned neighborhoods. Finally, using an analysis of variance with a Tukey post hoc test, the mean values of road characteristics and street tree structure were compared between neighborhoods. Minitab software was used for the statistical analyses, with a threshold probability value of 5% set.

## 3. Results

### 3.1. Main Characteristics of Roads

Table 2 summarizes the road characteristics of the two studied neighborhood types. In unplanned neighborhoods, the width and length of roads varied from 8 m to 12 m and 210 m to 1650 m, respectively. In general, as compared to unplanned neighborhoods, the roads situated in planned neighborhoods were about three times longer and 2–3 m wider, with only 8% of the roads being covered by the trees for both neighborhoods. There is a significant difference between planned and unplanned neighborhoods regarding the tree-covered roads. Accordingly, among the tree-covered roads, the values recorded for trees that cover the roads of the planned neighborhoods were 3-fold higher than that of the unplanned neighborhoods.

**Table 2.** Main characteristics of roads surveyed in the planned and unplanned neighborhoods of Lubumbashi city.

| Road Characteristics | Unplanned Neighborhoods | | Planned Neighborhoods | | *p*-Value |
|---|---|---|---|---|---|
| | Kabulameshi | Kalebuka | Makutano | Kiwele | |
| Maximum length (m) | 1650 | 1475 | 3765 | 2575 | - |
| Minimum length (m) | 210 | 245 | 300 | 340 | - |
| Average length (m) | 895 ± 47 c | 857 ± 35 c | 2245 ± 675 a | 1720 ± 490 b | 0.000 |
| Maximum width (m) | 12 | 12 | 15 | 15 | - |
| Minimum width (m) | 8.75 | 8 | 12.50 | 10 | - |
| Average width (m) | 10.20 ± 2.40 ab | 9.40 ± 3.26 b | 13.15 ± 2.60 a | 10.95 ± 1.95 ab | 0.000 |
| Average length of trees/Average street length | 0.07 ± 0.01 c | 0.09 ± 0.01 c | 0.27 ± 0.11 a | 0.22 ± 0.09 b | 0.000 |

Data were obtained from Google Earth. The different letters next to the averages indicate significant differences for the Tukey test with a threshold probability value set at 5%.

### 3.2. Street Tree Diversity and Distribution

Globally, 1596 trees clustered into 40 species, 33 genera and 17 families were recorded. Of the 40 identified species, 26 were exotic (65%) while only 14 were native (35%). In terms of tree abundance, the native species occupied a very small proportion (4.7%) while about 95.3% of the trees (1521 individuals) were exotic species from which, 1005 belonged to four species: *Jacaranda mimosifolia* (453 trees), *Leucaena leucocephala* (227 trees), *Mangifera indica* (186 trees), and *Acacia auriculiformis* (138 trees, Table 3). At the neighborhood level, 30 and 27 tree species were inventoried in planned and unplanned neighborhoods respectively. Both neighborhoods were dominated by exotic species, representing almost 77% and 66% in planned and unplanned neighborhoods, respectively. In unplanned neighborhoods, *L. leucocephala* was commonly found with about 63 trees, while only one single tree per species for the other species (*Ficus* sp., *J. mimosifolia*, *Julbernardia aniculate*, *Melia azedarach* and *Senna siamea*) was observed. Surprisingly, *J. mimosifolia* was the most common species in planned neighborhoods, while, *Albizia antunesiana*, *Brachystegia boehmii*, *Ficus thonningii* and *Thevetia peruviana* were the least (Table 3).

**Table 3.** Species, family and number of trees (NT) according to neighborhood types and occurrence on street. Plant species in the street trees of Lubumbashi city have been categorized in ornamental (O), utilitarian (U), and mixed (M) according to their uses. The origin status was defined in exotic € and native (N). The relative frequency of the number of trees (NT) and the number of streets (NS) where species are found are compared between unplanned neighborhoods (UN) and planned neighborhoods (PN). The species are listed in alphabetical order.

