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Monitoring and perception of allergenic pollen in urban park environments

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HIGHLIGHTS

- Parallel pollen monitorings and a park visitors' survey on park use and allergy symptoms were conducted.
- 'Despite high pollen concentrations, most of the allergy sufferers did not change their park visitation routine.
- Respondents with allergies rather seemed to regulate the pollen-related allergic symptoms through the use of medication.
- Survey participants recommended urban green space planning should consider planting more non-allergenic trees and improving public pollen information and warning systems.

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ABSTRACT

Urban green spaces are highly important for the health and well-being of urban residents, especially under conditions of ongoing climate change and urbanisation. However, vegetation in urban parks may also present a risk to human health through the presence of allergenic plants and release of allergy-inducing pollen. Using the city of Leipzig as a case study, we monitored pollen abundance in two inner city parks and on the roof of a central university hospital during the pollen season in 2021. We also conducted a questionnaire survey with 186 city residents. Questions related to their allergic symptoms, perceived physical and mental health impairment, potential behavioural adaptations due to expected pollen exposure, and suggestions for urban planning. We found nine plant genera with particularly high concentrations of pollen across the monitoring sites, including especially *Alnus* and *Betula*. While a high proportion of trees planted in one of the parks were *Betula*, potentially explaining the high concentrations we monitored, the high pollen load for *Alnus* could not be explained by the local presence of *Alnus* trees at either park. A majority of respondents (61%) indicated they suffered from pollen-related allergic symptoms, with *Betula* pollen most often mentioned as a main cause of their health impairment. Of respondents with symptoms, 82% indicated they did not change their park visitation patterns due to expected pollen exposure. However, nearly two-thirds of the respondents took allergy medication at least once per week. Participants' recommendations for urban planning included considering allergies when selecting species for planting, improving urban air quality, and advancing public pollen information and warning systems. We conclude that particularly allergenic trees, such as *Betula*, should be avoided in densely populated urban areas, because of the potential for a large number of residents to experience allergy symptoms. However, such species should not be

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completely avoided, as plant diversity is still a crucial element of ecosystem resilience in the face of climate change and urbanisation. Combining objective and subjective data on the burden of allergenic pollen, as was done in our study, can help derive such targeted policy recommendations.

1. Introduction

The health of urban residents is impacted by a diversity of environmental challenges related to climate change and ongoing urbanisation. For instance, high air temperatures more frequently occur in urban areas due to the increasing prevalence of heat waves (IPCC, 2021) and the sealing of soil with impervious surfaces, which creates an urban heat island effect (Kabisch et al., 2017; Kabisch, Remahne, et al., 2023; Oke, 1982). Exposure to heat has negative health effects, including increased cardiovascular and respiratory morbidity, hospital admissions and excess mortality (Ebi et al., 2021). Likewise, traffic-related air and noise pollution also have adverse physical (Mueller et al., 2018; 2020) and mental health effects (Van Den Bosch & Meyer-Lindenberg, 2019) on people exposed. Furthermore, there is even increasing evidence that exposure to heat and air pollution, when co-occurring in urban areas, have negative synergistic effects on health (Anenberg et al., 2020).

Urban green spaces, such as parks or road-side verges with trees, provide a number of ecosystem services that help mitigate and adapt to these challenges arising from climate change and urbanisation (Bayulken et al., 2021). Park vegetation and street trees reduce air temperatures through shading and transpiration (Kraemer & Kabisch, 2022) and have the potential to buffer air pollutants from adjacent street environments (Kabisch, Kraemer, Brenck, et al., 2021). Urban green spaces also provide recreational ecosystem services that contribute to health promotion and well-being. For instance, urban green spaces provide opportunities for social interaction and physical exercise, which have been observed to benefit both physical and mental health in numerous ways (Besser & Lovasi, 2023; Bratman et al., 2019; Gascon et al., 2015; Kabisch, Basu, et al., 2023; Mueller et al., 2020; van den Bosch & Sang, 2017). Even under conditions of heat, physical activity and relaxation in urban green spaces enables stress relief (Kabisch, Kraemer, Brenck, et al., 2021).

However, urban green spaces can also create risks to physical and mental health, such as through the release of allergenic pollen from plants. Amongst people who are sensitised, exposure to allergenic pollen may cause clinical symptoms related to allergic rhinitis, allergic asthma or atopic dermatitis, and negative mental health effects, such as fatigue (Cariñanos & Marinangeli, 2021; Damialis et al., 2019). For instance, people exposed more frequently to street trees with high allergenic potential experience increased asthma hospitalization rates (Lai & Kontokosta, 2019). A recent review found that people living near green spaces with higher levels of allergenic pollen can exhibit worse mental health, which may be partly due to allergic symptoms and subsequently altered park visitation behaviours (Legg & Kabisch, 2024).

These potential risks posed by urban green spaces are particularly relevant given that the potency of allergenic pollen and vulnerability of people may also be increasing. The share of people diagnosed with pollen-related allergies in Europe has increased, particularly over the last decade, with between 15–40% of the population now affected (Traidl-Hoffmann, 2021). The rising prevalence is hypothesised to be related to changes brought about by climate change and urbanisation, among other reasons (Bergmann et al., 2023; Damialis et al., 2019). For instance, climate change related increases in average temperatures contribute to an earlier start to the pollen season (Bergmann et al., 2023; Clot, 2003; Cuinica et al., 2015; Steckling-Muschack et al., 2021; Ziska et al., 2019). In addition, temperature changes have also allowed some non-native species whose pollen is highly allergenic, such as *Ambrosia artemisiifolia* or *Ailanthus altissima*, to become widely established in central Europe (Agnew et al., 2018; Bergmann et al., 2023; Prenzel et al., 2022; Treudler & Simon, 2013). As a result, children born and living in urban areas have been observed to exhibit significantly higher rates of allergic rhinitis and eye- and nose-related allergic symptoms (Fuertes et al., 2014), and those living in the centre of cities have been found to be more likely to be sensitised to outdoor allergens (He et al., 2019; Treudler et al., 2018).

