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The Restoration of Degraded Landscapes along the Urban–Rural Gradient of Lubumbashi City (Democratic Republic of the Congo) by *Acacia auriculiformis* Plantations: Their Spatial Dynamics and Impact on Plant Diversity

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Abstract: This study examines the spatio-temporal dynamics of *Acacia auriculiformis* in Lubumbashi city, southeastern Democratic Republic of Congo, in the context of rapid urbanization following the liberalization of the mining sector. The city has experienced significant demographic growth and unplanned spatial expansion, resulting in a decrease in vegetation cover. The introduction and proliferation of *A. auriculiformis*, an exotic tree species, have occurred without strategic planning or monitoring. Utilizing digitized remote sensing imagery from 2006, 2014, and 2021, we quantified the expansion of *A. auriculiformis* along the urban–rural gradient. Additionally, a floristic inventory conducted in 2021 provided insights into tree diversity within *A. auriculiformis* plantations. Our findings indicate a substantial increase in the number and area of *A. auriculiformis* patches, predominantly in urban zones. However, the patch values, highest in 2006, were shown to decline by 2021, especially in urban areas. The floristic inventory identified 39 tree species within *A. auriculiformis* plantations, including predominant species such as *Albizia lebbeck*, *Albizia alba*, and *Leucaena leucocephala*. Notably, 20 of these species are exotic, with half being invasive. In contrast, the 19 indigenous species were primarily found in peri-urban areas. While a greater number of tree species were observed in urban zones, larger average diameters were recorded in peri-urban zones. The persistence and expansion of *A. auriculiformis* in a landscape characterized by declining tree cover suggest its potential sustainability in this setting. However, *A. auriculiformis* plantations have facilitated the establishment of predominantly exotic and potentially invasive species. These findings highlight the need for the strategic management of *A. auriculiformis* and associated exotic flora to mitigate their spread and to consider their role in the restoration of degraded lands.

Keywords: urbanization; green infrastructure; urban forestry; biological invasion; ecological restoration

1. Introduction

More than half of the world's population now lives in cities, and by 2050 this is expected to increase by about 3 billion people [1]. Accordingly, 90% of this growth will be concentrated in Africa and Asia, where urbanization rates are expected to be around 56% and 64%, respectively. Landscape transformations due to urban development, which occurred in the northern hemisphere in the 20th century [2], currently dominate the landscape dynamics of southern countries [3–5], particularly due to rural–urban migration and the intrinsic demographic changes of the urban population itself [3]. This situation is particularly crucial on the African continent [6], where several generations of urban development master plans have proved to be completely inadequate for the extent of demographic growth and the economic fragility of the population [7]. In particular, the situation is worrying in sub-Saharan Africa, where the urban population is expected to grow fivefold from 200 million in 2000 to one billion in 2050, while the urbanized area is expected to increase twelvefold from ±26,500 km^2 in 2000 to ±325,500 km^2 in 2050 [3]. Increasing urban land cover is expected to have profound effects on local and global species' diversity patterns [4]. Consequently, the future of vegetation is thus largely dependent on the management of the spatial pattern of cities [8], which are constantly expanding in peripheral rural areas [9]. In response, decision-makers, planners, and scientists are focusing their efforts in and around cities to restore the remnants of natural diversity. Indeed, as the restoration of the natural landscape in urban areas receives considerable attention, urbanization is promoting the creation of novel ecosystems where alien plant species are being introduced [10] to provide, augment, or restore specific ecosystem services [11]. Yet, cities are the sources of non-native species' invasions into the natural habitats of the surrounding suburban and rural areas [12]. For example, in Singapore, nine invasive alien species (*Acacia auriculiformis*, *Cecropia pachystachya*, *Falcataria moluccana*, *Leucaena leucocephala*, *Manihot carthaginensis* subp. *glaziovii*, *Muntingia calabura*, *Piper aduncum*, *Pipturus argenteus*, and *Spathodea campanulata*) are dominant in all stages of plant succession on most of the abandoned land, where they have developed a dense canopy forest dominated by invasive species [13]. The presence of alien species may negatively alter ecosystem functions, reduce the flows of ecosystem services, and reduce native biodiversity, including in surrounding natural areas [14]. Ultimately, this hurts local economies and human well-being [15].

Invasive species are under-studied in sub-Saharan Africa compared to other parts of the world [10,16], with the spatial expansion of invasive alien plants and its impact on the phytodiversity receiving little recent attention in the literature. The south-eastern part of the DRC, which has some of the largest copper and cobalt deposits in the world [17,18], is no exception to this trend [19]. The exploitation of these deposits is prone to damaging the land cover, as the greater fragmentation and less diverse vegetation observed in the vegetation are generally found on soils polluted by atmospheric deposits resulting from mining activities. However, the natural ecosystems within and around Lubumbashi city are also modified to fit the needs of the human population, like housing, energy, agriculture [20,21]. In this area, Lubumbashi city, which was created ex nihilo in a formerly rural area within a miombo woodland, represents an interesting case study for the anthropization of natural landscapes [22,23]. The city has been strongly modified by mining activities and through strong industrialization of the landscape [24], attracting people from the surrounding rural areas in search of gainful employment [25]. Rapid population growth has led to various anthropogenic effects, including deforestation [24], and rapid and poorly planned spatial urban growth after the country's independence in 1960 [19,24]. Within 25 years (1984–2009), Lubumbashi City experienced a drastic rise in its spatial expansion rate from 100 ha to 500 ha [24].

Although the deforestation around the city was accelerated as of 1960, after the country's independence, it began as soon as the city was created in 1910 and has continued ever since, following the demographic growth commonly associated with an increased consumption of charcoal and agricultural products [22]. As a result, a 70% loss of forest was noted within a 25 km radius of Lubumbashi city between 1956 and 2009 [24]. Within the city, the set of admirable green spaces that were once carefully maintained have been neglected and replaced by anthropogenic land cover/use [22], with numerous harmful effects on the environment. Indeed, urbanization and industrialization are therefore accompanied by a strong presence of bare soil in the urban and peri-urban areas of Lubumbashi city. However, green spaces, which correspond to surfaces covered with vegetation [26], contribute to the purification of air and water, the treatment of waste, the regulation of the microclimate, etc. [27]. In addition, their presence also provides people with aesthetic pleasures, recreational opportunities, and physical and psychological well-being [28].