| Species | Family | NT (%) | | NS (%) | | Origin Status | Uses |
|---|---|---|---|---|---|---|---|
| | | UN ($n$ = 182) | PN ($n$ = 1414) | UN ($n$ = 27) | PN ($n$ = 39) | | |
| *Acacia auriculiformis* Benth. | Fabaceae | 11.54 | 8.35 | 6.06 | 34.85 | E | M |
| *Albizia antunesiana* Harms | Fabaceae | 0.00 | 0.07 | 0.00 | 1.52 | N | M |
| *Albizia lebbeck* (L.) Benth. | Fabaceae | 2.75 | 1.20 | 1.52 | 13.64 | E | O |
| *Bauhinia reticulata* DC. | Fabaceae | 0.00 | 0.78 | 0.00 | 9.09 | E | M |
| *Bauhinia variegata* L. | Fabaceae | 1.10 | 0.71 | 3.03 | 9.09 | E | M |
| *Brachystegia boehmii* Taub. | Fabaceae | 2.20 | 0.07 | 3.03 | 1.52 | N | M |
| *Brachystegia longifolia* Benth. | Fabaceae | 2.20 | 0.00 | 1.52 | 0.00 | N | M |
| *Brachystegia spiciformis* Benth. | Fabaceae | 0.00 | 1.77 | 0.00 | 10.61 | N | M |
| *Callistemon speciosus* (Sims) Sweet | Myrtaceae | 1.10 | 3.39 | 3.03 | 15.15 | E | M |
| *Citrus lemon* (L.) Osbeck | Rutaceae | 1.10 | 0.00 | 3.03 | 0.00 | E | M |
| *Delonix regia* (Hook.) Raf. | Fabaceae | 0.00 | 6.86 | 0.00 | 7.58 | E | O |
| *Eucalyptus grandis* W. Mill ex Maiden | Myrtaceae | 2.75 | 0.42 | 3.03 | 7.58 | E | U |
| *Ficus* sp. | Moraceae | 0.55 | 0.78 | 1.52 | 12.12 | N | O |
| *Ficus thonningii* Blume | Moraceae | 0.00 | 0.07 | 0.00 | 1.52 | N | O |
| *Harungana madagascariensis* Lam. ex Poir. | Hypericaceae | 0.00 | 0.21 | 0.00 | 4.55 | N | M |
| *Heinsia crinita* (Afzel.) G. Taylor | Rubiaceae | 1.65 | 0.00 | 3.03 | 0.00 | E | O |
| *Jacaranda mimosifolia* D.Don | Bignoniaceae | 0.55 | 31.97 | 1.52 | 30.30 | E | O |
| *Julbernardia paniculata* (Benth.) Troupin | Fabaceae | 0.55 | 0.00 | 1.52 | 0.00 | N | M |
| *Leucaena leucocephala* (Lam.) de Wit | Fabaceae | 34.62 | 11.60 | 7.58 | 40.91 | E | M |
| *Mangifera indica* L. | Anacardiaceae | 11.54 | 11.67 | 15.15 | 33.33 | E | M |
| *Maranthes floribunda* (Backer) F. With | Chrysobalanaceae | 1.10 | 0.00 | 1.52 | 0.00 | N | O |
| *Melia azedarach* L. | Meliaceae | 0.55 | 1.91 | 1.52 | 6.06 | E | M |
| *Moringa oleifera* Lam. | Moringaceae | 0.00 | 0.78 | 0.00 | 4.55 | E | M |
| *Ochna schweinfurthiana* F. Hoffm | Ochnaceae | 1.10 | 0.00 | 1.52 | 0.00 | N | O |
| *Pericopsis angolensis* (Baker) Meeuwen | Fabaceae | 0.55 | 0.00 | 1.52 | 0.00 | N | M |
| *Persea americana* Mill. | Lauraceae | 3.85 | 0.99 | 6.06 | 7.58 | E | M |
| *Picea abies* (L.) H. Karst. | Pinaceae | 1.10 | 0.00 | 1.52 | 0.00 | E | O |
| *Piliostigma thoningii* (Schumach.) Milne-Redh. | Fabaceae | 6.04 | 0.00 | 4.55 | 0.00 | N | O |
| *Pinus sylvestris* L. | Pinaceae | 2.20 | 2.26 | 3.03 | 13.64 | E | O |
| *Plumeria alba* L. | Apocynaceae | 0.00 | 0.92 | 0.00 | 4.55 | E | O |
| *Plumeria rubra* L. | Apocynaceae | 0.00 | 0.21 | 0.00 | 3.03 | E | O |
| *Polyalthia longifolia* (Sonn.) Thwaites | Annonaceae | 0.00 | 1.06 | 0.00 | 4.55 | E | O |
| *Psidium guajava* L. | Myrtaceae | 1.65 | 0.85 | 3.03 | 15.15 | E | M |
| *Pterocarpus angolensis* DC. | Fabaceae | 1.65 | 0.00 | 1.52 | 0.00 | N | O |
| *Senna siamea* (Lam.) H.S. Irwin & Barneby | Fabaceae | 0.55 | 4.38 | 1.52 | 15.15 | E | O |
| *Senna spectabilis* (DC.) H.S. Irwin & Barneby | Fabaceae | 1.65 | 1.49 | 3.03 | 7.58 | E | O |

**Table 3.** *Cont.*

| Species | Family | NT (%) | | NS (%) | | Origin Status | Uses |
|---|---|---|---|---|---|---|---|
| | | UN (*n* = 182) | PN (*n* = 1414) | UN (*n* = 27) | PN (*n* = 39) | | |
| *Spathodea nilotica* Seemann | Bignoniaceae | 0.00 | 1.13 | 0.00 | 12.12 | E | O |
| *Syzygium guineense* (Willd.) DC. | Myrtaceae | 0.00 | 0.28 | 0.00 | 6.06 | N | M |
| *Terminalia mantaly* H.Perrier | Combretaceae | 3.85 | 3.75 | 1.52 | 25.76 | E | M |
| *Thevetia peruviana* (Pers.) K. Schum. | Apocynaceae | 0.00 | 0.07 | 0.00 | 1.52 | E | M |

In unplanned neighborhoods, *M. indica* was observed on about one-third of the streets while the presence of *Albizia lebbeck*, *Brachystegia longifolia*, *Ficus* spp., *J. mimosifolia*, *J. paniculata*, *Maranthes floribunda*, *M. azedarach*, *Ochna schweinfurthiana*, *Pericopsis angolensis*, *Picea abies*, *Pericopsis angolensis*, *S. siamea*, and *Terminalia mantaly* was less frequent. However, the planned neighborhoods showed a higher presence of *L. leucocephala* (69.2%) when species such as *A. antunesiana*, *B. boehmii* and *T. peruviana* were only found on one street (Table 3).