The allergenic potential of urban green spaces is determined by several aspects, including the tree and grass species present, the specific allergenicity of these species, the number of such allergenic species in the area, and local environmental conditions (Buters et al., 2008). For instance, urbanisation may influence the actual allergenicity of pollen (Beck et al., 2013; Cuinica et al., 2015; Motta et al., 2006), as air pollution particles interact and merge with pollen particles, creating allergen-containing aerosols and leading to worsening of symptoms amongst those exposed (Cuinica et al., 2015; Frank & Ernst, 2016; Lin et al., 2018).

Against this background of ongoing climate change and urbanisation, the health benefits of urban green spaces and their potential for pollen-related adverse health effects, this interdisciplinary study sought to explore relations between objective pollen measurements, the subjective perception of potentially allergenic pollen by urban park visitors and their park visitation behaviours. Many prior studies on urban pollen abundance, distribution and allergenicity have so far not considered these aspects, such as studies examining the relevance of allergenicity of urban tree plantings (Bergmann et al., 2012), the relation of park trees and local pollen emissions (Cariñanos et al., 2017; Kasprzyk et al., 2019), or the spatial distribution of pollen concentrations within a city (Werchan et al., 2017). However, some studies have examined the interactions of objective or subjective pollen presence with park perception, perceived mental health and visitation behaviours (for a review, see Legg & Kabisch, 2024).

To further supplement the yet limited evidence, we used the city of Leipzig as a case study and monitored the abundance of pollen of nine plant genera in two inner city parks and on the roof of a central university hospital for the pollen season in 2021. We also conducted a questionnaire survey with city residents which explored perceptions of the burden of allergenic pollen in relation to urban green space use, individual preventive or adaptation measures, and their suggestions for related adaptive urban planning. Our specific objectives were to investigate: (i) if local plant communities in urban parks affect pollen composition; (ii) if urban residents suffering from allergic symptoms related to pollen reported adapting their park visitation behaviours due to pollen flight; and, finally, (iii) what recommendations urban residents may have for urban green space planners to mitigate the potential health burden of exposure to allergenic pollen in urban green spaces.

2. Methods

2.1. Case study

2.1.1. Leipzig and two inner-city parks: Friedenspark and Lene-Voigt-Park

Leipzig is a large city located in the central German Federal State of Saxony. The city covers an area of 298 km^2 (Stadt Leipzig, 2023b). The total population increased by about 22% from 508,775 inhabitants (2010) to 610,000 inhabitants in 2021 (Stadt Leipzig, 2023b), accompanied by large-scale residential development and urbanisation (Wolff et al., 2017). The impacts of climate change have become increasingly tangible over the last two decades. For instance, Leipzig faced severe heat and drought periods in the years 2018, 2019, and 2020, which were characterized by an increase in the annual mean air temperature by 2.5 °C (2018, 2019) and 2.6 °C (2020) compared to the long term mean of 8.8 °C. Also, the mean annual precipitation was reduced 34%, 22.3% and 16.8%, respectively, compared to the long term sum precipitation of 511 mm (Stadt Leipzig, 2024). Across the city, the share of urban green space is 17%, including urban (riparian) forests, urban parks, cemeteries and allotment gardens (Stadt Leipzig, 2021).

To monitor pollen abundance across Leipzig, three sites were chosen as locations to place pollen traps: two urban parks (Friedenspark and Lene-Voigt-Park) and the roof of the central building of the university hospital (Fig. 1). The parks were selected because they are located in the dense inner-city area with typical residential and commercial urban structures in close proximity. The parks differ in their vegetation and infrastructure characteristics (Kabisch, Kraemer, Masztalerz, et al., 2021). The Friedenspark is a 17.5 ha sized park developed on a former cemetery. The park has a dense stock of mature trees (61% tree coverage, mean tree height above 13 m). Fig. 2A shows the main tree genera in the Friedenspark (Stadt Leipzig - Amt für Stadtgrün und Gewässer, 2018) with street and ornamental trees in a 50 m buffer around the park including *Tilia* (lime tree, 39%, mainly *Tilia cordata* (11%) and *Tilia x vulgaris* (10%)), *Aesculus* (chestnut, 19%, mainly *Aesculus hippocastanum* (16%)), *Quercus* (oak, 10%, mainly *Quercus robur* (9%)), and *Acer* (maple, 7%, mainly *Acer pseudoplatanus* (3%)). A total of 12 different plant genera with allergenic potential (see Cariñanos and Marinangeli, 2021) were found within the park, with *Quercus robur* (9%), *Acer* (7%), *Fraxinus excelsior* (4%, ash), and *Betula pendula* (2%, birch) being the most prominent.

The Lene-Voigt-Park is a 5.8 ha sized park located north of the Friedenspark (500 m distance, Fig. 1). The park, which was a former railway brownfield site, was regenerated and opened for public use in 2004 (Kabisch, 2019). The former railway site is still visible in the park's structure, characterised by its rectangular shape, huge open grass areas and total tree coverage of 14%. Trees were planted initially as part of the urban regeneration and park redevelopment process but have also been

