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Residential Greenery: State of the Art and Health-Related Ecosystem Services and Disservices in the City of Berlin

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Received: 18 February 2019; Accepted: 23 March 2019; Published: 26 March 2019

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Abstract: Inclusively accessible green areas are essential for livable cities. The residential greenery on a door's step of urban dwellers has rarely been the subject of research. Here we provide insights into the state of the art of residential greenery in Berlin, Germany. We focus on socially disadvantaged neighborhoods exposed to high loads of environmental stressors and belonging to four relevant building types of Central European cities. 32 plots in eight sample areas were randomly chosen and surveyed during 2017 and 2018. We surveyed the presence of structural elements, the presence and abundance of woody species and the health-related ecosystem (dis-)services (i.e., species' air filtration and allergenic potential). We analysed the similarity among tree species to assess plant use patterns. The air cleaning and allergenic potential of woody species were assigned based on literature. In order to discuss strategies to improve residential greenery, we performed an analysis of strengths, weaknesses, opportunities and threats of these green spaces. We revealed a high dissimilarity of woody species assemblages across sites and within different building types, indicating no common plant use fashion. Recorded species provide moderate to high air filtering capacity. One to two third of all trees have a high allergenic potential that has to be addressed in future plant use decisions. Bike racks, benches, lights and playgrounds are common elements, whereas bioswales, facade-bound greening, atrium, fountains or ponds are rare. Their implementation can enhance the health and wellbeing of local residents. Building-attached greenery can improve densely built up areas of the Wilhelminian period, whereas space-intensive measures can be implemented in the spacious greenery of row–buildings settlements of the 1920s–1970s and of large housing estates of the 1970s–1980s. We revealed a high motivation for (co-)design and care by residents and discussed strategies on transformation towards multi-functional, healthy and biodiversity-friendly residential greeneries.

Keywords: allergenic potential; ecosystem services; green gentrification; wellbeing; multifunctional living environments; urban horticulture

1. Introduction

The quality of the living environment, especially in urban areas, has become an important issue for residents and a fundamental theme in spatial planning [1]. Low quality of air, water, climate and the decreasing availability of green space per capita affect the physical and mental health of urban residents [2–5]. Consequently, urban planners and policymakers have to address easy access and high quality green areas as a part of common health promotion [5].

Contact with urban nature such as public parks fosters wellbeing and human health in cities [6,7]. Access to green space is associated with a greater probability of being physically active [5]. Moreover, species richness present in a green area and perceived by local people is positively linked to a greater connection with nature and a better site satisfaction [8]. If the environment is aesthetically appealing and space allows opportunities for gardening and for recreation, people are encouraged to visit it, improving social cohesion within the neighborhood, which in turn can generate beneficial effects on wellbeing [9,10]. In addition, trees provide several ecosystem services that contribute to increase human wellbeing and can mitigate the negative impacts of urbanization, e.g., [11,12]. Citizens seem to have a greater sense of community when more commonly shared green space is around their house [13]. Up to now urban planning has not taken the development of a city as a socio-ecological and macroeconomic system into proper consideration [14].

Urban greenery research generally focuses more on parks and public gardens [15–17], whereas the residential greenery has not been investigated. We defined residential greenery as mainly semi-public green spaces with direct connection to residential buildings, regularly created during the construction of the buildings with great importance for less-mobile people, for children and for after-work recreation [18].

To close this research gap, our study focused on the residential greenery of the four most relevant building types in Berlin, which are also representative of other Central European cities. As quality of and access to local green affects mainly low-income people [19], we focused our analysis on disadvantaged neighborhoods in Berlin. Our objective was to provide a description of the status quo of the residential greenery. We focused on tree and shrub composition and the structural elements (e.g., benches, paths, parking areas) that determine health-related ecosystem services such as cooling and air filtering and foster physical activity and the wellbeing of residents. We also included the allergenic potential of the plants as a health-relevant disservice [20–23]. We explored the strengths, weaknesses, opportunities and threats (SWOT analysis) of residential greenery to develop general strategies to enhance health-relevant ecosystem services and social cohesion.

2. Materials and Methods

2.1. Study Area

Berlin, the capital of Germany, is the largest city in the country, with 3.65 million inhabitants [24]. It covers an area of approximately 892 km^2, resulting in a population density of 4170 people/km^2. Two thirds of the population are living in housing complexes of modernism of four different eras: 1. Five story block-edge development with cross buildings enclosing several courtyards (the classical Wilheminian tenements of the 1870s to 1920s, Figure 1A); 2. five story block-edge development with green courtyards (the reformed block edge developments of the 1920s to 1940s, Figure 1B); 3. up to five story row-buildings settlements of the 1920s to 1970s (Figure 1C); and 4. large multi-storied housing estates of the 1960s to 1980s (Figure 1D).

Berlin is widely acknowledged as a green city and meets the planning target of 6m^2 of green space per inhabitant [25]. The city administration aims to face the increasing demand of affordable housing by intensified internal development and consolidation, leading to greater pressure towards urban green spaces within the city namely towards the semi-public residential greenery.