In this study, tree flora was also differently observed across neighborhood types. Overall, 17 species were inclusively registered in both planned and unplanned neighborhoods, which has led to 43% as similarity rate of tree species richness along the streets for both neighborhoods, according to Jaccard's index. Thirteen tree species (*A. antunesiana*, *Bauhinia reticulata*, *Brachystegia spiciformis*, *Delonix regia*, *Ficus thonningii*, *Harungana madagascariensis*, *Moringa oleifera*, *Plumeria alba*, *Plumeria rubra*, *Polyalthia longifolia*, *Spathodea nilotica*, *Syzygium guineense*, and *T. peruviana*) and 10 tree species (*B. longifolia*, *Citrus lemon*, *Heinsia crinita*, *J. paniculata*, *M. floribunda*, *O. schweinfurthiana*, *P. angolensis*, *P. abies*, *Piliostigma thoningii* and *Pterocarpus angolensis*) were exclusively found in planned or unplanned neighborhoods, respectively (Table 3). However, our results show that 18 street tree species are planted for ornamental purposes (i.e., *J. mimmosifolia*), while only one utilitarian species was observed. The other tree species are planted for both ornamental and various other uses, such as the production of edible fruits, provision of shade, or medicinal properties (i.e., *M. indica*). Among the 30 inventoried tree species in the planned neighborhoods, 12 are ornamental, 17 species are mixed-use and only one species is found to be exclusively utilitarian. Of the 27 species found in the unplanned neighborhood, 17 are mixed-use, while nine and only one are ornamental and utilitarian, respectively.

Furthermore, the Shannon and Simpson indices have been found to be higher in planned neighborhoods, which might be indicative of a higher diversity of street tree species. However, there is a low dominance of tree species along streets in unplanned neighborhoods compared to planned neighborhoods, where only trees of a few species frequently occurred (Table 4).

**Table 4.** Diversity of street trees in the unplanned and the planned neighborhoods of Lubumbashi city.

| Indices | Unplanned Neighborhoods | | Planned Neighborhoods | |
|---|---|---|---|---|
| | Kabulameshi | Kalebuka | Makutano | Kiwele |
| Simpson_1-D | 0.8669 | 0.8132 | 0.8622 | 0.8510 |
| Shannon_H | 2.591 | 2.263 | 2.432 | 2.419 |
| Pielou's Equitability (E) | 0.7398 | 0.7424 | 0.7098 | 0.7125 |
| Species richness | 21 | 10 | 26 | 25 |
| Individuals | 148 | 34 | 292 | 1122 |

Of the 17 recorded families, the Fabaceae was the most dominant, with up to 16 species while families such as Anacardiaceae, Annonaceae, Chrysobalanaceae, Combretaceae, Hypericaceae, Lauraceae, Meliaceae, Moringaceae and Ochnoceae had only one single species each. Globally, out of the 1596 inventoried trees, the Fabaceae family had for itself 646 trees (40.5%) divided into 119 and 527 trees for unplanned and planned neighborhoods, respectively (Table 5). Statistical analyses (chi-squared = 50.114, df = 16, $p$-value = 0.00002198) revealed significant differences between the proportions of families between the two neighborhoods. Thus, the unplanned neighborhoods showed higher proportions of trees belonging to Bignoniaceae, Apocynaceae, Annonaceae, Moringaceae, Meliaceae and Hypericaceae while trees from Fabaceae, Lauraceae, Rubiaceae, Rutaceae, Chrysobalanaceae and Ochnaceae were found to be more frequent in planned neighborhoods (Table 5).

**Table 5.** Relative frequency (in percentage) of botanical families of street trees in unplanned and planned neighborhoods of Lubumbashi city.

| N° | Family | Unplanned Neighborhood ($n$ = 182 trees) | Planned Neighborhood ($n$ = 1414 trees) |
|---|---|---|---|
| 1 | Fabaceae | 65.38 | 37.27 |
| 2 | Bignoniaceae | 0.55 | 33.10 |
| 3 | Anacardiaceae | 11.54 | 11.67 |
| 4 | Myrtaceae | 5.49 | 4.95 |
| 5 | Combretaceae | 3.85 | 3.75 |
| 6 | Pinaceae | 3.30 | 2.26 |
| 7 | Meliaceae | 0.55 | 1.91 |
| 8 | Lauraceae | 3.85 | 0.99 |
| 9 | Apocynaceae | 0.00 | 1.20 |
| 10 | Annonaceae | 0.00 | 1.06 |
| 11 | Moraceae | 0.55 | 0.85 |
| 12 | Moringaceae | 0.00 | 0.78 |
| 13 | Hypericaceae | 0.00 | 0.21 |
| 14 | Rubiaceae | 1.65 | 0.00 |
| 15 | Rutaceae | 1.10 | 0.00 |
| 16 | Chrysobalanaceae | 1.10 | 0.00 |
| 17 | Ochnaceae | 1.10 | 0.00 |