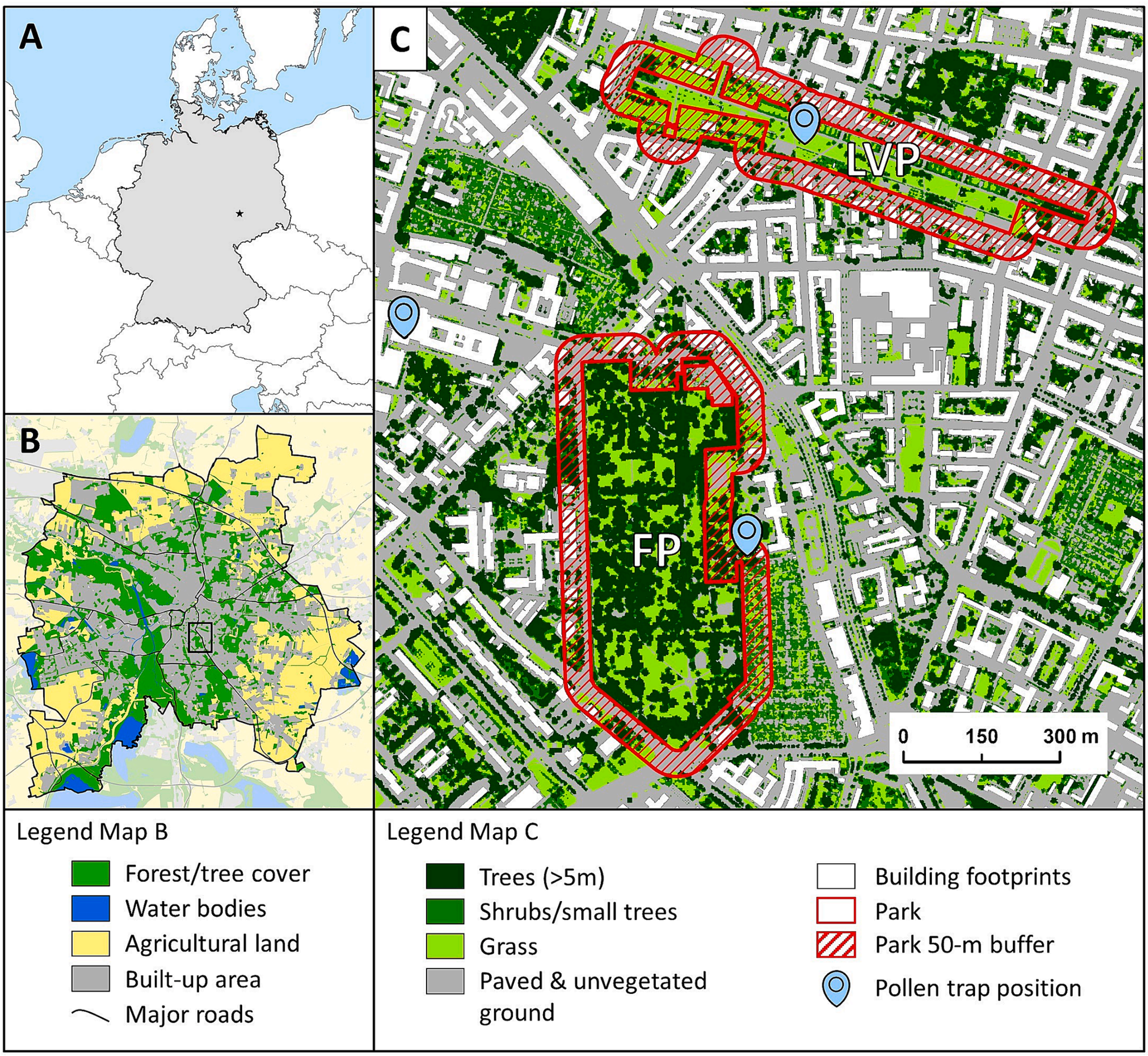

Fig. 1. A: Location of the city of Leipzig in Germany. B: Location of the study area (black rectangle) in the city of Leipzig. C: Study area with land cover and two urban parks, Friedenspark (FP) in the south and Lene-Voigt-Park (LVP) in the north. Map data: OpenStreetMap contributors, 2018; Stadt Leipzig – Amt für Geoinformation und Bodenordnung (Banzhaf & Kollai, 2018); GeoSN, 2018.

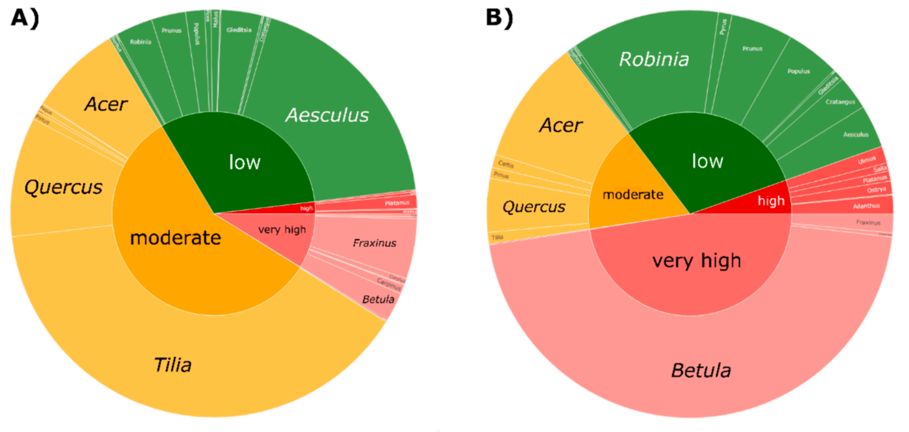

Fig. 2. Percentage composition of tree abundance in (A) Friedenspark and (B) Lene-Voigt-Park, including street and ornamental trees within a 50 m buffer around the park (Stadt Leipzig - Amt für Stadtgrün und Gewässer, 2018). The inner circle denotes the potential allergenicity of the tree genus (denoted in outer circle) according to Cariñanos and Marinangeli (2021), ranging from 'low' (green) over 'moderate' (yellow) and 'high' (red) to 'very high' (light red). For evaluation of small-percentage groups see Table Supplementary Table 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

added to continuously over the last few years. The trees within the park, and the 50-m buffer area around it, are primarily *Betula* (46%), with mainly *Betula utilis* (46%), *Robinia* (12%), and *Acer* (10%). Some other genera are also present, but with an occurrence of less than 5%. Potentially allergenic trees include *Betula*, which were planted on the complete length of the northern park border, and some others including *Quercus* sp., *Fraxinus excelsior*, *Ailanthus altissima* (tree of heaven), *Platanus* (plane tree) *x acerifolia*, *Acer*, or *Ulmus* (elm tree, in total 12 genera) (Figs. 1 and 2B).