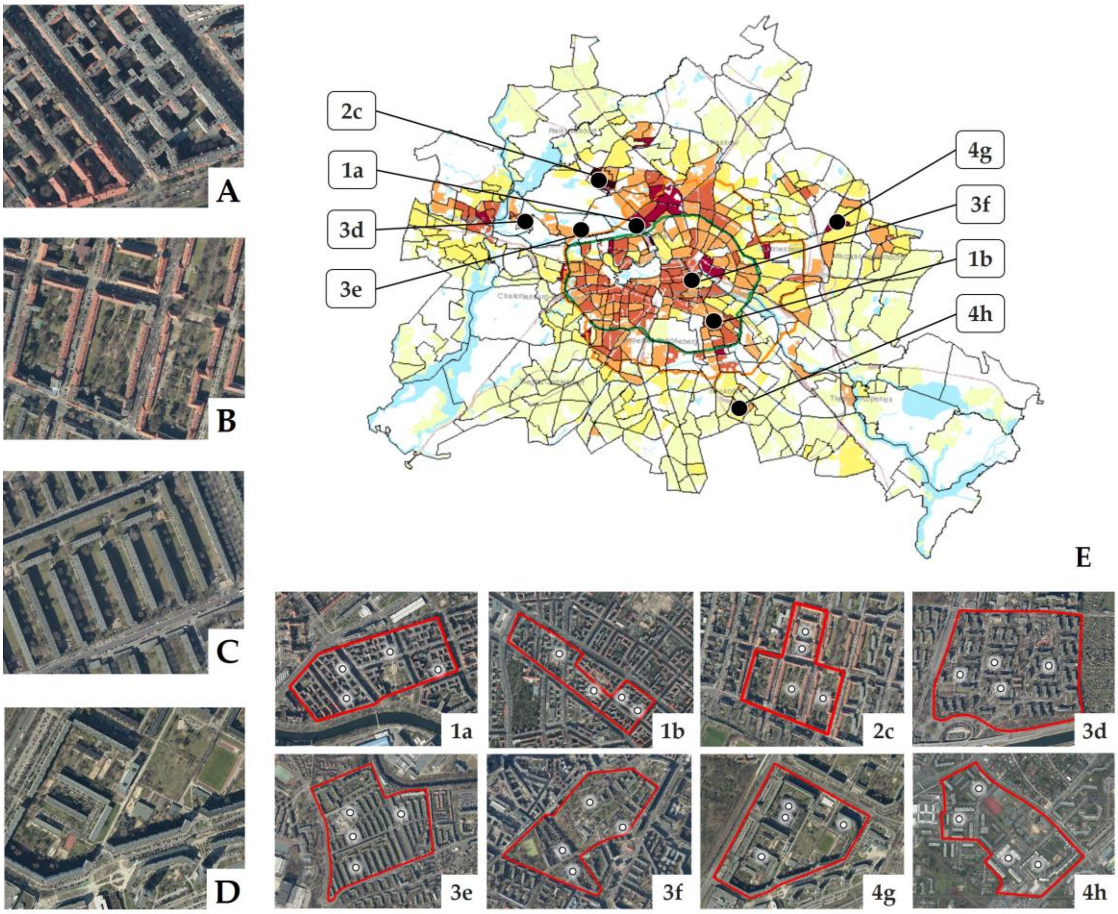

Figure 1. (**A**–**D**) Overview of typical building structures of Berlin ((**A**) dense and closed block-edge development from 1870s to 1920s; (**B**) block-edge development with large green backyards from 1920s to 1940s; (**C**) parallel and free row development with a landscaped residential greenery from 1920s to 1970s; (**D**) large housing estates with towers and high rise buildings from 1960s to 1980s). (**E**) Study areas in Berlin in residential areas with low social status and high level of environmental stressors, based on Berlin's Map of Environmental Justice [26]. For indicator values of each study area see Table 1. Red lines indicate the study areas (1a, Sprengelkiez, Wedding; 1b, Ideal-Passage, Neukölln; 2c, General Barby Siedlung, Reinickendorf; 3d, Paul-Hertz-Siedlung, Charlottenburg; 3e, Haselhorst, Spandau; 3f, Alte-Jakobstrasse, Mitte; 4g, Marzahn; and 4h, Gropiusstadt, Neukölln). White spots indicate the sample plots. Adapted from Fisbroker/Umweltatlas Maps of Berlin [26].

2.2. Study Design and Data Analysis

Firstly, we analysed the map of different building structures and selected all areas of the housing complexes of the four main construction eras in Berlin. Then, using the Berlin map on environmental justice [26], we assigned the health-relevant characteristics (i.e., air and noise pollution, bioclimatic stress, access to green space and social status) to these areas. The noise indicator estimates the average noise load. Bioclimatic stress is estimated by the thermal index PET (Physiologically Equivalent Temperature). Air pollution was determined by considering the highest level of $PM_{2.5}$ or NO_2. The access to green areas describes the availability of green spaces for a given housing block. The social status index is based on unpublished data from the Berlin monitoring on social urban development in 2013 and is calculated from the status indicators (i.e., unemployment and child poverty). Finally, we selected and characterized eight study areas with a low social status index, high levels of environmental stressors and low access to public green (Table 1 and Figure 1).

Single houses or flats within houses of the classical Wilheminian tenements are partially owned by natural persons, whereas the other areas are commonly owned and managed by different real estate companies. In contrast to other European countries, 86% of all apartments in Berlin are rented and not owned by the residents [27].

After defining eight study areas in Berlin, four sample plots were randomly chosen within those sites (Figure 1E). To exclude edge effects of neighboring public green spaces, we excluded sites where there are public green spaces situated at a distance of less than 500 m from the center of the housing blocks, which corresponds to five to ten minutes walking, and are, therefore, easily accessible to local residents. The sample plots correspond to the central space between two or more communicating building rows. The geometric shape of each sample was kept as simple as possible, following building edges, fences and paths. In each plot we accounted the structural elements of the residential greenery by field surveys: Number of green balconies, bioswales, laundry drying areas, ground-based and façade-bound greenery, atrium, fountains, ponds, parking areas, paths, playgrounds, bike racks, lights and benches.

We recorded the presence and abundance of tree species in each sample plot. Mature and newly transplanted trees were considered. We analyzed the degree of similarity among the tree species present in the eight sample areas, performing the Jaccard and the Bray-Curtis indexes, two widely used abundance-based similarity indexes [28]. For calculation we used the software Past 3.14 [29]. The Jaccard index (d_J) is related to the total number of species (presence/absence) that the sample areas have in common. For binary data, the absence is coded as 0 and the presence is coded as 1. When comparing two rows, a match is counted for all columns with presences in both rows. Past 3.14 uses M for the number of matches and N for the total number of columns with a presence in just one row; so that we have:

$$d_J = M/(M + N) \tag{1}$$

The Bray-Curtis index (d_{BC}) is based on the abundance of species:

$$d_{BC} = 1 - \frac{\sum_i |x_{ji} - x_{ki}|}{\sum_i (x_{ji} + x_{ki})} \tag{2}$$

where x_{ji} represents the entry in the ith row and jth column of the data matrix. Similarly, x_{ki} is the count for the ith species in the kth sample.

The presence/absence of shrub species was also surveyed. The abundance was not calculated because shrubs were often found in large and dense planting areas with mixed species. The woody species seedlings (born spontaneously) were not considered as they are subjected to maintenance operations, such as the mowing of lawns. Lawns were always present in the sample plots, except for Sprengelkiez and Ideal-Passage Neukölln, as the general matrix of residential greenery. The field data collection was carried out from April to August 2017 and 2018.