The tree diameter distributions in planned and unplanned neighborhoods are illustrated in Figure 2. It was observed that more seedlings were found in the unplanned neighborhoods than in the planned ones. The most abundant diameter class in the unplanned neighborhoods was 0–10 cm, leading to an inverted J-shape curve similar to the structure of natural forests in full regeneration. Conversely, the street trees of the planned neighborhoods were mostly characterized by trees with a diameter greater than 50 cm. In addition, the street tree densities in unplanned neighborhoods were about twofold lower than those in planned neighborhoods ($p$ = 0.000). Furthermore, as compared to unplanned neighborhoods, the highest values of trees in terms of height and crown diameter were observed in planned neighborhoods ($p$ = 0.001); *mimosifolia* (40 m) and *E. grandis* (25 m) were the highest trees in the planned and unplanned neighborhoods, respectively. For the crown diameter, the highest value was recorded for *L. leucocephala* (37 m) in planned neighborhoods and the lowest one for *P. thoningii* and *H. crinite* in planned neighborhoods (Table 6). The results of the variance analysis revealed that avenue trees in planned neighborhoods had higher crown diameter values compared to those in unplanned neighborhoods ($p$ = 0.000).

### *3.3. Protective Equipment and Its Condition*

Protective structures are used to protect trees from various human and animal pressures. In this context, the seedlings (i.e., the majority in unplanned neighborhoods) in our study should be more commonly accompanied by protective equipment. Surprisingly, our results showed that more than half of the street trees did not have protective equipment irrespective of the neighborhoods, with only 5.3% and 33.5% of the trees being protected in planned and unplanned neighborhoods, respectively (Figure 3). Although trees with protective equipment were six times higher present in unplanned neighborhoods than in planned neighborhoods, the opposite situation was observed with regard to the condition of the protective equipment. Thus, 46.7% of protected trees in planned neighborhoods were found to be well equipped when the same was observed with only 6.6% in unplanned neighborhoods.

**Table 6.** Street tree height, crown diameter, and density in unplanned and planned neighborhoods of Lubumbashi city. The different letters next to the averages indicate significant differences for the Tukey test with a threshold probability value set at 5%.

| | **Unplanned Neighborhoods** | | **Planned Neighborhoods** | | ***p*-Value** |
|---|---|---|---|---|---|
| | **Kabulameshi** | **Kalebuka** | **Makutano** | **Kiwele** | |
| Maximum height (m) | 25.0 | 22.5 | 40.0 | 37.0 | - |
| Minimum height (m) | 1.25 | 1.5 | 2.0 | 2.0 | - |
| Average height (m) | 7.3 ± 2.1 b | 6.8 ± 2.8 b | 11.0 ± 3.9 a | 10.6 ± 2.7 a | 0.000 |
| Maximum crown diameter (m) | 16.0 | 14.0 | 37.0 | 32.0 | - |
| Minimum crown diameter (m) | 1.0 | 1.0 | 1.0 | 1.0 | - |
| Average crown diameter (m) | 4.8 ± 2.4 b | 4.9 ± 3 b | 6.5 ± 3.8 a | 5.5 ± 3.2 ab | 0.001 |
| Trees density (trees number/km) | 8.4 ± 1.7 c | 7.3 ± 2.3 c | 24.5 ± 6.4 a | 12.25 ± 4.1 b | 0.000 |