The rest of the study area around the two parks is not only characterised by structures of the urban built environment, but also additional green spaces, including allotment garden colonies of about 5 ha size each. Built environment structures include the Wilhelminian-time residential building blocks of around 20 m height in the north-eastern area and some high-rise buildings with a height of over 50 m in the southwest of the two parks. More than one third of the study area is covered by impervious surfaces such as streets, sidewalks, or other artificial surfaces (see Kraemer & Kabisch, 2022 for more detailed information on the location, the parks and the built environment structure). Both parks are closely located to the Leipzig University Medical Centre, where a third pollen trap was installed on the roof of the central university hospital building as a reference point for comparison, as pollen traps located on roofs have been noted to collect pollen from a broader and more regional area (Maya-Manzano et al., 2022; Pfaar et al., 2017).

While we are aware of some disagreement about thresholds and placing of certain taxa, we decided to include all listed taxa based on species or genus classification by Cariñanos and Marinangeli (2021) in order to allow a rough point of comparison to findings emerging from other research (Bonini et al., 2022).

2.1.2. Aerobiological monitoring

Pollen monitoring was carried out from 23rd February to 4th May 2021. However, due to technical problems, monitoring could not be performed in the Lene-Voigt-Park between 9th April and 22nd April 2021. Pollen was collected with seven-day recording volumetric Hirst-type pollen and spore traps (Burkhard Manufacturing Ltd., Hertfordshire, UK). These traps were located at heights of 17.3 m asl on the roof of the University hospital in Leipzig (51.330847 N 12.387845E), 1.5 m asl in the Friedenspark (51.327247 N, 12.397459E), and 1.5 m asl in the Lene-Voigt-Park (51.334421 N 12.398669E). The volumetric flow rate was set to approximately 10 L/min. A vaseline-covered strip on a drum was turned by clockwork in a defined movement over one week in order to collect and trap pollen it came into contact with. This strip was replaced weekly, with the old strip used as a sample to count the daily mean pollen concentration, including all identifiable pollen. The analysis followed the European regulation DIN EN 16868 for pollen and fungal spore sampling. Fig. 3 shows pictures of the pollen traps at the three sites.

2.1.3. Questionnaire survey

The questionnaire survey was conducted online using the Google Survey tool. It was available from 12th April to 3rd July 2021. Information about the survey was distributed to the email addresses of employees working near both parks via the authors' networks, whereby ca. 2000 employees were reached. In addition, information sheets were placed at the entrances to both parks, on fences and poles within the parks, and in cafés and shops located in close proximity. On these sheets, visitors could find details about the study and were invited to participate in the survey via a QR-code that took them to the survey website.

The survey consisted of 18 questions and took an estimated 10 min to complete (see Supplementary Material 1 for the complete version). Questions were clustered by topics including: (i) park visitation patterns and perceived functions of parks and trees; (ii) park use during the COVID-19 pandemic; (iii) allergic symptoms, allergy medication intake, which pollen types cause the greatest impairments, etc.; (iv) recommendations for improving urban planning to mitigate the potential health burden of exposure to allergenic pollen in urban green spaces; and (v) demographics, such as gender, age and current employment status. The survey was anonymous and participants were not asked to specify their residential address. We used Likert scales for pre-defined answers but also allowed for open-ended responses, such as to the question on recommendations for urban planning.

2.2. Data analysis

Pollen data were analysed under a light microscope with 40 X magnification, following the guidelines of DIN EN 16868 for pollen and fungal spore sampling. The microscope used for pollen identification and analysis was an Olympus BH-2 with WHK 10x/20 Oculars and an Olympus S PLAN APO 40 objective. Other objectives were not used for analysis. Pollen analysis followed the horizontal transect method from the European standard (DIN EN 16868). Hence, three horizontal transects (field of view 0.65 mm; in total 14% of the complete slide surface) were analysed per slide to obtain daily pollen concentrations per m^3 air. We referred to own reference slices and also used an open access data

Fig. 3. Pictures of pollen trap survey sites. Pictures by authors.

base (Stebler, 2024). Afterwards the data were visualised using R-Software version 4.2.1 (R Core Team 2022) with the packages *plotme*, *ggplot2* and *dplyr*.

Survey data were exported from Google Survey and imported into IBM SPSS 23.0. We used simple descriptive and bivariate statistics to show results in the context of the previously defined research questions. The answers to open-ended questions, such as the one asking for potential recommendations for urban planning, were sampled, read intensively, and thematically organised through discussion among the team of authors. The answers were grouped into four clusters and presented according to this thematic analysis.

3. Results

3.1. Pollen abundance over the pollen release season in 2021

In the considered timeframe, we recorded nine allergenic pollen types in all three traps (Fig. 4, Supplementary Table 1). The highest pollen concentrations were measured for *Alnus*, *Fraxinus* and *Betula* (Fig. 4), with peak concentrations for *Alnus* at the end of February and the beginning of March, *Fraxinus* at the beginning of April, and *Betula* in mid-April. Other pollen taxa were also identified in both parks, including *Populus, Platanus, Carpinus,* Cupressaceae, *Corylus* and *Quercus*.

For interpreting the results in the context of pollen-related allergic symptoms, we assumed certain threshold levels of pollen concentration beyond which allergic symptoms may occur, based on current scientific literature (Steckling-Muschack et al., 2021). Such threshold levels are used to inform people about the risk of developing allergic symptoms. However, general threshold levels for different pollen types are not yet conclusively determined and individual threshold levels depend on a range of factors (Steckling-Muschack et al., 2021). The threshold values that we assumed for the different pollen types can be found in Fig. 4.

Alnus pollen concentrations were highest at the sites of the university hospital and Friedenspark (and were above the assumed threshold of allergic symptoms), despite *Alnus* trees being not abundant in both parks. If the *Alnus* pollen originated elsewhere outside the parks, it remains unclear why the *Alnus* pollen concentrations were much lower in Lene-Voigt-Park compared to Friedenspark.