We evaluated health-related ecosystem services of woody species based on a literature evidences analysis. Reference selection was carried out using the PRISMA Protocol [30]. Three search engines were used: PubMed, Web of Science and JSTOR. The keywords used were: "Tree" AND "Ecosystem Services" AND "City" AND "Health". Taking into consideration the papers published in English in the last 20 years, 1466 titles and abstracts were analyzed. In total, 17 scientific papers have been selected to cover three categories of benefits provided by woody species in urban environments. Trees, depending on species, considerably remove air pollution (e.g., [4,8,14,31–33]). The main difference is between conifers (high capacity of air pollution removal) and broadleaf trees. The latter are divided into deciduous (moderate capacity) and evergreen (high capacity) trees (e.g., [31,32]). Bioclimatic stress is reduced by the shading and cooling of trees (e.g., [12,34–36]). In addition, trees provide a wide set of social benefits such as building a stronger sense of community, improving overall wellbeing and providing opportunities for residents to experience nature [11,37–41]. Ecosystem disservices, such as those related to the allergenic potential of trees, cannot be neglected [42–45].

Consequently, the surveyed woody species in the 32 sample plots were analyzed, assigning a level of allergenic and air pollution removal potential, based on the published literature.

Table 1. General characterization of study areas regarding building type and period, study area, code used in this study (see Figure 1), health relevant characteristics (i.e., air and noise pollution, bioclimatic stress, access to green space and social status), total sample area, population density and percentage of pervious and impervious surface (adapted from [26]). For details on relative environmental justice indicators see the Materials and Methods section. We surveyed two types of block-edge development (Type I: Dense and closed block-edge development from the 1870s to 1920s; and Type II: Block-edge development with large green backyards from the 1920s to 1940s, see Chapter Study Area and Figure 1A,B).

Building Type (Construction Period)	Study Area	Code	Noise	Air Pollution	Access to Public Green Spaces	Bioclimatic Stressors	Social Status Index	Total Sample Area (ha)	Number of Residents Per ha	% of Pervious Mean Surface	% of Impervious Mean Surface
Lock-edge developments (Type I, 1870s–1920s)	Sprengelkiez, Wedding	1a	Low	High	Low	High	Low	16.5	517	22	78
	Ideal-Passage, Neukölln	1b	Medium	High	Low	High	Low	12.6	533	17	83
(Type II, 1920s–1940s)	General Barby Strasse, Reinickendorf	2c	High	High	Low	High	Low	9.6	201	51	49
Row-building settlements (1920s–1970s)	Paul-Hertz Siedlung, Charlottenburg	3d	Medium	High	Medium	High	Low	35.5	208	57	43
	Haselhorst, Spandau	3e	High	Medium	High	High	Low	33.8	232	52	48
	Settlements along Alte-Jakobstr., Mitte	3f	High	High	Medium	High	Medium	28.7	315	61	39
Large housing estates (1970s–1980s)	Marzahn	4g	Medium	High	Low	High	Low	30	337	55	45
	Gropiusstadt, Neukölln	4h	Medium	Medium	Medium	High	Low	23.6	312	55	45

In order to discuss the strengths, weaknesses, opportunities and threats of residential greenery and to point out the strategies to improve it, a SWOT/TOWS analysis was performed [18,46].

3. Results

3.1. Structural Elements and Woody Species Composition

Block-edge developments of the Wilhelminian era (Figure 1A) have the highest population density and lowest percentage of pervious surface compared with other types (Table 2). This results in the lowest availability of residentially greenery for local residents. In the following construction period of block-edge developments with large green backyards in the 1920s to 1940s (Figure 1B), half of the areas are unsealed. The percentage of pervious surface of the other building types is similar or higher than in this type (Table 1). Population density depends on the floor numbers and is higher in the large estates of Marzahn and in the row-building settlements of Mitte (Figure 1: 3f, 4g) than the other same-aged building types considered.

Green spaces are an integral part of a town and have characterized residential greenery since the 1920s (Table 2). Lawns were always present as the general matrix of residential greenery (except in Sprengelkiez and Ideal-Passage, both from the Wilhelminian era). We identified a set of elements almost present in the residential greenery of all construction periods including bike racks, benches, lights and playgrounds. The number of benches, bike racks and lights varied largely between the areas and depended on the average size of the sample plots (Table 2). The laundry drying areas, often present in Germany, were found in the study areas of Alte Jakob Str., Mitte and Marzahn. Bioswales were only located in the sampling area of Haselhorst. Some elements were not detected: Façade-bound greening, atriums, fountains and ponds.

The tree and shrub species richness was similar in all building types (Table 3). In the 32 sample plots, 60 species of plants were identified, with 523 trees sampled (Appendix A). The most common species were: *Acer platanoides* L., *Betula pendula* Roth, *Quercus robur* L. and *Tilia cordata* Mill. The rare species were: *Corylus colurna* L., *Fagus sylvatica* L., *Alnus glutinosa* (L.) Gaertn. and *Celtis australis* L. Considering the number of trees of each species in each sample plot, we could determine the most frequent tree species. In some cases, the presence of one common species (the number of individuals is at least double compared with the other species) was detected, such as *Aesculus hippocastanum* L. in one of the block-edge developments of the Wilhelminian era (i.e., Sprengelkiez Wedding) and *Pinus sylvestris* L. in the green spaces around the large housing estates of Gropiusstadt (Neukölln).

Regarding shrubs, the species richness varies between 6 and 10 among all building types (Table 3). The presence of the shrub species in the study areas is reported in Appendix B. In some cases, such as *Carpinus betulus* L., some species have been considered as shrubs for the function performed and the growing habit and dimensions. The most frequent species in the areas are *Mahonia aquifolium* (Pursh) Nutt. and *Syringa vulgaris* L. Table 4 reports the results of the Jaccard and Bray-Curtis indexes. The matrix similarity of abundance and presence of woody/tree species across different building types shows that there is no similarity, because the values are lower than 0.5 (0 means no similarity; 1 means full similarity). Even within the same building type (e.g., 1a and 1b), similarity is not detectable. Therefore, planting patterns of residential greenery do not follow common design lines, unlike the built parts.

Table 2. Number of the structural elements of the residential greenery recorded in the sampling areas of this study (for details see the Materials and Methods sections, Table 3 for most frequent species and Appendices A and B). We surveyed two types of block-edge development (Type I: Dense and closed block-edge development from the 1870s to 1920s; and Type II: Block-edge development with large green backyards from the 1920s to 1940s, see Chapter Study Area and Figure 1A,B).