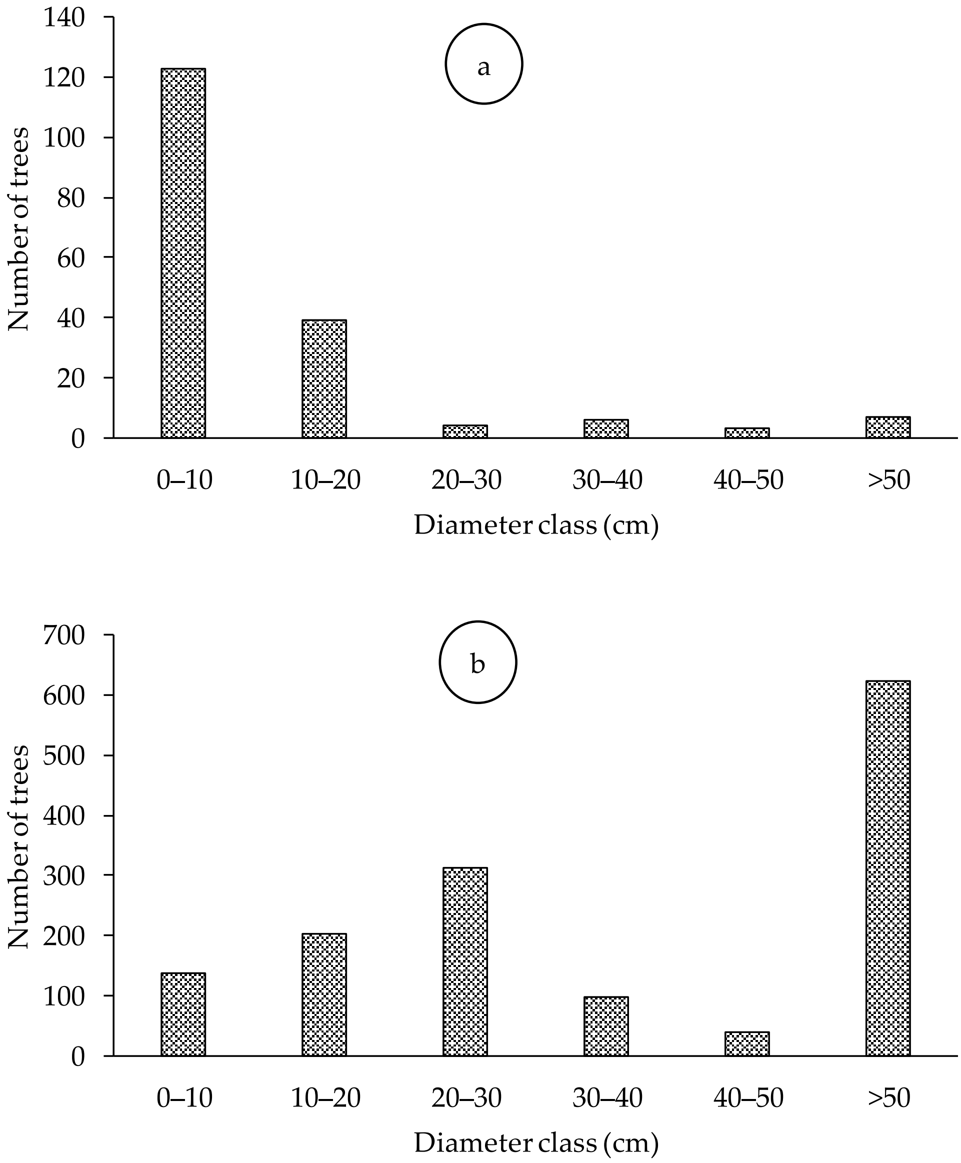


**Figure 2.** Distribution of street tree diameter in (**a**) unplanned and (**b**) planned neighborhoods.

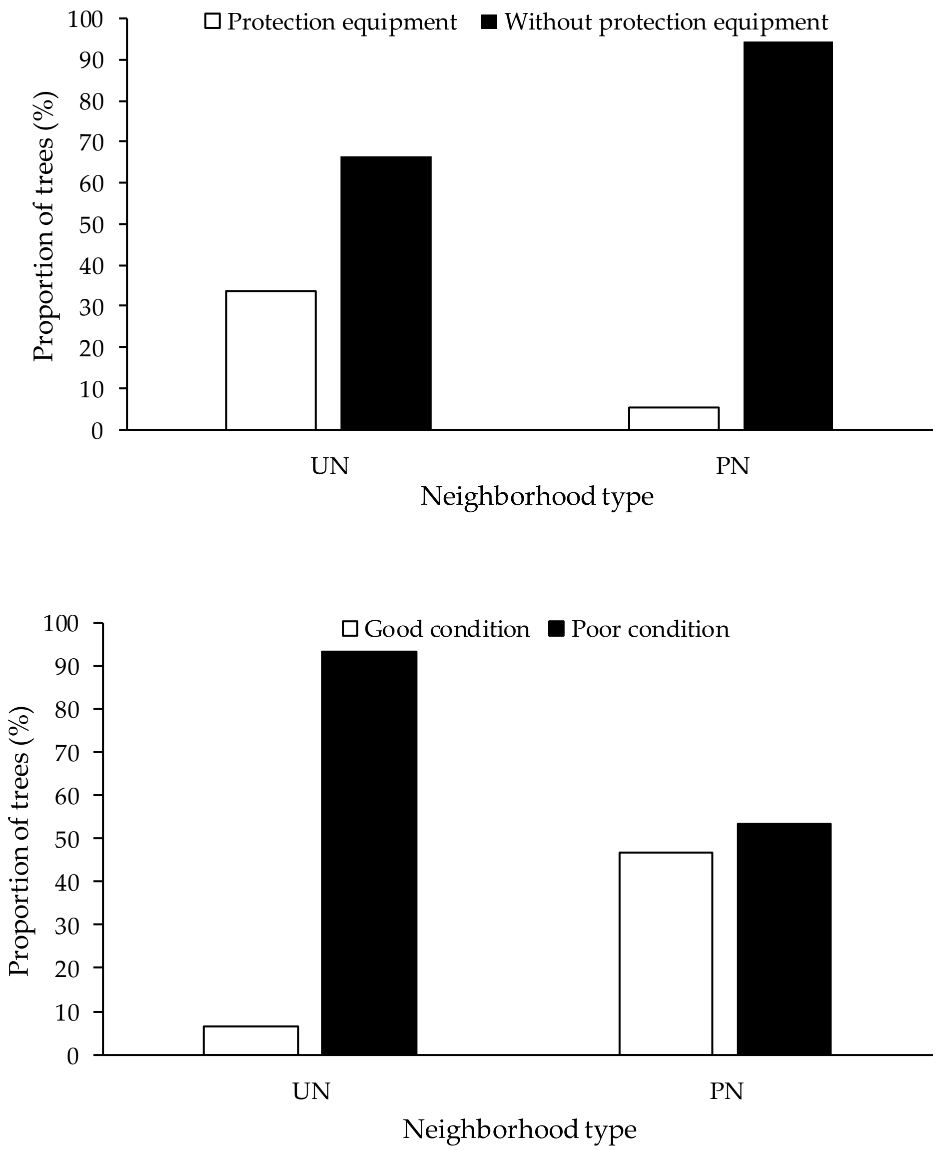


**Figure 3.** Protective equipment (top; $n$ = 182 trees in the unplanned neighborhoods; $n$ = 1414 trees in the planned neighborhoods) and their condition (bottom; $n$ = 61 trees in the unplanned neighborhoods; $n$ = 75 trees in the planned neighborhoods) around street trees of Lubumbashi city.

## 4. Discussion

### *4.1. Diversity of Street Trees and Urban Forest Structure*

The planned neighborhoods of Lubumbashi city were mainly built during the colonial era (i.e., before 1960) [34]. After political independence, systematic non-investment in urban planning caused cities to expand exponentially [35]. Although the planned neighborhoods were laid out in a grid pattern with wide roads, the widths of these roads have been narrowed due to the residents frequently moving the boundaries of their plots towards the roads. We confirmed that anarchic urbanization in unplanned neighborhoods has led to a reduction in the width and length of streets.

As usually observed in planned neighborhoods, wider and straighter streets are more exposed to ventilation and insolation. To solve this issue, a number of trees have been planted along roadsides [28], explaining the presence of higher trees density in planned neighborhoods. However, most of the trees have been gradually disappearing as a consequence of accidents or age. The same trend was also reported by [54] who noted that every accident caused by a falling tree became an argument for cutting down adjacent trees in Polish cities. On the other hand, in unplanned neighborhoods, the lack of planning might explain why the streets have a lower tree cover. Furthermore, in these spontaneous neighborhoods, streets trees are also sometimes planted by residents. It is shown that residents plant trees in front of their plots in Pennsylvania, but with support from the public authorities (USA) [55], which is not the case in our study, due to the lack of practical tools and training for most public staff.

It was demonstrated in this study that 65% of the tree species were exotic, which is common in a developing country such as the DR Congo, where the introduction of exotic species in the country was driven by accidental or deliberate introductions of plant species by humans for the various purposes including ornamentation, cultural and economic needs [56]. The same trend was observed in the Eastern Cape of South Africa where 60% of the most frequently occurring tree species were alien [57]. Similarly, in Bangalore (India), 67% of the street trees were alien to India [56]. In Ghana, 65% of the tree species in Kumasi city are exotic [58]. Unfortunately, it was demonstrated that the presence of a high number of introduced species alters the structure and function of ecosystems [59]. In addition, some of these exotic species are reported to be invasive with severe consequences to biodiversity, thereby potentially affecting the economies of the countries [60,61].