In the context of Lubumbashi city, the spread of invasive species is directly encouraged by human activity, through the deliberate and accidental movement of plants. Particularly, invasive species are spread through the creation of green spaces planted with exotic and fast-growing trees, like *A. auriculiformis*. *A. auriculiformis* is an alien invasive species of the Fabaceae family with creamy yellow fragrant flowers that tolerates many types of soil, including degraded lands. *A. auriculiformis* has a high N2-fixing potential, given its excellent nodulation, observed in many soils [29]. The species is known for its high litter content, which can be used for soil fertility enhancement, and its prunings have also been used in alley cropping as a biofertilizer [30].

Introduced into Lubumbashi city in early 2000, it is considered a beneficial nurse crop used as an ornamental plant, shade tree, and as firewood [31]. Although the urban and peri-urban woody green spaces of Lubumbashi city are dominated by miombo woodland species, *A. auriculiformis* has remained the most common species [32]. Within the landscape of Lubumbashi city, *A. auriculiformis* is often used to compensate for the loss of native forests, to restore disturbed minelands or other types of wasteland [33]. However, Richardson et al.'s [34] findings revealed the reduction in the species richness of indigenous plants as one of the major problems associated with the presence of dense stands of invasive alien trees and shrubs in the Fynbos Biome (South Africa), but this aspect is not understood, as far as *A. auriculiformis* stands, in Lubumbashi city. Yet, there are no studies that have investigated the change in landscape pattern due to its expansion, and its impact on plant diversity since its introduction in Lubumbashi. Likewise, a greater understanding of the spatial expansion and the ecological role of alien species might help to reduce controversy surrounding their purposeful use in restoration [35,36], as recently documented by Watanabe et al. [37], who advocate for the use of native species (*Brachystegia spiciformis*, *Combretum collinum*, and *Pterocarpus tinctorius*) in the restoration of land degraded by human activities, instead of *Acacia* or *Eucalyptus*.

With the recent development of remote sensing images coupled to GIS and landscape ecology, the spatial expansion of plant communities can be mapped and quantified [37]. The expansion of plant communities that modify the ecological functioning of landscapes can be highlighted by an assessment of the properties of landscapes and the ecosystem services they provide [38,39], particularly through biodiversity analysis [40]. The present study characterizes the spatial evolution and the phytodiversity in *A. auriculiformis* plantations along the urban–rural gradient. We hypothesized that the positive anthropization of the landscape through the creation of *A. auriculiformis* plantations could be accompanied by an increase in the patch number as well as area, either in urban or peri-urban zones, promoting the establishment of mostly exotic plant species.

2. Materials and Methods

2.1. Study Area: The Urban Zone and Peri-Urban Zone of Lubumbashi City

Lubumbashi city (Figure 1) covers an area of nearly 747 km^2 (11°27′–11°47′ S and 27°19′–27°40′ E) at an altitude varying between 1200 and 1300 m. The climate is Cw type of the Köppen classification system [41], with a dry season (May to September), a rainy season (November to March), and two transition months (April and October).

In the second half of the last century, the average annual temperature was around 20.1 °C [41], though recent reports indicate ongoing warming [42]. In the dry season, winds from the Indian Ocean generally prevail, blowing in the east-southeast and east-northeast directions, which accelerates the spread of fumes from mining companies, and contributes to the pollution of the city [43]. The soils of the city are very ferralitic [41]. Natural wooded vegetation, currently in a fragmented state, is located several kilometers away from the city [24]. The population is around 2.5 million and is mainly engaged in agriculture, residential livestock, services, mining, and trade [44].