Building Type (Construction Period)	Neighborhood	Code	Mean Sample Plot Size (m^2)	Green Balconies/All Balconies (%)	Bioswales	Laundry Drying Areas	Ground-Based Greening	Parking Areas	Paths	Playgrounds	Lights	Bike Racks	Benches
Block-edge developments (Type I, 1870s–1920s)	Sprengelkiez, Wedding	1a	620	17/40 (43%)	0	0	1	1	0	1	3	8	2
	Ideal-Passage, Neukölln	1b	440	0	0	0	0	0	2	1	0	13	3
(Type II, 1920s–1940s)	General Barby Strasse, Reinickendorf	2c	8430	123/163 (75%)	0	0	0	0	3	2	9	8	21
Row-building settlements (1920s–1970s)	Paul-Hertz Siedlung, Charlottenburg	3d	1500	93/128 (73%)	0	0	0	0	3	2	10	10	3
	Haselhorst, Spandau	3e	3330	114/208 (55%)	4	0	0	2	0	0	7	3	1
	Settlements along Alte-Jakobstr., Mitte	3f	3030	127/200 (64%)	0	2	3	3	2	3	18	12	10
Large housing estates (1970s–1980s)	Marzahn	4g	5700	199/428 (46%)	0	1	0	2	0	2	1	9	11
	Gropiusstadt, Neukölln	4h	3000	157/313 (50%)	0	0	0	1	1	4	8	5	8

Table 3. Shrub and tree species richness and frequent trees species of the residential greenery mapped in the sample plots. Species were considered frequent if their presence was more than 10% of the total number of trees sampled. Bold species dominated tree composition, as the number of individuals was at least double compared with the number of individuals of other tree species (for details see Appendices A and B). Neighborhood codes: 1a, Sprengelkiez, Wedding; 1b, Ideal-Passage, Neukölln; 2c, General Barby Siedlung, Reinickendorf; 3d, Paul-Hertz-Siedlung, Charlottenburg; 3e, Haselhorst, Spandau; 3f, Alte-Jakobstrasse, Mitte; 4g, Marzahn; and 4h, Gropiusstadt, Neukölln. Bold characters indicate the most frequent species.

Building Type (Construction Period)	Code	Species Richness Trees	Species Richness Shrubs	Frequent Tree Species
Block-edge developments (Type I, 1870s–1920s)	1a	12	6	***Aesculus hippocastanum*** L.; *Acer platanoides* L.; *Fraxinus excelsior* L.; *Juglans regia* L.; *Pinus sylvestris* L.; *Prunus avium* L.; *Quercus robur* L.
	1b	13	8	*Betula pendula* Roth; *Acer pseudoplatanus* L.; *Taxus baccata* L.
Block-edge development with large green backyards (Type II, 1920s–1940s)	2c	23	9	***Betula pendula*** Roth; *Abies alba* Mill.; *Acer platanoides* L.; *Crataegus monogyna* Jacq.; *Ilex aquifolium* 'J.C. van Tol'; *Pinus strobus* L.; *Robinia pseudoacacia* L.
Row-building settlements (1920s–1970s)	3d	17	8	***Styphnolobium japonicum*** (L.) Schott; *Acer negundo* L.; *Acer platanoides* L.; *Ailanthus altissima* (Mill.) Swingle; *Betula pendula* Roth; *Ginkgo biloba* L.; *Malus domestica* Borkh.; *Prunus avium* L.
	3e	15	8	***Betula pendula*** Roth; ***Pinus strobus*** L.; *Acer negundo* L.; *Acer platanoides* L.; *Pinus nigra* J.F. Arnold; *Prunus avium* L.; *Prunus cerasifera* Ehrh.; *Robinia pseudoacacia* L.
	3f	15	10	*Acer campestre* L.; *Acer platanoides* L.; *Pinus sylvestris* L.; *Populus alba* L.; *Prunus cerasifera* 'pissardii nigra'; *Robinia pseudoacacia* L.; *Taxus baccata* L.; *Tilia cordata* Mill.
Large housing estates (1970s–1980s)	4g	32	9	***Quercus robur*** L.; *Acer platanoides* L.; *Betula pendula* Roth; *Carpinus betulus* L.; *Prunus serotina* Ehrh.; *Tilia cordata* Mill.
	4h	13	10	***Pinus sylvestris*** L.; *Acer platanoides* L.; *Styphnolobium japonicum* (L.) Schott

Table 4. Matrix similarity of abundance of woody or tree species across different building types using Jaccard and Bray-Curtis (italic) indexes. Building types: Block-edge developments (Type I: Without large green backyards of the 1870s–1920s; Type II: With large green backyards of the 1920s–1940s); row-building settlements of the 1920s–1970s and large housing estates of the 1970s–1980s. Neighborhood codes: 1a, Sprengelkiez, Wedding; 1b, Ideal-Passage, Neukölln; 2c, General Barby Siedlung, Reinickendorf; 3d, Paul-Hertz-Siedlung, Charlottenburg; 3e, Haselhorst, Spandau; 3f, Alte-Jakobstrasse, Mitte; 4g, Marzahn; and 4h, Gropiusstadt, Neukölln.

		Jaccard Index							
Building Types		**Block-Edge Developments**			**Row-Building Settlements**			**Large Housing Estates**	
		Type I		**Type II**					
		1a	**1b**	**2c**	**3d**	**3e**	**3f**	**4g**	**4h**
Bray-Curtis Index	**1a**	1	0.19	0.30	0.12	0.13	0.42	0.26	0.39
	1b	*0.20*	1	0.20	0.07	0.17	0.12	0.25	0.30
	2c	*0.18*	*0.13*	1	0.18	0.36	0.36	0.31	0.24
	3d	*0.16*	*0.11*	*0.17*	1	0.23	0.14	0.17	0.25
	3e	*0.18*	*0.18*	*0.37*	*0.33*	1	0.32	0.31	0.23
	3f	*0.37*	*0.13*	*0.31*	*0.12*	*0.27*	1	0.31	0.33
	4g	*0.18*	*0.12*	*0.37*	*0.12*	*0.22*	*0.25*	1	0.32
	4h	*0.24*	*0.18*	*0.18*	*0.21*	*0.16*	*0.27*	*0.23*	1

3.2. Ecosystem Services and Disservices Provided by Trees in the Sample Areas

Starting from the census of all trees in the residential greenery, the air pollution removal potential and allergenic potential were calculated for each sample area and building type (see Appendix A for potential value for air removal and allergy found in literature for each species in the sample areas, and Table 5 for a general summary of those data). The air pollution removal potential and the allergenic potential have been attributed to each tree species of the 32 sample plots (93% of the species are represented, no specific data were found in the literature for the remaining 7%).

Of the tree species sampled, 79% had a moderate potential to remove air pollution (i.e., deciduous trees, which represented 75% of all individual trees). Paul-Hertz-Siedlung and Marzahn had the lowest percentage of species with a high potential to remove pollution. Over all sampled areas, all trees had a moderate to high potential to remove pollution (Table 5). Tree composition in the study area of Gropiusstadt was ranked best as 60% of the plants showed a high value due to the frequent use of conifers (Table 5). Air pollution in Gropiusstadt was considerably lower compared to other study areas also due to the position outside the inner city of Berlin (Table 1).