In the first *Betula* peak period at the beginning of April, pollen concentrations were highest in the Lene-Voigt-Park and above the assumed threshold level for allergic symptoms, while in Friedenspark and at the university hospital building, measured pollen concentrations were lower. This first peak period was low compared to peak concentrations later in the year, but unfortunately the pollen trap in the Lene-Voigt-Park was not working properly during this period. Therefore, the subsequent *Betula* pollen season could only be followed at the other two sites. During the third peak of *Betula* pollen around 20th April, concentrations in the Friedenspark and at the university hospital building were comparable. At the end of April all pollen traps worked properly again and showed that pollen concentrations were higher in both parks compared to the station on the roof of the university hospital.

Corylus pollen concentrations were higher in the Friedenspark and the university hospital than the Lene-Voigt-Park. We observed concentrations of Cupressaceae pollen which were approximately two times higher in the Friedenspark compared to the other two stations at the end of March. At the end of the monitoring period, at the beginning of May, the concentrations of *Platanus* and *Quercus* pollen showed higher values. We observed the highest concentrations of *Quercus* in the Friedenspark and *Platanus* in the Lene-Voigt-Park.

3.2. Perceived burden of allergenic pollen

A total of 188 respondents participated in the survey, of which 186 completed the questionnaire (Table 1). With 61%, a majority of the respondents (n = 114) reported experiencing allergic symptoms due to tree pollen at particular times throughout the year. Of those 114 respondents, 66 classified themselves as female, 46 as male and 2 as diverse. Nearly half of the respondents were aged between 30 and 39 years (46%), 17% were aged between 19 and 29 years, and 19% were aged between 40 and 49 years. Around 28% (n = 52) of the respondents reported living very close to the park they usually visit (within a 250 m distance), while it was most common to live within 250–750 m (40%; n = 75).

When asked which pollen taxa cause the greatest impairments, respondents identified *Poaceae* (18%), *Betula* (17%), and *Corylus* (13%) pollen most frequently. Only 5% of participants named *Fraxinus* and *Ambrosia* pollen. Interestingly, a considerable share of respondents mentioned that they did not know which pollen types mainly cause their impairments, despite reporting allergic symptoms (12%), and 6% indicated that the relevant allergen was not mentioned in the questionnaire. When asked for the severity of their allergic symptoms in general, 43% reported to suffer from weak symptoms, 47% from moderate symptoms, and 24% from strong allergic symptoms. The identified allergic symptoms due to pollen exposure included increased sneezing, stuffy and runny nose, and watery eyes, as well as breathing problems and skin symptoms, as well as mental health related symptoms, namely irritability, impairment of concentration, and sleep problems (Fig. 5).

When broadly asked for the severity of the impairment to their physical and mental health, 55% of the respondents suffering from