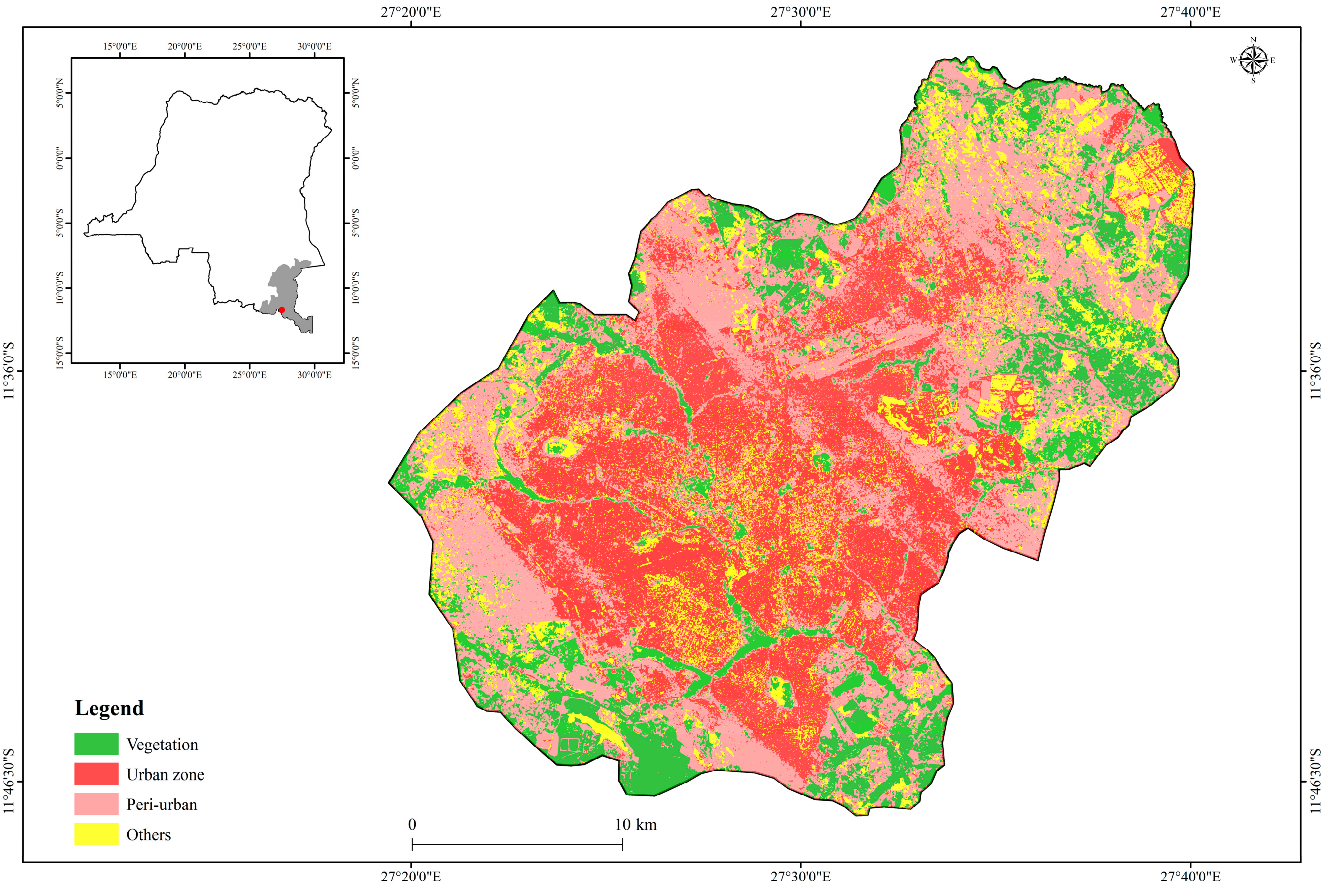

Figure 1. Geographical location of the study area, the city of Lubumbashi (The red dot on the map above) in the Haut-Katanga province, the Democratic Republic of the Congo. The land cover map of the city of Lubumbashi was created from a Landsat image taken in July 2021. The urban zone occupies the central part of the town and is surrounded by an aureole formed by the peri-urban zone. The vegetation in these two zones is very sparse.

2.2. Exploratory Visits and Spatial Analysis

Exploratory field visits were carried out from 1 to 19 June 2021 to locate *A. auriculiformis* plantations within the administrative boundaries of the city of Lubumbashi, considered to be areas with a collection of *A. auriculiformis* trees planted either by the public authority or by private individuals. In each municipality of Lubumbashi city, we communicated with local authorities to present the objectives of the study to the local authorities and seek their permission to undertake the study. The person in charge of administration or an influential member of the community was then instructed by the leaders to establish and deliver a list and the addresses of all *A. auriculiformis* within their jurisdictions. The listed plantations have been visited based on local knowledge and located using a GPS Garmin 64st (±3 m precision). In addition, for each plantation visited, its position in the urban–rural gradient was given using the decision tree of [9], which is based on the morphological characteristics of urbanization (proportion, density, and continuity of the built-up). Accordingly, the urban zone is characterized by densified and continuous built-up areas while the discontinuity of the otherwise less dense built-up areas characterizes the peri-urban zone.

This study utilized high-resolution imagery from Google Earth, captured in July of 2006, 2014, and 2021. These intervals represent around 5, 13, and 20 years post the introduction of *A. auriculiformis* in the study area, respectively. Google Earth provides a comprehensive combination of satellite and aerial imagery, predominantly from the past decade, enabling detailed terrestrial visualization [45]. Lubumbashi city, as a focal economic hub, benefits from comprehensive coverage in Google Earth's database. This facilitates accurate land cover and land use analysis, essential for monitoring urban and environmental changes. The ESRI ArcGIS software (version 10.5) suite was employed for cartographic representation. The spatial resolution of Google Earth imagery was meticulously considered, taking into account both the geographical coordinates and the specific year of image capture [46]. For this study, individual *A. auriculiformis* trees situated within residential areas and rural settings—areas minimally affected by urbanization—as well as plantations smaller than 250 square meters, were excluded from the analysis. In contrast, larger plantations of *A. auriculiformis* were digitized from the Google Earth imagery and subsequently converted into vector formats using the ESRI ArcGIS software (version 10.5). To quantitatively assess the distribution pattern of *A. auriculiformis* across the urban–rural gradient, three key landscape metrics were computed: the total class area (CA), rate of change (RC), and patch number (PN). These indices are critical in evaluating the anthropogenic influences on landscape patterns [47].

2.3. Floristic Data Collection and Analysis

To determine species richness, plots of 100 m^2 were established on each *A. auriculiformis* plantation and the number of plots was adapted to the area of each plantation. A total of 27 plots, including 13 plots on a single peri-urban plantation and 14 plots in urban plantations (2–4 per plantation), were studied from July to August 2021. It has been noted that for species richness determination, Liang et al. [48] suggest plots of 1 m^2, 4 m^2, and 100 m^2 for herbaceous species, shrubs, and trees, respectively. This period of floristic inventory corresponds to the dry season in the Lubumbashi plain, which is why the herbaceous plants which develop favorably during the rainy season have not been studied. Indeed, many herbaceous plants in the Lubumbashi plain spend the unfavorable period, the dry season, in a state of organ regeneration (seeds, tubers, stumps, rhizomes). Herbaceous flora has not been studied as it is more sensitive to disturbance (i.e., droughts) and even edaphic variation than woody flora [49]. However, the tree age was estimated based on its stage of development (seedling and adult). Then, the average height and circumference at 1.30 m above the ground of adult *A. auriculiformis* trees were estimated and measured, respectively. The data collected made it possible to define the species richness with a floristic list of plant species present in a site.

In terms of the identification of plant species, some species were identified using our knowledge of plant systematics and others using available flora [50]; specialized literature [10,51] was also utilized. The origin status of species was determined. Thus, exotic species were considered species that were not indigenous to Africa; while Afro-Asian species were considered indigenous [10]. Among these exotic species, the biological invasion status of each species was assembled from online databases and specialized literature [52–56]. According to Meerts et al. [57], an alien invasive species is a non-native, naturalized species, showing a rapid expansion dynamic in its territory of introduction. The status of native miombo species was specifically determined based on the checklists established by [58]. For each identified species, a specific abundance and specific frequency were calculated. The specific abundance was defined as the number of individual trees for each species, while the specific frequency was considered to be the number of sites where the species was present [59]. Indeed, the relative frequency was calculated as the ratio between the frequency of the species and the total number of sites surveyed [60]. It should be noted that abundance and frequency were used to calculate diversity indices such as Simpson's index and Shannon's index using Paleontological Statistics software (PAST version 4.03). Shannon's index is believed to emphasize the richness component of diversity, and Simpson's index to emphasize the evenness component [61].