It has been demonstrated in this study that *J. mimosifolia* and *L. leucocephala* are two species grown for ornamental purposes [34]. As a subtropical tree belonging to the Bignoniaceae family, *J. mimosifolia*, is widely grown for its beauty and long-lasting blue summer bloom. Technically, this species is well known for its ease and speed of growing, reaching up to 15 m height [62] in addition to being dominantly woody. In Lubumbashi city, *J. mimosifolia* was found to be dominant in urban and peri-urban woody green spaces [37]. Our study reported also the presence of *L. leucocephala* in several streets, yet it is considered an invasive alien species [37,63]. However, due to the economic regression in DRC [64], more utilitarian trees have been planted by local residents. Thus, species like *Mangifera indica* can be used both for fruits and traditional medicine purposes [38].

Our results which reveal that only four tree species tend to be dominant in both types of neighborhoods are in line with those of [65], who revealed that a few species dominate in urban areas and reflect the role of urbanization in biotic homogenization [59]. Due to strong human preferences, Refs. [13,66,67] also noted a dominance of four, five and four tree species, respectively, in Abidjan (Côte d'Ivoire), Daloa (Côte d'Ivoire) and Grand-Popo (Benin). Our results are, however, in contrast with the study by [57], who counted 1101 trees spread over 70 species in Accra, Ghana. This can be explained by the difference in climatic conditions and the involvement of public services. Indeed, Ghana has rich experience in democratic governance and a decentralized local governance system [68]. Differences between neighborhood types in terms of tree diversity were also recorded because most of the streets of unplanned neighborhoods are secondary. In line with this, [69] recorded differences in street tree diversity for primary and secondary roads are studied separately.

The tree species diversity found in the planned neighborhoods in Lubumbashi city is the result of the presence of trees planted since the colonial era [34], which public services try to maintain in good condition, and of recent plantations carried out a few decades ago by the public services. In planned neighborhoods with a high standard of living, other trees are also planted in front of the plots by the residents who can sell trees directly in plant nurseries [46]. However, as the old street trees in the planned neighborhoods are falling due to old age, generally without replacement, we can assume a reduction in species richness in the short term. Furthermore, compared to the density given by [34], it appears that the number of individuals is falling, although species richness may be increasing, due to various stresses.