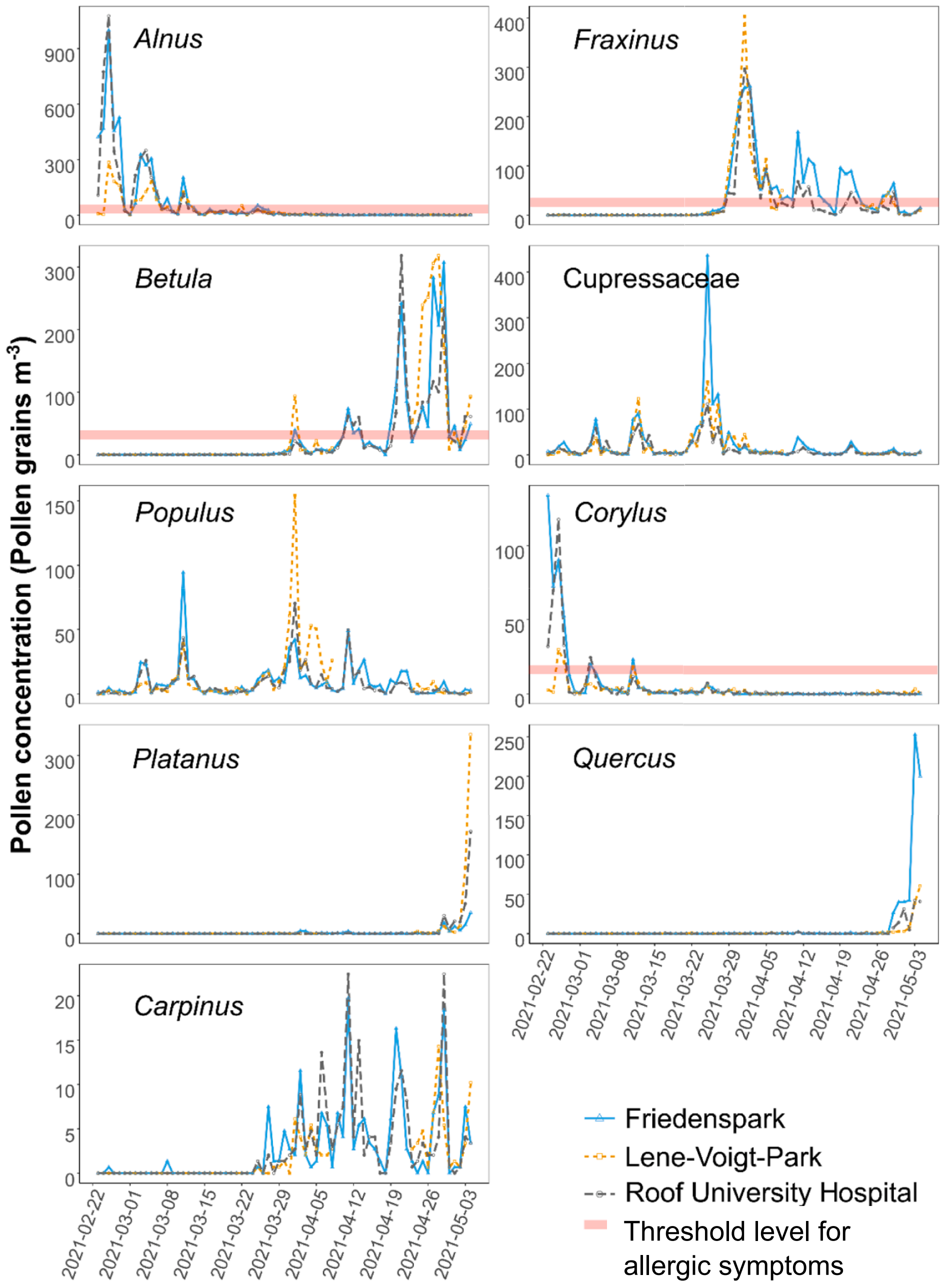

Fig. 4. Daily pollen concentration per m^3 collected by Hirst-type pollen traps in Friedenspark, Lene-Voigt-Park and at the roof of the university hospital between mid-February and beginning of May 2021. Sorted from top-left to bottom-left and top-right to bottom-right according to the Seasonal Pollen Integral (SPIn) that was obtained by summing the average daily pollen concentration over the whole sampling period. Assumed threshold pollen concentration levels for allergic symptoms are marked as red: for Alnus (alder) 18.25–35.5 grains/m^3; Betula (birch): 45 grains/m3; Fraxinus (ash) 18–28 grains/m3; Corylus (hazel) 15–23 grains/m3 (based on statistically significant effects as identified in the review by Steckling-Muschack et al., 2021). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

allergic symptoms indicated that their physical health was strongly or moderately impaired. A lower share of respondents with allergies (25%) reported medium or strong impairment to their mental health (Fig. 5). Nearly two-thirds of respondents with allergies noted to take allergy medication at least once per week (Table 2). Of those, 19 participants also reported to be receiving an Allergen Immunotherapy (AIT).

3.3. *Adaptation of park visitation behaviour due to expected pollen exposure*

Table 3 summarizes the frequency of respondents who changed or adapted their park visitation behaviours due to expected pollen exposure. From the respondents that identified as having experienced symptoms, the majority (n = 94; 83%) did not report any change in park use behaviour patterns. The remaining 20 respondents, mostly those

Table 1
Descriptive statistics from questionnaire survey.

		Symptoms	No Symptoms	Total	%
Allergic symptoms due to pollen		114 (61%)	72 (39%)	186	100
Gender	*Female*	66	43	109	58.6
	Male	46	26	72	38.7
	Diverse	2	2	4	2.2
Age	*19–29*	19	12	31	16.7
	30–39	50	36	86	46.2
	40–49	21	14	35	18.8
	50–59	18	5	23	12.4
	≥60	3	3	6	3.2
Residence distance to park (m)	*<250*	34	18	52	28.0
	250–750	44	31	75	40.3
	750–1500	20	13	34	18.3
	1500–3000	8	5	13	7.0
	>3000	4	3	7	3.8
Pollen types causing the greatest impairments	Poaceae	62			18
	Betula	57			17
	Corylus	45			13
	Unknown	41			12
	Secale	34			10
	Alnus	30			9
	Artemisia	20			6
	Other	19			6
	Fraxinus	18			5
	Ambrosia	18			5
	Total	344			100

with medium and strong symptoms, reported avoiding being outdoors in general (n = 7), visiting parks at other times of the day (n = 4), or using different parks (n = 2).

3.4. Recommendations for urban planning by respondents

Table 4 shows a summary of the respondents' answers to the open-ended question asking what they would suggest and recommend to urban planners to mitigate the potential health burden of exposure to allergenic pollen in urban green spaces. A high percentage of the participants provided an answer to this question (n = 157; 84%). We clustered them into four main groups by theme, including suggestions relating to (i) new green space planning projects, (ii) green space management, (iii) improving the urban climate, and (iv) supporting individual preventive measures.

The highest number of suggestions concerned green space planning, particularly the planting of trees and design of green spaces. Respondents suggested avoiding the planting of trees with allergenic potential, developing more green spaces, improving biodiversity in general and also providing "safe spaces" for city residents impaired by specific allergies. A high number of respondents also pointed to the urgent need to improve air quality through the reduction of individual motorised transport and improvement of public transport.

Several respondents also suggested improving (the accessibility of) public information systems and enhancing pollen forecasts. This included strategies such as the provision of pollen distribution maps and forecasts shown regularly in public transport, placement of warning and information signs in parks.

4. Discussion

In this interdisciplinary study, we monitored pollen abundance in two inner-city parks and on the roof of the university hospital building in the city of Leipzig. We compared these data with results from a questionnaire survey of residents living in close proximity to the parks in the city. With closer investigation of pollen of nine plant genera, we found the highest pollen concentrations for *Alnus* at the end of February and *Betula* during mid-April, with values higher than the assumed threshold for allergic symptoms. Comparing the pollen monitoring data to the species of trees present in the parks revealed that measured pollen concentrations could partly be explained by local tree composition, such as with *Betula* pollen in Lene-Voigt-Park. We did, however, also find increased pollen concentrations related to tree species that were not present in the parks, such as with *Alnus*. The results of the survey on the health burden of exposure to allergenic pollen showed that *Betula* pollen was also most often mentioned as a main cause for allergy-related health impairments. Most of the survey respondents experiencing weak or moderate allergic symptoms, in general, did not adapt their park visitation behaviours due to potential pollen exposure, while more than half of those suffering from strong allergic symptoms indicated changes. A high share of participants further indicated that they treated their

Table 2
Allergy medication intake and status of Allergen Immunotherapy (AIT).