Table 5. Tree composition in the study areas according to air pollution removal potential (modified by [13,23]) and allergenic potential (modified by [42–45], 93% of tree species are represented). Building types: Block-edge developments (Type I: Without large green backyards of the 1870s–1920s; Type II: With large green backyards of the 1920s–1940s); row-building settlements of the 1920s–1970s and large housing estates of the 1970s-1980s. Neighborhood codes: 1a, Sprengelkiez, Wedding; 1b, Ideal-Passage, Neukölln; 2c, General Barby Siedlung, Reinickendorf; 3d, Paul-Hertz-Siedlung, Charlottenburg; 3e, Haselhorst, Spandau; 3f, Alte-Jakobstrasse, Mitte; 4g, Marzahn; and 4h, Gropiusstadt, Neukölln.

	All Sampling Areas				Building Type							
					Block-Edge Developments			Row-Building Settlements			Large Housing Estates	
					Type I		Type II					
	Species		Individuals		1a	1b	2c	3d	3e	3f	4g	4h
	(n)	(%)	(n)	(%)	(% of trees per area)							
Air pollution removal potential												
moderate	49	79	395	75	80	88	82	95	78	76	94	40
high	13	21	113	22	20	13	18	5	23	24	6	60
Allergenic potential												
low	22	38	122	25	16	25	34	26	30	22	30	5
moderate	12	21	152	31	36	13	28	34	38	41	9	66
high	18	31	141	29	40	44	14	24	15	33	41	23
very high	6	10	80	16	8	19	24	16	18	4	21	6

Regarding the allergenic potential of plants (i.e., an ecosystem disservice) in the 32 sample plots, 18 species had a high allergenic potential while 6 species had a very high allergenic potential (Table 5). Over all sampled areas, two thirds of all species and three quarters of all trees had a moderate to very high allergic potential (Table 5). Considering the number of plants, 31% had a moderate allergenic potential while 45% had a high or very high allergenic potential value. Analyzing the percentages of trees, it was noticeable that in areas of Sprengelkiez, Ideal-Passage in Neukölln and Marzahn, nearly half or more of the trees (48%, 63%, and 62% respectively) had a high or very high allergenic potential. Lower allergenic potential was detected in General Barby Siedlung, Haselhorst and Marzahn (34%, 30% and 30% respectively).

3.3. Results of the SWOT Analysis

We detected the following strategies to address the strengths, opportunities, weaknesses and threats of the residential greenery across all our sample plots. Up to now green spaces have been designed and maintained in top down approaches by planners and gardeners of the real estate companies. Thus, green spaces invite residents to stay and use, but not to participate in the design and maintenance processes. Here, co-creation of the ongoing optimization processes is a helpful strategy to involve local citizens, foster the responsibilities of local residents to enhance welcoming qualities and care for the adaptations of greenery to changed needs (Table 6).

We identified strategies to improve the residential greenery (Table 6) considering external (threats and opportunities) and internal (weaknesses and strengths) factors of the residential greenery of our study areas, resulting in a strategy based on four different combinations [47].

Table 6. Examples for strategies to improve residential greenery by SWOT/TOWS matrix (see Methods).

	OPPORTUNITIES	THREATS
STRENGTHS	**SO-Strategies** • Co-design and Co-implementation (e.g., nature based solutions for health risks, biodiversity friendly playgrounds and experience trails) • Transfer of responsibilities for design, care and maintenance to residents • Implementation of missing residential greenery elements to foster cooling and filtering and biodiversity effects	**ST-Strategies** • Organisation of initial meetings and communication events to overcome barriers • Financial benefits with appropriate management • Plant use guide to reduce disservices of ornamental plants and enhance cooling and air filtering effects
WEAKNESSES	**WO-Strategies** • Transformation to multi-functional, healthy and biodiversity-friendly areas • Enhance welcoming qualities and motivation to be physically active (e.g., by implementation of barefoot paths and sport devices) • Empower integration friendly places for resilient neighborhoods	**WT-Strategies** • Foster easy-to-implement and low-cost solutions to avoid hard-to-transfer "lighthouse projects" or green gentrification • Information campaigns and workshops

4. Discussion

The residential greenery in the past has often been considered as the empty space between buildings or an area for ornamental purposes, rather than a green area with multiple functions serving the wellbeing of local residents. Figure 2 shows the main elements of the residential greenery in the study areas. It is mainly determined by design and plant use choices. Interestingly, we found no similarity in terms of abundance and presence of woody species within residential greenery (Table 3). Even within the same building type, similarity i low. The planting patterns of residential greenery do not follow common design guidelines or maintenance practices when individual trees or shrubs are replaced. We detected a largely unused potential to enhance health effects of residential greenery by a predominant use of woody species that provide health-relevant ecosystem services.

In general, urban trees in our study areas provide moderate to high benefits by absorbing air pollution. Evergreens and conifers play an important role in this regard [31,32]. Across all sampling sites, we revealed that one to two thirds of all trees have a high to very high allergenic potential (Table 5). Their presence, growth and management must be considered at the planning phase to maximize the provision of ecosystem services and to reduce potential disservices [23,42–44]. Instead of an increasing body of literature on health impacts of allergenic plants in urban areas [48–50], this topic has been scarcely considered in public or semi-public green area design. A plant use guide for residential greenery will assist real estate companies and managers of residential greenery to address this issue. High allergenic species such as *Alnus glutinosa* (L.) Gaertn., *Betula pendula* Roth, *Carpinus betulus* L., *Corylus colurna* L., *Cupressus sempervirens* L., *Fagus sylvatica* L., *Fraxinus excelsior* L., *Morus alba* L., *Quercus robur* L. and *Ulmus laevis* Pall. have to be avoided in these green spaces.

In the classic buildings of the Wilhelminian period in Germany (1870s to 1920s), different building laws and economic factors led to a perimeter block development without a noteworthy open-space structure and almost no living environment. The typical late 19th century courtyards in Berlin, with several backyards, used as traffic and storage areas, formed an almost complete overbuilding of the inner city. The residential greenery in the block-edge developments of the Wilhelminian area is smaller than in the other areas studied. Over 500 inhabitants are living in these areas per hectare with low access to public greenery, high air pollution and high bioclimatic stress. Eighty per cent of the surface is sealed (Table 1). The main elements of this era were street trees and some trees and shrubs in the small backyards. Commonly, the presence of plants is limited to a few individuals, however the number of trees per area is not significantly different from the other areas. Only a few benches, lights, playgrounds or paths were found mainly due to the small size of greenery (Table 2); however, the number of bike racks demonstrates that the use of bicycles and related physical activity is very common in Berlin's inner city districts. The number of balconies is low compared to other areas and 43% of them are greened by residents. Due to the lack of open space, we identified the need for the implementation of building-attached green (e.g., green wall measures, green roof or pervious parking areas, Figure 2B). Installing some more benches could provide meeting points in the small green realms of these densely over-built areas.