The propagation of similar plants in the unplanned neighborhoods of Lubumbashi city is due to the actions of residents that copy, adapt, exchange plants and suggest ideas at a local scale [6,46], especially since Lubumbashi city lacks specialized services for this purpose. Yet, these species with a high frequency of occurrence may induce floristic uniformity [59]. However, some *miombo* tree species were found in Lubumbashi city, with a higher proportion occurring in the unplanned neighborhoods. The presence of some *miombo* woodland species was regarded as evidence of some level of degradation or regeneration of certain original *miombo* woodland patches [37]. According to the urban–rural gradient theory, most unplanned neighborhoods are located in peri-urban parts of the city and combine, hence introducing tree species from urban zones and some *miombo* woodland tree characteristics of rural zones [5]. Furthermore, while unplanned neighborhoods record an expansion of the built-up area, some trees of *miombo* woodland species of socio-economic interest are preserved in front or within the plots. This is the case with *S. guineense*.

The study also showed that trees that belong to the Fabaceae family were more common than those of other families. This explains the ability of woody plants of this family to adapt to tropical regions, which resulted in divided leaves that allow these trees to pass the long dry season without losing much water [70–75]. Additionally, their ability to fix atmospheric nitrogen allows them to adapt to a wide range of soils, including poor ones [57].

The values of the Shannon and Simpson indices obtained in our study are close to those recorded in eight European and American cities (Simpson index: 0.75–0.95; Shannon index: 1.73–3.64) due to the dominance of a few species [76]. Accordingly, in China, most cities are also dominated by only a few species of trees, and a large proportion of these trees are non-native tree species, indicating that streetscapes are likely not favorable to biodiversity [77]. However, the Pielou index values ranged between 0.70 and 0.74 according to the neighborhood types, such as that found in other studies [78]. The lower evenness in the planned neighborhoods indicates a tendency towards uniformity.

The larger diameters of street trees in the planned neighborhoods suggest that these areas were planted decades ago. Thus, the difference in street tree diameters between planned and unplanned neighborhoods is consistent with the findings of [34], revealing that the residential neighborhoods are older than most unplanned neighborhoods.

In the context of Lubumbashi, the presence of trees prevents the dispersion of dust (the cause of several diseases) in the dry season; the trees also provide shade. These roles are mainly performed by streets trees [79], which are unfortunately less common in unplanned neighborhoods. Yet, these areas contain high proportions of bare soil and dirt roads [43] from which dust is dispersed. In some unplanned neighborhoods near mining sites, it is believed that the dust is rich in trace metals which are potentially toxic to people [80]. Thus, the role of trees on local climates and human well-being is undeniable, and people are aware of it [81–83]. This could explain the trend towards planting trees in unplanned neighborhoods of Lubumbashi city. The contribution of streets trees in coping with dust while providing shade and fruit has been demonstrated in the settlements of Bele and Tzaneen (Limpopo Province, South Africa) by [84] and in Karachi, Pakistan by [85]. Reducing human exposure to dust, which can sometimes contain toxic metals in the mining context of Lubumbashi city, undoubtedly contributes to improving the well-being of local populations [74,79].

Overall, the street trees of Lubumbashi city receive less maintenance due to their cost. Ref. [21] reported that the management of mature trees is not an easy task in line plantations, parks and gardens. Yet, in the city, trees are constantly exposed to abiotic or biotic stress, which causes their degradation [86–89]. Furthermore, regarding the protective structures that street trees benefit from, the majority are in poor condition due to diverse forms of vandalism in Lubumbashi city. As compared to unplanned neighborhoods, the higher amount of protective equipment observed around street trees in the planned neighborhoods is due to the actions of the municipality, mainly in urban areas [90,91]. This survey revealed that the work performed by public services involved in tree management is very selective and still far from all expectations. Consequently, only a few trees in the present study were found to be protected in unplanned areas. This situation results in the poor growth and high mortality rates of street trees [25]. Additionally, this protection is provided by the residents in unplanned neighborhoods, which results in a diversity of the protective equipment used. A similar situation has been reported in South African cities [25]. We confirmed that due to the high concentration of utility activities in the planned neighborhoods, it is expected that the trees along the street of the planned neighborhoods will be further protected by devices in good condition.

### *4.2. Implication for Neighborhood Planning and Biodiversity Conservation*

Over the last five decades, Lubumbashi has increasingly experienced a lack of urban planning, which is worsened by the city expansion due to a drastic increase of the demographic rate, specifically in planned neighborhoods with high socio-economic standards. This leads to the deterioration of the overall infrastructure, including the green infrastructure. In these neighborhoods, the high residential mobility of populations towards more spacious and quiet peripheral neighborhoods has also been observed, but where urbanization occurs spontaneously. On the other hand, the unplanned neighborhoods have been anarchically urbanized with roads widths being narrowed in favor of residential plots. Again, while tree crowns provide shade for pedestrians, negative impacts can be observed on power lines and other traffic. In addition, due to a lack of training, practical tools and appropriate budget by the municipality member in charge of urban planning and environment, street tree management is only carried out in planned neighborhoods. Therefore, in unplanned neighborhoods, tree planting is performed by local communities without any master plan and consultation, leading to a high diversity of trees on the same street without adequate protection measures. It also results in the absence of streetscape design. As the unplanned neighborhoods and tree plantations are mostly recent, the trees are unfortunately still in young growth stages and prone to destruction by vehicles due to the narrowness of streets.