		All respondents		Respondents receiving AIT	
		freq.	%	freq.	%
Allergy medication intake frequency	no	35	30.4	2	9.5
	once per week	17	14.8	2	9.5
	several times a week	20	17.4	5	23.8
	daily	38	33.0	12	57.1
	No information provided	5	4.3		
	Total	110	100.0	21	100.0

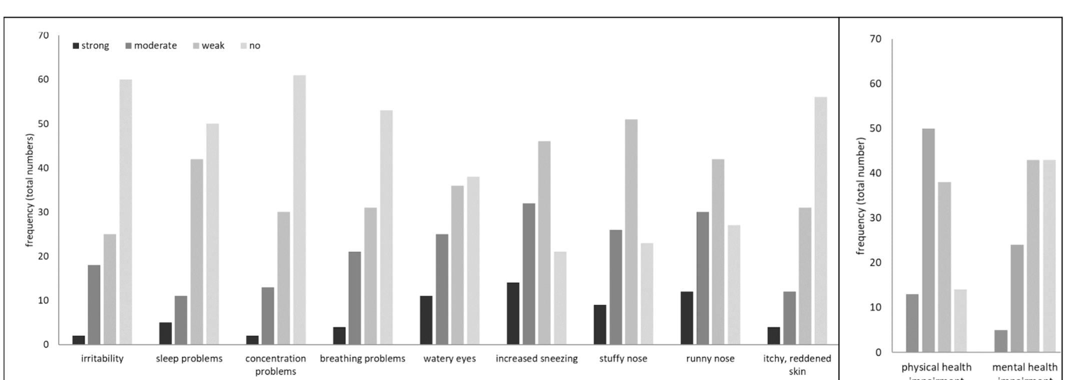

Fig. 5. Frequency of allergic symptoms, stratified by severity, and reported level of physical and mental health impairment.

Table 3
Frequency (no.) of respondents adapting their park visitation behaviour due to pollen flight, classified by reported allergic symptom severity.

		Change in park use pattern						
		No change	Other parks	More in the morning	More in the evening	Avoid being outdoors	Other	Total
Reported allergic symptom severity	Weak	42	0	0	0	0	1	43
	Medium	41	0	2	0	2	2	47
	Strong	10	2	0	2	5	5	24
Total		93	2	2	2	7	8	114

Table 4
Frequency of groups and clusters of recommendations and suggestions by survey respondents to urban planners for mitigating the potential health burden of exposure to allergenic pollen in urban green spaces.

Suggested recommendations for urban planning for	Freq.
A) Green space planning	**84**
• Consideration of allergic potential in species planning and planting, consideration of major wind directions and air circulation situation	50
• More forests, green spaces, green roofs, revitalization of wastelands	9
• Improvement of biodiversity of planted trees and plants	8
• Creation of safe spaces for persons with specific allergies	8
• More trees (windbreaker, precipitation induction)	3
• More blue spaces	3
• Implementation of dedicated allergy-friendly parks	2
• More female trees	1
B) Green space management	**8**
• Control and eradication of invasive allergenic species (e.g. *Ambrosia*)	4
• Regular mowing of meadows, consideration of blossom periods	2
• Reduction of leaf blower use	1
• Regular dust cleaning	1
C) Improvement of urban climate	**24**
• Improvement of air quality, reduction of motorized individual traffic, improvement of public transport	20
• Climate change mitigation (safeguarding of constant and sufficient precipitation periods)	3
• Improvement of fresh air supply	1
D) Support of individual preventive measures	**26**
• Improvement of public information provision and accessibility, enhancement of pollen forecasts (e.g. provision of maps, forecasts in public transport, warning signs in parks)	14
• Investigation and mitigation of allergy causes, promotion of healthier and more natural lifestyles ("allergy is the problem, not the pollen")	6
• Free provision of FFP2 masks during pollen season	5
• Better healthcare provision for persons with allergies	1

allergies using medication. Respondents provided several planning recommendations related to green space planning and management, including the further development and improvement of urban green spaces, improving air quality in general, as well as the provision of pollen information material.

Highest pollen concentrations were measured for *Alnus* pollen on the roof of the university hospital and at the Friedenspark, while in Lene-Voigt-Park *Alnus* concentrations were lower. Interestingly, *Alnus* trees are not located in either of the parks or in the general city centre. Thus, the presence of *Alnus* might be explained by the release of high amounts of pollen at more distant places and the subsequent homogenous distribution by wind across distances of several kms (Rantio-Lehtimäki et al., 1991). The main habitat of *Alnus* species is alluvial- or riverside vegetation and dense populations of *Alnus* trees can be found in Leipzig's riparian forest. Possible reasons for the lower concentration in the Lene-Voigt-Park, compared to the hospital roof, could be the dense built environment around the park and possible deviation of wind direction, as well as the heightened and more exposed location of the hospital roof sampling site. Similar situations have been observed elsewhere, such as in the case of purple alder in Switzerland, where the concentrations of *Alnus spaethii* measured at different stations depend on the wind direction (Gehrig et al., 2015), rather than local vegetation. Despite the highest measured pollen concentrations being *Alnus* in our study, only 9% of participants mainly related their allergy-related impairments to *Alnus* pollen. Broader research in Europe has noted that the concentrations of *Alnus* pollen in cities does correlate with the number of people displaying allergies to *Alnus* in the form of positive skin prick tests (Smith et al., 2007). Beyond this, others have noted that sensitivity to *Alnus* is not often tested for in skin prick tests despite it being closely related to *Betula* (Biedermann et al., 2019; Jantunen et al., 2012). Hence the finding of 9% might be below the actual share of participants allergic or sensitive to *Alnus*.

Betula pollen was found in high concentrations in our study, which is unsurprising given it belongs to the most dominant tree species in Northern and Central Europe (Biedermann et al., 2019). The concentration of *Betula* pollen was highest in the Lene-Voigt-Park and above the assumed threshold level for allergic symptoms, which was not the case in Friedenspark and on the roof of the hospital. The high concentration in the Lene-Voigt-Park could be related to the number of *Betula* trees (with a share of nearly 50% of all trees in the park), resulting from an entire avenue of *Betula* having been planted throughout (Stadt Leipzig, 2023a). In this case, the planted *Betula* trees could be considered a relevant local emission source, with potentially negative health effects for park visitors or residents in the direct neighbourhood. Others have also noted high *Betula* pollen concentrations in parks containing *Betula* trees (Kasprzyk et al., 2019; Werchan et al., 2017), despite it also being known as a species that has high dispersal capacity and can be measured even in parks without the trees present (Borycka & Kasprzyk, 2018; Kowarik et al., 2013). Hence, it is important to not only measure pollen concentrations regionally on the roof of buildings, but to also obtain local measures in parks due to possibly deviating values.