3. Results

3.1. The Mapping and Spatial Pattern of A. auriculiformis Plantations

It was revealed from the spatial pattern dynamics analysis that there was an increase of about 30% in *A. auriculiformis* plantations from 2006 (12 plantations) to 2021 (17 plantations).

In terms of surface area, two tendencies were noted. A twofold area increase (15.28 ha to 29.38 ha) of *A. auriculiformis* plantations was observed between 2006 and 2014, followed by a slight decrease of about 5% (29.38 ha to 27.89 ha) in the period from 2014 to 2021 (Table 1).

Table 1. Types of green space covered by *Acacia* plantations in the urban and peri-urban zones of the city of Lubumbashi from the digitization of Google Earth images from 2006, 2014, and 2021. PN: patch number; CA: class area (ha); PZ: peri-urban zone; UZ: urban zone; and RC: rate of change (%). These area values correspond to the total area covered by *A. auriculiformis* plantations.

	Attached Green Space		**Park**		**Street Trees**	
	PN	**CA (ha)**	**PN**	**CA (ha)**	**PN**	**CA (ha)**
			2006			
PZ	1	1.60	0	0.00	0	0.00
UZ	7	12.33	1	0.14	3	1.21
			2014			
PZ	2	4.18	1	4.36	0	0.00
UZ	8	18.36	1	0.33	5	2.15
			2021			
PZ	1	0.65	1	5.27	0	0.00
UZ	9	18.21	1	0.14	5	3.62

Analysis along the urban–rural gradient reveals an increase in the number of *A. auriculiformis* plantation patches from 11 (2006) to 14 (2014) and from 14 (2014) to 15 (2021) in urban areas. Meanwhile, the area occupied by *A. auriculiformis* plantations almost doubled from 13.68 ha in 2006 to 21.97 ha in 2021. In the peri-urban zone, the period of 2006–2014 was characterized by an increase in the patch number, which tripled, while the class area increased fivefold. In the following period (2014–2021), the patch number of *A. auriculiformis* plantations decreased from 3 to 2. Over the same period, the class area was reduced by about 31% (Table 1 and Figure 2). In addition, it is important to note that the rate of land use change by *A. auriculiformis* plantations in the urban area has continued to increase significantly over time. Between 2006 and 2014, this rate was 52.33 and, between 2014 and 2021, it rose to 113. These figures demonstrate the continued expansion of *A. auriculiformis* plantations in the urban area. As for the peri-urban area, the rate of change in land use was positive, at a high rate of 433.75 between 2006 and 2014, also indicating a significant increase in *A. auriculiformis* plantations. However, between 2014 and 2022, this rate became negative, at −30.68, suggesting a reduction or decline in the presence of *A. auriculiformis* plantations in the peri-urban area. These results highlight an overall expansion of *A. auriculiformis* plantations in the landscape studied, particularly in the urban zone.

These results also show that the *A. auriculiformis* plantations belong to three green space types: parks, street trees, and attached green spaces. Parks and street trees showed a simultaneous increase in their patch number and in their class area. By contrast, in the case of parks, the number of patches doubled from 1 in 2006 to 2 in 2021, while the area increased 39-fold from 0.14 ha to 5.41 ha in the same period. As for street trees, the number of patches and the class area have, respectively, doubled and tripled. Indeed, the number of patches almost doubled from 3 in 2006 to 5 in 2021, while the class area increased by about threefold from 1.21 ha to 3.62 ha in the same period. Conversely, although the patch number of attached *Acacia* and its class area increased by 20% and 40% from 2006 to 2014, respectively, a slight decrease (18%) in its class area was recorded from 2014 to 2021 (Table 1).