This situation can be improved by implementing a master plan for the development of street trees in Lubumbashi city. On the other hand, during the last 45 years, a great increase in tree species beyond the 22 previously identified has been observed [34]. However, of hese species, some of them (*Cassia siamea* Lam., *Cassia spectabilis* DC., *Cupressus lusitanica* Mill., *Monotes africanus* (Welw.) A. DC., *Dodonaea viscosa* (L.) Radlk., *Plumeria acuminata* Ait., *Adenathera pavonica* L., *Ceiba petandra* (L.) Gaertn., *Grevillea robusta* A. Cunn., *Pinus khasya* Royle., *Thuya orientalis* L., *Araucaria* sp., and *Maesopsis eminii* Engl.) have disappeared probably because of little care in the planned neighborhoods of Lubumbashi city. The few tree replacements are performed steadily using exotic species because of their rapid growth, as is the case with *A. auriculiformis*. Another threat to the conservation of street trees in the planned neighborhoods is the emergence of modern buildings, which stimulates the cutting of trees for good visibility. The fact that people are involved in tree planting to some extent constitutes another threat to biodiversity conservation. Furthermore, due to the fact that species richness is related to the width and length of the streets, tree species diversity is supposed to decrease, with a high possibility of the plot sizes being enlarged. The city should urgently implement a master plan for sustainable integration of these street trees, involving the public through various collaborative and co-management schemes [92,93]. This city master plan is also required to control the anarchic urbanization and the resulting decrease in road length. Measures to promote the plantation of native species and to halt the spread of invasive species, thereby preventing new invasions are also required. Planting exotic species that are biologically less invasive and useful to local populations, such as *M. indica*, can also be improved, increasing the street trees population and compensating for the loss of the remnant forest patches. Indeed, street trees planting must be consistent with the local soil and climate conditions, while also meeting the socio-ecological needs of the local population [92]. Tree development practices carried out by qualified personnel that allow the long-term survival of street trees in Lubumbashi city should thus be envisaged. However, it is critical to ensure that planning regulations are reinforced, to promote collaboration among institutions and to raise community awareness of the benefits of street trees [94].

## 5. Conclusions

In this study, we attempted to analyze the diversity, structure and protection measures of street trees along a land-use planning gradient in Lubumbashi city. Overall, our findings confirm that the city lacks a street tree governance policy, particularly in unplanned neighborhoods with relatively narrow streets and discontinuous tree planting. Regardless of the neighborhood type, exotic species dominate street trees, with the most common species being *L. leucocephala* in unplanned neighborhoods and *J. mimosifolia* in planned neighborhoods. This is the result of intentional species introduction for various purposes. The Fabaceae family has dominant among the street trees inventoried, although other species are also well represented. Our findings also revealed the presence of street trees that are distinctively characteristic of both unplanned and planned neighborhoods, with species richness being higher in planned neighborhoods. The concentration of public service activities in terms of care in the planned neighborhoods, manifested in particular by the presence of certain intact protection equipment, justifies the high diversity of trees, albeit mostly in the adult stage. Street trees in unplanned neighborhoods, on the other hand, which are in their juvenile stage, are less protected and constantly threatened by the narrowness of the roads. Unfortunately, the process of replacing new trees in planned neighborhoods and planting new ones in unplanned neighborhoods favors exotic species, some of which have proven to be invasive and can spread to the adjacent rural zone. This endangers the native flora, particularly the species of the *miombo* woodland, the number of which has significantly decreased in both planned and unplanned neighborhoods. The presence of some *miombo* woodland species in both planned and unplanned neighborhoods suggests that certain original *miombo* woodland patches have degraded.

It is important to widen roads to spare trees from damage by heavy vehicle traffic in unplanned neighborhoods. Our results also highlight the urgent need to monitor large and old trees in planned neighborhoods and to select native species, but also exotic species of interest, but without risk of biological invasion, for new street trees plantings in both planned and unplanned neighborhoods. Furthermore, there is also an urgent need to ensure the protection of seedling street trees against diverse anthropogenic pressures.

**Author Contributions:** Conceptualization, Y.U.S., F.M. and J.B.; Data curation, Y.U.S.; Formal analysis, Y.U.S., F.M. and J.B.; Funding acquisition, J.B.; Investigation, A.M.K., J.Y.M. and D.N.N.; Methodology, Y.U.S., F.M. and J.B.; Project administration, Y.U.S. and J.B.; Resources, Y.U.S.; Software, A.M.K., J.Y.M. and D.N.N.; Supervision, Y.U.S., F.M. and J.B.; Validation, Y.U.S., F.M. and J.B.; Visualization, Y.U.S., A.M.K., J.Y.M., D.N.N., F.M. and J.B.; Writing—original draft, Y.U.S.; Writing—review and editing, Y.U.S., A.M.K., J.Y.M., D.N.N., F.M. and J.B. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by ARES (Belgium): CHARLU Project.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Conflicts of Interest:** The authors declare no conflict of interest.

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