Occasionally socio-political cooperatives implemented reform ideas of green block courtyards at the beginning of the 20th Century (e.g., study area in Reinickendorf and Figure 1A). At the end of the First World War, there was a lack of housing and a promotion of small residential complexes with gardens (1924). In that historical period there was the need to ensure 'air and light' for all residents, creating a free space in the housing area and pouring into the building of row constructions. The quantity and the quality depended on whether the land for the settlement was owned by the city or not, and on the level of involvement of builders and planners in the surrounding green spaces [18]. The residential greenery in these modernist settlements of the 1920s contrasts sharply with the Wilhelminian period. The percentage of unsealed surface increased (e.g., 49% in Reinickendorf, Table 1). Both the tenants' gardens and the shared lawns were present, along with different structural elements such as laundry areas, playgrounds, paths and seating areas. Our study area in Reinickendorf presents a great diversity of woody species; real estate companies there pay particular attention to the maintenance of residential greenery. The number of balconies and number of benches increased manifold in this building type (Table 2). Seventy-five per cent of the balconies are greened by the residents. Due to the large size of the greenery, elements such as bioswales or ponds can be implemented, enhancing biodiversity, providing cooling effects and functioning for effective stormwater management.

The construction of multi-storey housing in the 1920s–1970s (e.g., sample areas of Paul Hertz Siedlung, Haselhorst and Mitte) was linked to modernist settlement ideas [18]. The row-building settlements were built loosely and criss-crossed by green spaces, where the inhabitants could walk and enjoy greenery on different paths. More than the half of the areas remain unsealed and the number of inhabitants per hectare is low (Table 1). The design of open spaces followed mainly two different ideas of parceling as tenants or the design of the area as a "park landscape". Tenant gardens were seen as a way to save costs of land care, a way of self-sufficiency of the inhabitants (especially after the Second World War) and as recreational areas [18]. The buildings have a high number of balconies often greened by residents (Table 2). The residential greenery in the study areas of Haselhorst and Mitte does not present particular plant composition, but offers ample space to spend pleasant moments, especially during the summer. Paul Hertz Siedlung holds a greater diversity of plant species compared to the other two study areas of this era (Table 2). Bioswales are implemented in one of our sample plots in Haselhorst.

The largest areas of residential greenery with integrated gardens, playgrounds and benches are typical for large housing estate of the 1960s to 1980s; however, welcoming qualities have been questioned as they were mostly designed from the perspective of architects and not of local residents [10]. Real estate companies in Berlin Hellersdorf and Hohenschönhausen (both neighboring quarters of Marzahn) addressed this with the successful implementation of gardens attached to the buildings, where local residents can co-design their private planting lot within the semi-public green spaces [51]. Recently the companies of Gropiusstadt invested money in the reconstruction of some gardens.

Figure 2. Residential greenery of the study areas (**A**, pervious parking in a courtyard in Sprengelkiez; **B**, courtyard in Neukölln with big improvement potential; **C**, playground in Haselhorst; **D**, disabled old lady with young adult sitting on a bench in the residential green area of Paul-Hertz-Siedlung; **E**, swale in Haselhosrt; **F**, newly-built greenery in Gropiusstadt; **G**, self-made garden in Gropiustadt; **H**, playground in Gropiusstadt; **I**, green alley between buildings, Gropiusstadt; photos: Pille).

In general, the residential greenery has an easy access for residents and invites to relate and communicate with neighbors. It is possible to enjoy the benefits of urban nature directly on the doorstep. Almost all residential greeneries examined in this study have a high diversity of tree and shrub composition. Parking lots and garages are rarely present, leaving space for lawns and ornamental plants. Up to now, only a few ground-based greening and bioswales were implemented (i.e., Haselhorst, Table 2). The laundry-drying areas, elements historically present in the residential greenery in Germany, unfortunately disappeared with the technical development of washing machines with dryers and today can be found as relicts in the study areas of Mitte/Alte Jakob Str. and Marzahn. The playgrounds are fairly distributed in the sites and are generally in good condition.

Paths especially designed to enhance physical activities, such as bare foot paths or devices for sport and physical exercises beyond classical play grounds are missing. Bike racks are common elements of all sample areas, but residents' demands in the sample plots are often higher. This leads to an accumulation of bicycles on the corners of the green areas, especially in the block-edge developments of the Wilhelminian area. To enhance the adaptability of residential greenery to changing residents' needs, multifunctionality of these areas has to be fostered also including the organization of social and sport activities with the aim to improve the fruition of those spaces.

The current state in residential greeneries, however, demonstrates the (partially) small size and high fragmentation of these green areas. Sometimes, if not designed and managed with care, the residential greenery does not have high welcoming qualities (i.e., Marzahn, Haselhorst). Usage conflicts (e.g., parking and dumpsters versus leisure and pleasure) are also evident for the residential greenery. Finally, these green spaces are perceived predominantly as a functional space for parking and waste management rather than as a space for recreation, physical activities, education or to come together with neighbors. Thus, our field survey highlighted these conflicts within usage among local citizens. As an example, while some enjoy using the residential greenery with their children, older neighbors complain about the noise generated.

The possibility of implementing residential greenery, enhancing the supply of ecosystem services and improving the wellbeing of the inhabitants are many. Among the elements that can be implemented, worthy of note are the green walls, which can help to increase the level of biodiversity and reduce the urban heat island effect [52,53]. This improves the aesthetic quality of the residential greenery, encouraging residents to stay longer in the area.

Residential greenery has a high re-naturation potential (i.e., using nature-based solutions) and there is a current trend that invites urban gardening activities. All this means it is useful to have new urban realms for urban biodiversity and to respond to the need to create resilient neighborhoods by increasing the identity of the place and its security, while creating a strong sense of community. The image of the residential greenery will change by visible transformations that are more accepted and used and better maintained when residents are invited to co-create their green spaces on their door steps in bottom-up processes, rather than in top down designs. There is the fear of contact with neighbors or an initial difficulty in relationships due to social and cultural barriers. Moreover, the poor maintenance and care of the residential greenery can return as a negative image of the place, which can lead to an increase in vandalism. The responsibilities and especially the initial costs of building and managing such green areas are high, potentially implying the green gentrification [54,55]. We also revealed evidence for a high motivation for (co-)design and care by residents with reimbursement effects also for the housing estate companies (i.e., General-Barby Str.).