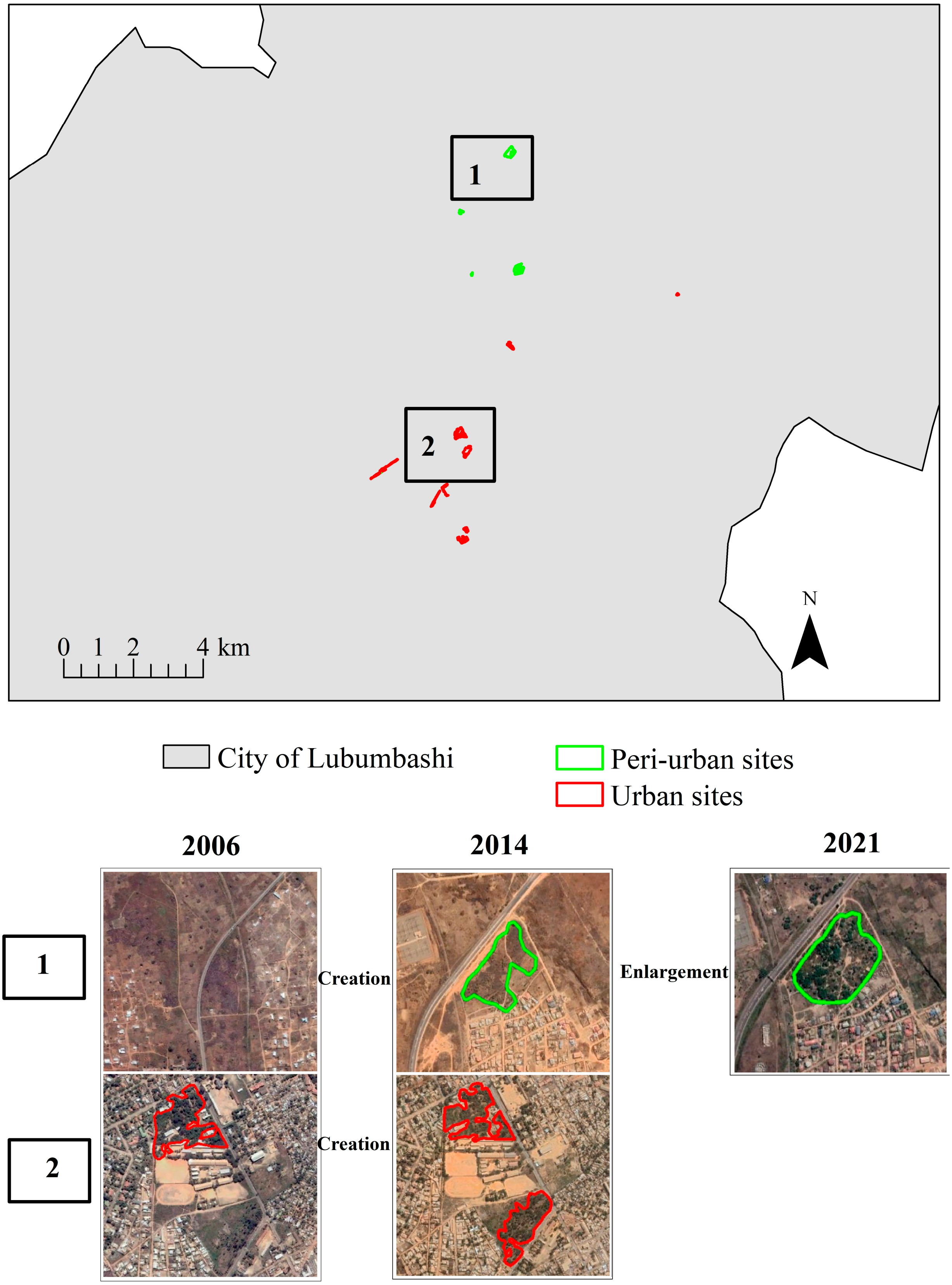

Figure 2. Maps of the evolutionary trends in the area and the number of patches of *A. auriculiformis* plantations in urban and peri-urban zones of the city of Lubumbashi from the digitization of Google Earth images from 2006, 2014, and 2021, according to Bogaert et al. [47].

3.2. Flora Richness and Diversity in the Plantations of A. auriculiformis along the Urban–Rural Gradient of Lubumbashi City

The data on floristic spectra revealed a total of 39 species in the plantations of *A. auriculiformis*, with 29 species in the urban zone and 10 in the peri-urban zone. Slightly higher diversity index values were recorded in the urban zone compared to the peri-urban zone (Table 2). Moreover, Table 3 shows that the proportions of adult trees are higher than those of seedlings in the *A. auriculiformis* plantations in both urban (94.2% against 5.8%) and peri-urban plantations (89.3% against 10.7%). However, no significant variation ($p > 0.05$) was found regarding height and tree diameter in the studied zones of the urban–rural gradient (Table 4).

Table 2. Diversity of trees and shrubs in *A. auriculiformis* plantations in the urban and peri-urban zones of Lubumbashi city. PZ: peri-urban zone; UZ: urban zone.

Indices	**UZ**	**PZ**
Species richness (n = 39)	29	20
Genera (n = 29)	20	16
Family (15)	11	9
Simpson_1-D	0.76	0.68
Shannon_H	2.34	1.63

Table 3. Proportions of age (adult and seedling) of *A. auriculiformis* trees in plantations in urban and peri-urban areas. PZ: peri-urban zone; UZ: urban zone.

	Proportion of Adult (%)	**Proportion of Seedling (%)**
UZ (n = 207)	94.2	5.8
PU (n = 150)	89.3	10.7

Table 4. Average height and average diameter of *A. auriculiformis* trees in urban and peri-urban plantations in Lubumbashi. PZ: peri-urban zone; UZ: urban zone. T= student's *t*-test, ns = $p > 0.05$.

	Average Height (m)	**Average Diameter (cm)**
UZ (n = 104)	10.87 ± 4.09	28.02 ± 14.8
PZ (n = 61)	11.03 ± 10.6	30.4 ± 15.7
T	0.11	0.96
p-value	ns	ns

Table 5 shows that 39 species were inventoried across all *A. auriculiformis* plantations in Lubumbashi. *A. auriculiformis* plantations in the urban zone revealed 29 species, while the plantations in the peri-urban zone revealed only 20 species. Naturally, *A. auriculiformis* was the most abundant species in the plantations of the urban and peri-urban zones, with a proportion of 46.6% and 45.5%, respectively, while the other species had abundance proportions of less than 5%, except *L. leucocephala*, which had an abundance of 30.6% in the peri-urban zone. Moreover, the relative frequency was 100% for *A. auriculiformis* in all plantations. This is followed by *A. lebbeck*, *A. alba*, and *L. leucocephala*, with 50% frequencies in the plantations of the urban zone, while the remaining species represented 25% of flora. In the *A. auriculiformis* plantations of the peri-urban zone, species showed a relative frequency of 50%. The results also showed that 20 species out of the 39 species found were exotic (51.3%) and only 19 species were indigenous (48.7%). It should be noted that 18 of the 19 indigenous species inventoried are characteristic of the miombo woodland (94.7%), all except *E. guineensis*. Furthermore, our results show that 10 of the 20 exotic species recorded have been reported in the literature as invasive species, namely *Acacia melanoxylon*, *Acacia heterophylla*, *Acacia auriculiformis*, *Acacia mangium*, *Melia azedarach*, *Leucaena leucocephala*, *Callistemon viminalis*, *Eucalyptus camaldulensis*, and *Eucalyptus globulus*.

Table 5. Relative abundance (RA), relative frequency (RF), species status, and origin of species in *A. auriculiformis* plantations in the urban zone (UZ) and peri-urban zone (PZ) of Lubumbashi city. Ex: exotic species; In: indigenous species. Species preceded by * are characteristic of the miombo woodland. RA is calculated as the ratio of the total number of individuals of a given species to the total number of individuals of all species in the plantations. RF is the ratio of the total number of observations of the species to the total number of investigated plantations. + Invasive species according to [34,52–55].