5. Conclusions

Residential greenery is an essential and low cost tool to enhance sustainable social cohesion and the health and wellbeing of local residents. Here, we analyzed the state of the art of residential greenery in disadvantaged neighborhoods of Berlin considering structural elements, woody species and its health-related ecosystem services and disservices. These green areas are impressively significant within the city, both for their accessibility to the local population and for their contribution to the biodiversity of Berlin's greening. Our results highlight the extremely differentiated character of residential greenery among different neighborhoods and within the same neighborhood. We identified strategies to foster health relevant ecosystem services, physical activity and wellbeing of residents. Health-adapted plant use guidelines have to consider the allergenic potential of ornamental plants and the enhancement of cooling and air-filtering effects. Moreover, it is crucial to enhance welcoming qualities and the motivation to be physically active (e.g., by implementation of structural elements such as bike racks, barefoot paths or sport devices). The multifunctionality of residential greenery has to be fostered to maximize the adaptability to diverse and changing residents' needs across different cultures and generations. Moreover, there is a high motivation for co-creation of inclusive green spaces and care by residents on their door-step with long-term reimbursement effects also for the housing estate companies. The same approach can be used in other cities, focusing on wellbeing and the willingness of residents to improve the state of green areas. Design and management of residential greenery requires an inclusive multi-stakeholder approach, a cross-sectoral integration of existing knowledge from sociology, planning, ecology, agronomy, landscape architecture and urban planning, among others. These needs, which can no longer be postponed, must be addressed from a socio-ecological point of view in order to increase urban wellbeing conditions for the future generations.

Author Contributions: Conceptualization, I.S.; methodology, I.S., L.B. and L.P.; software, L.B. and L.P.; validation, I.S., T.W. and F.L.; formal analysis, L.B.; investigation, L.B., L.P. and T.W.; resources, I.S.; data curation, L.B. and L.P.; writing—original draft preparation, L.B. and L.P.; writing—review and editing, I.S., F.L., T.W. and L.B.; visualization, F.L.; supervision, I.S. and F.L.; project administration, I.S.; funding acquisition, I.S.

Funding: This research was funded by Fritz and Hildegard Berg Stiftung in the Deutscher Stifterverband, "HealthyLiving-Strategie und Planungsinstrument für gesundheitsförderndes Wohnumfeldgrün in der Stadt der Zukunft".

Acknowledgments: We thank our *Healthy Living* research team members Sylvia Butenschön, Frederike Büttner, Ewelina Skulimowska, Sonja Mohr Stockinger, Jan Hogrefe, Hannah-Lea Schmid and Lea Matscheroth for field assistance and fruitful discussion on health-related ecosystem services of residential greenery. We thank the reviewers for their helpful suggestions to improve the manuscript.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study, in the collection, analysis or interpretation of data, in the writing of the manuscript or in the decision to publish the results.

Appendix A

Table A1. List, number, air pollution removal potential (modified by [31,32]) and allergenic potential (modified by [42,43,45,48], 93% of tree species are represented) of all woody and tree species sampled in the 32 sample plots divided by building type. Building types: Block-edge developments (Type I: Without large green backyards of the 1870s–1920s; Type II: With large green backyards of the 1920s–1940s); row-building settlements of the 1920s–1970s; and large housing estates of the 1970s–1980s. Neighborhood codes: 1a, Sprengelkiez, Wedding; 1b, Ideal-Passage, Neukölln; 2c, General Barby Siedlung, Reinickendorf; 3d, Paul-Hertz-Siedlung, Charlottenburg; 3e, Haselhorst, Spandau; 3f, Alte-Jakobstrasse, Mitte; 4g, Marzahn; and 4h, Gropiusstadt, Neukölln.

Building Types	Number of Trees per Sample Area								Total Number of Trees Across Sampled Areas	Allergenic Potential	Air Pollution Removal Potential
	Block-Edge Developments			Row-Building Settlements			Large housing ESTATES				
	Type I		Type II								
Species	1a	1b	2c	3d	3e	3f	4g	4h			
Abies alba Mill.	1	0	4	0	0	2	1	3	11	low	high
Acer campestre L.	1	0	1	0	0	3	0	0	5	moderate	moderate
Acer negundo L.	0	0	2	2	3	1	4	0	12	moderate	moderate
Acer platanoides L.	3	0	6	2	4	4	12	10	41	high	moderate
Acer platanoides ‘Crimson King’	0	0	0	1	0	0	0	0	1	high	moderate
Acer pseudoplatanus L.	0	2	0	0	0	0	8	3	13	high	moderate
Acer saccharinum L.	0	0	0	1	0	0	0	0	1	moderate	moderate
Aesculus hippocastanum L.	6	1	1	0	1	2	4	3	18	moderate	moderate
Ailanthus altissima (Mill.) Swingle	0	0	0	3	0	0	0	0	3	high	moderate
Alnus glutinosa (L.) Gaertn.	0	1	0	0	0	0	1	0	2	high	moderate
Betula pendula Roth	0	2	20	4	6	0	22	3	57	very high	moderate
Betula utilis D.Don	0	0	1	0	0	0	0	0	1	high	moderate
Carpinus betulus L.	0	0	0	1	1	2	9	2	15	very high	moderate
Carpinus betulus ‘pyramidalis’	0	0	0	0	0	0	6	0	6	-	moderate
Castanea sativa Mill.	0	0	2	0	0	0	0	0	2	moderate	moderate
Catalpa bignonioides Walter	0	1	0	0	0	0	1	2	4	high	moderate
Celtis australis L.	0	0	0	0	0	2	0	0	2	high	moderate
Citrus spp.	0	1	0	0	0	0	0	0	1	low	high
Corylus colurna L.	0	0	0	1	0	0	0	0	1	very high	moderate
Crataegus monogyna Jacq.	0	0	8	0	0	0	0	0	8	low	moderate
Cupressus sempervirens L.	0	0	3	0	0	0	0	0	3	very high	high
Eriobotrya japonica (Thunb.) Lindl.	0	0	0	0	0	0	3	0	3	low	high
Fagus sylvatica L.	0	1	0	0	0	0	0	0	1	very high	moderate
Fagus sylvatica ‘atropurpurea’	0	0	0	0	0	0	0	3	3	-	moderate
Fraxinus excelsior L.	2	0	0	0	0	0	1	0	3	very high	moderate
Ginkgo biloba L.	0	0	0	2	0	0	0	0	2	moderate	moderate
Gleditsia triacanthos L.	0	0	0	0	0	0	2	0	2	low	moderate
Ilex aquifolium ‘J.C. van Tol’	0	0	15	0	0	0	0	0	15	-	high