Family	Species	RA UZ (n = 223)	RA PZ (n = 134)	RF UZ (n = 4)	RF PZ (n = 2)	Origin Status
Anacardiaceae	*Mangifera indica* L.	3.1	1.5	25.0	50.0	Ex
Apocynaceae	* *Diplorhynchus condylocarpon* (Muell. Arg.) Pichon	0.0	0.7	0.0	50.0	In
Arecaceae	*Elaeis guineensis* Jacq.	1.3	0.0	25.0	0.0	In
Ebenaceae	* *Diospyros discolor* Willd.	0.0	0.7	0.0	50.0	In
Fabaceae	+ *Acacia auriculiformis* A. Cunn. ex Benth.	46.6	45.5	100.0	100.0	Ex
Fabaceae	+ *Acacia heterophylla* Willd.	4.5	0.0	25.0	0.0	Ex
Fabaceae	+ *Acacia mangium* Willd.	2.7	3.0	25.0	50.0	Ex
Fabaceae	+ *Acacia melanoxylon* R.Br.	2.2	0.0	25.0	0.0	Ex
Fabaceae	* *Baphia bequaertii* De Wild.	0.0	0.7	0.0	50.0	In
Fabaceae	*Bauhinia variegata* L.	1.3	0.0	25.0	0.0	Ex
Fabaceae	* *Brachystegia boehmii* Taub.	3.1	0.7	25.0	50.0	In
Fabaceae	* *Brachystegia longifolia* Benth.	0.0	0.7	0.0	50.0	In
Fabaceae	* *Brachystegia spiciformis* Benth.	1.3	0.7	25.0	50.0	In
Fabaceae	*Ceratonia siliqua* L.	2.7	0.0	25.0	0.0	Ex
Fabaceae	*Delonix regia* (Bojer) Rafin	1.3	0.0	25.0	0.0	Ex
Fabaceae	* *Erythrophleum africanum* (Welw. ex Benth.) Harms	0.0	0.7	0.0	50.0	In
Fabaceae	* *Isoberlinia angolensis* (Benth.) Hoyle & Brenan	0.0	0.7	0.0	50.0	In
Fabaceae	* *Julbernardia paniculata* (Benth.) Troupin.	1.8	0.0	25.0	0.0	In
Fabaceae	* *Pterocarpus angolensis* D.C	0.0	0.7	0.0	50.0	In
Fabaceae	*Senna siamea* Lam.	0.4	0.0	25.0	0.0	Ex
Fabaceae	*Tipuana tipu* (Benth.) Kuntze	0.0	0.7	0.0	50.0	Ex
Kirkiaceae	* *Kirkia acuminata* Oliv.	0.9	0.0	25.0	0.0	In
Lamiaceae	* *Vitex madiensis* Oliv.	0.0	0.7	0.0	50.0	In
Lauraceae	*Persea americana* Mill.	0.9	0.7	25.0	50.0	Ex
Meliaceae	+ *Melia azedarach* L.	0.0	0.7	0.0	50.0	Ex
Mimosaceae	* *Albizia adianthifolia* (Schum.) W. F. Wight	1.3	6.7	25.0	50.0	In
Mimosaceae	*Albizia brevifolia* Schinz.	0.4	0.0	25.0	0.0	Ex
Mimosaceae	+ *Albizia lebbeck* (L.) Benth.	2.7	30.6	50.0	0.0	Ex
Mimosaceae	+ *Leucaena leucocephala* (Lam.) De Wit.	7.2	2.2	50.0	50.0	Ex
Moraceae	* *Ficus benjamina* L.	0.4	0.0	25.0	0.0	In
Moraceae	* *Ficus* sp.	0.9	0.0	25.0	0.0	In
Moraceae	* *Ficus sycomorus* L.	1.3	0.7	25.0	50.0	In
Myrtaceae	+ *Callistemon viminalis* (Sol. ex Gaertn.) G.Don	0.9	0.0	25.0	0.0	Ex
Myrtaceae	+ *Eucalyptus camaldulensis* Dehnh.	2.2	0.0	25.0	0.0	Ex
Myrtaceae	+ *Eucalyptus globulus* Labill.	0.9	0.0	25.0	0.0	Ex
Phyllanthaceae	* *Pseudolachnostylis maprouneifolia* Pax.	3.1	0.0	25.0	0.0	In
Pinaceae	*Abies alba* Mill.	2.2	0.0	50.0	0.0	Ex
Pinaceae	*Pinus pinea* L.	0.4	0.0	25.0	0.0	Ex
Rhamnaceae	* *Ziziphus mucronata* Willd.	1.3	0.0	25.0	0.0	In

These species are principally located in the peri-urban zone. All species inventoried belong to 15 families, the Anacardiaceae, Apocynaceae, Arecaceae, Ebenaceae, Fabaceae, Kirkiaceae, Lamiaceae, Lauraceae, Meliaceae, Mimosaceae, Moraceae, Myrtaceae, Phyllanthaceae, Pinaceae, and Rhamnaceae. In the *A. auriculiformis* plantations of the urban zone and peri-urban zone, the Fabaceae family predominated with, respectively, 37.9% and 50% of the species abundance, followed by the Mimosaceae family.

4. Discussion

4.1. Spatial Pattern Dynamics of A. auriculiformis and Its Impact on Phytodiversity

In Lubumbashi city, a thorough diagnosis of governance management has revealed unclear role attributions among different services in this city (municipality, province, state/division of housing, urban planning, land registry, roads/technical concessionaires), resulting in competence conflicts [62]. Moreover, a systematic lack of public budgeting has been noted, particularly for equipment and maintenance costs, especially regarding public green spaces. On the overall scale of the city, unplanned urbanization is accompanied by a dramatic regression of green spaces, through the densification of buildings and peri-urbanization, in which new housing estates are created [19]. Useni et al. [22] reported that the built-up area tripled from 94.14 km^2 to 291.31 km^2 between 1989 and 2014 in the city of Lubumbashi, while green areas diminished from 575.27 km^2 to 484.64 km^2 during the same period, with the most concerning loss being the cover of public green spaces. Further, GROUPE HUIT [62] concluded that there is virtually no provision for green spaces in most neighborhoods, with green spaces systematically destroyed to make way for constructions, notably fuel stations, mostly for those located at crossroads. This situation is exacerbated by the policy of land speculation, which means that even vacant, untended green spaces have a high monetary value when they are divided up and sold as plots. The populations in search of a space to erect buildings care little about the sustainability of green spaces [22], probably due to their lack of knowledge of the various functions performed by them. To get around this bleak situation, in certain sectors of life, the population has begun to organize what the 'bankrupt' state cannot do, through solidarity networks and neighborhood, professional, and even religious associations. It is in this context that *A. auriculiformis* plantations have been created to compensate for the loss of green spaces. As these plantations are often located in private areas, they enjoy the security of tenure and are thus protected from urbanization pressure. Jim [63] reported that formal green spaces are usually well protected. On the other hand, public green spaces, especially parks, mostly belonging to the state, are easily converted into other land cover/uses because they are not legally secure.

A visual analysis of change maps in the study areas showed an expansion of *A. auriculiformis* plantations, most noticeable in the urban area between 2006 and 2021, probably due to human preferences and for ornamental purposes. Indeed, the urban flora constitutes a subset of the species pool after passing through several filters, including the strong influences of private and public landowners' preferences [64]. Due to its rapid growth, *A. auriculiformis* is used to establish plantations; as reported by Williams et al. [65], in the absence of human disturbance, it takes nearly 40 years for native miombo species to reach the adult stage. Nevertheless, compared to the peri-urban zone, the number of *A. auriculiformis* patches in the urban zone is reported to be higher. Due to limited budgets, the attention of public services is mostly drawn in the urban zone to increase its visibility [66], justifying the increased number of parks and street trees planted with *A. auriculiformis*.

On the other hand, most of the public service buildings around which *A. auriculiformis* plantations are located occur in urban zones. The almost complete absence of public infrastructure in peri-urban areas has already been reported in Central Africa [66]. The increase in the patch number of *A. auriculiformis* plantations is accompanied by an increase in their area. This is not only due to the growth of the tree crown over time, but also to the densification of the plantation as the consequence of the development of new plants from seeds. Janzen [67] and Connell [68] hypothesized that specific seed and seedling viabilities depend on their distance to the parent plant or the density of young individuals. Mortality, due to pathogens and predators, modifies the initial distribution of seeds and leads to maximum recruitment at an intermediate distance from the parent plant [69]. It should be noted, however, that within the concessions of private or public landowners, the security of tenure also contributes to the easy expansion of *A. auriculiformis* trees. In this context, land insecurity could be a threat to the ecological restoration project within the city, particularly in the peri-urban zone, which is a dynamic zone that is characterized by rapid change because of an extension of the city and its associated infrastructures [70].

Although the regression of green space coverage has already been revealed in Lubumbashi city [22], our results showed an increase in the acreage of introduced patches of green space planted with *A. auriculiformis*, which follows the theory of patch origin [71]. Although progress is being made, it still appears that this landscape restoration with *A. auriculiformis* will not succeed in compensating for the loss of natural patches. This is in line with the findings of Toyi et al. [72], since exotic and potentially invasive species are used for this purpose, resulting in the ecosystem's damage, particularly when juxtaposed with native forests. Moreover, there is no longer sufficient space to implement large-scale reforestation programs in the urban zone and peri-urban zone of Lubumbashi city [62]. More plant species are accompanying *A. auriculiformis* in the urban zone than in the peri-urban zone, particularly exotic species, leading to high plant diversity. The process of urbanization has greatly transformed the landscape of Lubumbashi and has created heterogeneous urban vegetated lands with new environmental conditions, leading to an installation of exotic species [19]. However, the older plantations in the urban zone would explain this, as sites planted with *A. auriculiformis* have been recently developed in the peri-urban zone. This corroborates the results of Elliott et al. [73], which revealed a much higher species richness for ground flora in a 28-year-old forest compared to a 1-year-old field in the southern Appalachian watershed. In addition, the environmental conditions specific to the urban area (high temperatures, low water availability) constitute a filter that would have eliminated species not adapted to these conditions [74]. Indeed, urbanization mostly excludes species (native and non-native) with limited dispersal capacity and selects species capable of long-distance dispersal [64]. Since most of the native tree felling left the stumps, it appears that the presence of some miombo woodland species under *A. auriculiformis* plantations could be explained by stump regeneration, especially in the peri-urban zone. Indeed, a few years later they would have regenerated from the stumps. Several authors have shown that the stumps of miombo woodland species regenerate when there is no disturbance [75,76].

The nature of the region's economy, with a majority of poor populations, has a bearing on the popularity of Acacia or its receptiveness to the detriment of native species. Acacia does not require a great deal of labor to maintain its trees. Due to its ability to fix atmospheric N, over 350 ha of *A. auriculiformis* agroforestry plantations have been established on the outskirts of Lubumbashi, with 133 agroforestry farming families growing maize in association with it. Properly maintained, a half-hectare plot of *A. auriculiformis* can provide around 12 tons of charcoal after ten years [77]. On the other hand, it is known to be invasive [78], leaving the possibility for other species, more often invasive, to establish themselves. This was confirmed by our results, which indicate that half of the identified alien species are invasive and echo the hypothesis of ecological facilitation [79]. The results of the present study show an expansion of *A. auriculiformis* plantations in Lubumbashi. This is good news on the one hand, given the capacity of this species to improve edaphic and carbon storage factors. The ability of *A. auriculiformis* fallows to improve soil fertility has been demonstrated in the Bateke Plateau (D.R. Congo), notably through significant increases in organic carbon content, total nitrogen content, cation exchange capacity and the sum of base cations, OM content, and the soil pH in *A. auriculiformis* plantations [80]. Similarly, Kasongo et al. [81] demonstrated higher phosphorus levels under *A. auriculiformis* than in natural forests; Nsombo et al. [82] demonstrated a high carbon stock in *A. auriculiformis* plantations in forests in southern Benin. All these are important indicators in the current context of the pronounced regression of the miombo woodland in the Lubumbashi lowlands [19].