Table A1. *Cont.*

Building Types / Species	Number of Trees per Sample Area: Block-Edge Developments Type I 1a	1b	Type II 2c	Row-Building Settlements 3d	3e	3f	Large housing ESTATES 4g	4h	Total Number of Trees Across Sampled Areas	Allergenic Potential	Air Pollution Removal Potential
Juglans regia L.	2	1	1	0	0	0	1	0	5	high	moderate
Malus domestica (Borkh.) Borkh.	0	0	1	5	0	0	0	0	6	low	moderate
Morus alba L.	0	0	0	1	0	0	0	0	1	high	moderate
Picea glauca (Moench) Voss	0	0	0	1	0	0	1	0	2	low	high
Pinus nigra J.F. Arnold	0	0	0	0	3	0	0	0	3	moderate	high
Pinus sylvestris L.	2	0	0	0	0	4	2	46	54	moderate	high
Pinus strobus L.	0	0	8	0	6	0	0	0	14	moderate	high
Populus alba L.	0	0	0	0	0	4	0	0	4	moderate	moderate
Populus nigra 'Italica'	0	0	1	0	0	0	0	0	1	high	moderate
Populus tremula L.	0	0	0	0	0	0	4	0	4	-	moderate
Prunus avium L.	2	1	3	3	5	0	1	1	16	low	moderate
Prunus cerasifera Ehrh.	0	0	2	0	4	0	1	0	7	low	moderate
Prunus domestica L.	0	1	0	0	0	0	0	0	1	low	moderate
Prunus persica (L.) Batsch	0	0	0	0	1	0	0	0	1	low	moderate
Prunus cerasifera 'pissardii nigra'	0	0	1	0	1	3	3	0	8	low	moderate
Prunus serotina Ehrh.	0	0	0	0	0	0	14	0	14	low	moderate
Pseudotsuga menziesii (Mirb.) Franco	0	0	0	1	0	0	5	0	6	low	high
Quercus robur L.	3	0	2	1	0	2	35	2	45	high	moderate
Quercus robur 'fastigiata'	0	0	0	1	1	0	0	0	2	high	moderate
Quercus rubra L.	0	0	0	0	0	0	1	0	1	high	moderate
Rhus typhina L.	0	0	0	0	0	0	1	0	1	low	moderate
Robinia pseudoacacia L.	0	1	13	0	2	5	3	0	24	moderate	moderate
Salix caprea L.	0	0	0	0	0	0	1	0	1	high	moderate
Salix matsudana 'contorta'	1	0	0	0	0	2	0	0	3	high	moderate
Sorbus aucuparia L.	0	0	1	0	0	0	0	0	1	low	moderate
Sorbus intermedia (Ehrh.) Pers.	0	0	0	0	0	0	2	0	2	low	moderate
Styphnolobium japonicum (L.) Schott	0	0	0	8	0	0	0	5	13	moderate	moderate
Taxus baccata L.	1	2	2	0	0	5	1	2	13	high	high
Thuja orientalis (L.) Franco	1	0	0	0	0	0	0	0	1	low	high
Tilia americana L.	0	1	0	0	0	0	0	0	1	low	moderate
Tilia cordata Mill.	0	0	13	0	1	5	11	0	30	low	moderate
Ulmus laevis Pall.	0	0	0	0	1	0	1	0	2	high	moderate
									Mean ± SD		
Tree species richness	12	13	23	17	15	15	31	13	17±6		

Appendix B

Table A2. Presence/absence of shrub species and shrub species richness in the study areas. N: Number of sample areas with species presence. Building types: Block-edge developments (Type I: Without large green backyards of the 1870s–1920s; Type II: With large green backyards of the 1920s–1940s); row-building settlements of the 1920s-1970s and large housing estates of the 1970s–1980s. Neighborhood codes: 1a, Sprengelkiez, Wedding; 1b, Ideal-Passage, Neukölln; 2c, General Barby Siedlung, Reinickendorf; 3d, Paul-Hertz-Siedlung, Charlottenburg; 3e, Haselhorst, Spandau; 3f, Alte-Jakobstrasse, Mitte; 4g, Marzahn; and 4h, Gropiusstadt, Neukölln.

	Presence (+) of Shrubs Species								
Building Types	**Block-Edge Developments**			**Row-Building Settlements**			**Large Housing Estates**		
	Type I		**Type II**						
Shrub Species	**1a**	**1b**	**2c**	**3d**	**3e**	**3f**	**4g**	**4h**	**N**
Berberis darwinii Hook.							+		1
Berberis thunbergii 'atropurpurea'			+						1
Camelia japonica L.		+							1
Carpinus betulus L.								+	1
Cornus alba 'elegantissima'						+			1
Cornus kousa Buerger ex Miq.			+						1
Cornus mas L.					+				1
Ligustrum ovalifolium Hassk.								+	1
Photinia x fraseri			+						1
Spiraea japinoca L.					+				1
Cotoneaster dammeri C.K. Schneid			+						1
Cupressocyparis leylandii (Dallim. & A.B. Jacks.) Dallim.		+							1
Wisteria sinensis (Sims) Sweet		+							1
Hibiscus spp.								+	1
Ilex aquifolium L.							+		1
Pittosporum tobira Thunb.) W.T. Aiton	+								1
Lonicera nitida E.H. Wilson				+			+		2
Partenocissus quinquefolia (L.) Planch.					+	+			2
Rhododendron spp.	+							+	2
Corylus avellana L.		+		+			+		3
Berberis thunbergii DC.				+		+		+	3
Kerria japonica (L.) DC.		+			+	+			3
Parthenocissus tricuspidata (Siebold & Zucc.) Planch.			+		+			+	3
Juniperus spp.			+			+	+	+	4
Crataegus oxyacantha L.			+	+	+			+	4
Hedera helix L.	+	+		+		+			4
Sambucus nigra L.		+		+		+	+		5
Prunus laurocaerasus L.	+	+			+	+	+		5
Mahonia aquifolium (Pursh) Nutt.	+		+	+	+	+	+	+	7
Syringa vulgaris L.	+		+	+	+	+	+	+	7
									Mean ± SD
Shrub species richness	6	8	9	8	8	10	9	10	9±1

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