However, the expansion of *A. auriculiformis* plantations could determine a progressive loss of floristic identity if the management of these plantations is not assured, since this species is classified as potentially invasive [83]. Already, Gnahoua and Louppe [84] have reported a dominance of more than 85% of the soil cover by *A. auriculiformis* at the expense of other species in the classified forests of Ouèdo in Benin. The results of the floristic inventories carried out in this study show that native species are established in *A. auriculiformis* plantations. However, the ecological impacts of *A. auriculiformis* plantations are still unclear in the Lubumbashi region and in DR Congo. A report on the potential risks of *A. auriculiformis* plantations in the Bateke plateau was prepared by Hardarson et al. [78]. Based on their preliminary findings, the most important potential risks associated with non-native *Acacia* plantations were invasion of the species, the depletion of groundwater reserves, and reduced soil productivity. Indeed, with a trend towards increasing the area planted with *A. auriculiformis*, there could also be a risk to groundwater resources. Some exotic species can release chemical substances or modify the soil composition, thus altering groundwater quality. In addition, they can consume large quantities of water, reducing groundwater recharge. Also, the roots of exotic plants can modify the soil structure, affecting the soil's capacity to retain water [85].

The difference in plant diversity under *A. auriculiformis* plantations also results from the fact that urban landscapes have a different species composition of introduced species, following the landscape-divergence hypothesis. Fragments within the same landscape tend to converge in species composition, whereas those in different landscapes diverge in composition [86]. Accordingly, the highest plant diversity noted in the urban zone could be due to local-level landscaping aesthetics and socioeconomic characteristics, acting as dominant bottom-up anthropogenic forces [87]. The propagation of similar plants or landscape elements in neighborhoods is indeed due to the actions of residents that copy, adapt, exchange plants, and suggest ideas, a phenomenon referred to as the "neighbor mimicry effect" [88].

A. lebeck is one of the most abundant species accompanying *A. auriculiformis*. The choice of this species in the vegetation of disturbed areas is due to its adaptability and rapid growth as well as its high capacity to produce seeds to generate other trees [89]. However, these characteristics can increase the invasiveness of the species. Furthermore, some introduced species in cities have high invasiveness [14] due to their prolific seed production, widely dispersed seeds, and nitrogen-rich and warm habitat preference, making them able to establish and thrive along edges [90]. However, *A. auriculiformis* trees are larger in size and stem diameter in the peri-urban zone due to the lower plant diversity, which limits interspecific competition [91].

4.2. Implications for the (Peri-)Urban Landscape's Ecological Restoration

A. auriculiformis appears to be highly sustainable as a species in this landscape, in that it has persisted and spread in a landscape with degrading tree cover resources. In addition, *A. auriculiformis* plantations promote the establishment of species that are, however, mostly exotic and potentially invasive, with the risk of further degrading surrounding ecosystems. However, the peri-urban area of Lubumbashi where *A. auriculiformis* plantations are present constitutes an edge between urban and rural areas [92]. It is therefore possible that the species escapes from the peri-urban area and colonizes the adjacent rural area, where the vegetation still retains a certain level of naturalness [23]. This is not without socio-environmental problems. In rural areas, invasive species also harm livelihoods and increase human vulnerability through encroaching on land and reducing mobility or access. They can also decrease the supply of natural resources used by households and reduce agricultural production (livestock and/or crops), thus resulting in losses of income and increased vulnerability. Furthermore, some invasive species were seen to have negative implications for human health and safety and reduce the cultural value of landscapes [93]. Despite its various advantages (the creation of green space plots, ornamentation and shade, production of firewood, etc.), *A. auriculiformis* increases the level of soil acidity, as demonstrated in the Batéké plateau in Kinshasa [94]. Consequently, the process of restoring degraded land should favor native species like *Brachystegia spiciformis*, *Combretum collinum*, and *Pterocarpus tinctorius*, which are the most productive potential candidates for restoration, based on [95]. For this reason, managing the expansion of *A. auriculiformis* plantations and their associated risks requires an assessment of the potential impact on the local ecosystem, the regular monitoring of affected areas based on accurate mapping, and the selective elimination of other invasive species from the accompanying flora, using appropriate methods (e.g., selective cutting or uprooting). In addition, private landowners should be introduced to innovative management practices for exotic species, such as using their biomass for soil fertilization or cutting their wood for carbonization [96]. Finally, cooperative efforts between the government, non-governmental organizations, and local communities are needed to effectively combat the invasion of *A. auriculiformis* [97].

Although our study quantified the impact of the presence of *A. auriculiformis* plantations on plant diversity, it did not assess the influence of the edge effect or the seed bank on this plant diversity. Nevertheless, this study provides the first information on the importance of *A. auriculiformis* plantations as habitats and corridors for local and exotic flora. By monitoring the plant community over time, it becomes possible to assess the effectiveness of restoration efforts. Indeed, changes in floristic composition can reflect the success or challenges encountered in the restoration process. Also, a thorough knowledge of the plant community helps to avoid the excessive dominance of a single species, which could lead to ecological imbalances. Finally, some plants can have beneficial effects on others, promoting growth and regeneration. Others may play a role in nitrogen fixation, protection against pests, or the creation of a favorable microclimate.

5. Conclusions

The current study provides a detailed analysis of the spatio-temporal dynamics of *A. auriculiformis* plantations and their influence on plant diversity in degraded lands across the urban–rural gradient in Lubumbashi. Our findings demonstrate a significant increase in the extent of these plantations over a 15-year period, growing from 13.68 hectares in 2006 to 21.97 hectares in 2021. This expansion is attributed to the restoration efforts made in landscapes degraded by urbanization.

In terms of composition, *A. auriculiformis* plantations predominantly feature members of the Fabaceae family and a higher proportion of exotic species, especially in urban areas compared to peri-urban zones. Furthermore, 19 indigenous species were identified within these plantations, including 18 tree species typical of the *miombo* woodlands. Notably, a greater diversity of plant species was observed in urban plantations compared to those in peri-urban areas.

The increase in plantation area indicates a trend towards the re-vegetation of degraded lands, with *A. auriculiformis* plantations supporting both exotic and native *miombo* species. However, the long-term sustainability of these plantations is questionable due to the presence of numerous invasive alien tree species, which could potentially threaten local biodiversity. This study's methodology and findings offer a foundation for developing policies and technical strategies for ecological restoration in Lubumbashi.

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