Aligning with Jantunen et al. (2012), *Betula* pollen was mentioned most often by the respondents as the main cause of their allergy-related impairment. This is in line with the measured high *Betula* pollen concentrations. In addition, the cross-reactivity and sequential pollen seasons within the birch homologous group create a prolonged symptomatic allergy period beyond *Betula* pollen alone (Biedermann et al., 2019, Jantunen et al., 2012). Many plant food allergens contain homologs to Bet v 1, meaning that the majority of patients with *Betula* pollen allergy suffer from secondary pollen food syndrome. This further adds to the significant negative impact on health-related quality of life in patients allergic to *Betula* pollen (Biedermann et al., 2019; Jantunen et al., 2012). Importantly, plant species of the same genus can vary in terms of allergenicity (Schenk et al., 2011). In the case of *Betula utilis*, which is present in Lene-Voigt-Park, Schenk et al. (2011) measured a lower allergen concentration (Bet v 1) in comparison to native *Betula pendula*. However, this may not necessarily apply to our study, as site-specific environmental conditions, such as other air pollutants, can increase allergen concentrations and the allergenicity of pollen (Beck et al., 2013; Buters et al., 2008; Cuinica et al., 2015; Frank & Ernst, 2016; Maya-Manzano et al., 2022). Interestingly, we also identified earlier pollen release peaks compared to the long-term trends as indicated by the regional pollen calendar for central and east Germany in the period 2011–2016 (Werchan et al., 2019), supporting the observation that changes associated with global warming are making plants release pollen earlier (Bergmann et al., 2020; Clot, 2003; Cuinica et al., 2015;

Ziska et al., 2019). We conclude that such allergenic trees, like *Betula*, should not be included in green space planning in densely populated urban areas in the future.

More than 60% of the respondents in our study reported suffering from allergic symptoms during particular times of the year. Other estimates of the proportion of allergy sufferers in the general German adult population have found prevalence of around 30% (Bergmann et al., 2023), indicating that our finding is of a very high value. Our survey was conducted at the local level, on the one hand, and it may be the case that those suffering from an allergy were more eager to participate in the survey than those without allergies. Other explanations for the high rate of allergies among participants could be that inhabitants of metropolitan areas have a higher predisposition to allergic conditions (Krzych-Fałta et al., 2016; Treudler et al., 2018) or that several participants represented undiagnosed cases which are not generally considered in allergy statistics. It is also possible that, as allergy status was self-reported in this study, rather than recorded through a medical test, people potentially misidentified the symptoms they were experiencing as a result of pollen allergy.

Although a high share of respondents indicated they suffer from allergic symptoms, most of the respondents did not adapt their park routine visitation behaviours. The only exception to this was that slightly more than half of those with severe symptoms reported altering their behaviours, whereby the total number of those respondents was low ($n = 12$). However, the fact that most people said that they did not alter their behaviour may be explained by the high use of medical therapies, such as allergy medication intake or allergen immunotherapy. Nearly two thirds of the respondents suffering from allergic symptoms reported they did take medication at least once a week. A possible conclusion, which needs further scientific investigation, might be that people prefer to take medication, rather than changing or adapting their visitation of green spaces. The initial direct and indirect costs associated with medical allergy therapies and productivity loss may be high, although once care and professional treatment improve someone's condition, it may also lead to economic savings (Zuberbier et al., 2014). Nonetheless, the potential health costs of allergies should definitely be taken into account in sustainable, climate-adapted urban planning (Bergmann et al., 2023). The fact that the majority of urban residents in this case study preferred to maintain their park-visitation routines, even when there was a potential health risk, might be an indication of the importance urban residents place on urban green spaces. On the other hand, providing safe urban green spaces for people with specific allergies could contribute to relieving people's health burden, expand their opportunities to adapt their park visitation behaviours, and hence decrease the need for medical treatment. Providing such safe spaces was also given as a recommendation for city planning by the participants.

Several further recommendations for urban planning were suggested by the respondents, including very specific ideas about managing current green spaces, how to approach planting new species, improving the urban climate by reducing air pollution and methods for supporting individual information and preventive measures. In the case of Lene-Voigt-Park, several *Betula* trees were planted in the last few decades, likely because of aesthetics. In the future, a careful selection of appropriate trees and vegetation is recommended, for which close collaboration between urban green space planners with botanists, landscape designers, social scientists and allergologists might be of advantage, in order to effectively plan and develop healthy and resilient urban green spaces (Bergmann et al., 2023; Werchan et al., 2017). Besides medical aspects, tree resistance against heat, drought or diseases, production of biogenic volatile organic compounds, and provision of ecosystem services for humans and ecosystems, such as relaxation, air purification, nesting aid for birds, or food for pollinators, need to be thoroughly considered (Grote et al., 2016; Nowak & Ogren, 2021; Song et al., 2020). Tree planting in green spaces in the future should also consider population density, proximity to large roads (as it may increase pollen allergen severity), and ensuring a high diversity of city trees. The specific and scientifically reasonable recommendations of the participants further indicate possible benefits of a transdisciplinary and participatory approach in city planning.

Finally, the survey respondents indicated the need for an accessible pollen information platform that informs on potential health risks on a regular basis. Therefore, a city-wide *in-situ* monitoring, pollen forecasting and modelling approaches that provide information on a finer scale, are recommended (Kasprzyk et al., 2019). However, such an intervention has not yet been continuously implemented at the scale of a city with different measurement sites. In Germany, there is the German Pollen Information Service, which provides weekly forecasts on pollen (German Pollen Information Service Foundation, 2024), and an automatized pollen monitoring network (ePIN) which delivers pollen data at the scale of Bavaria for eight sites (Buters et al., 2021), although it is not clear to what extent the general public utilises and is aware of these resources. An integrated and comprehensive monitoring of environmental stressors such as pollen and other air pollutants has also recently been recommended by the German Advisory Council on Global Change in its recent report (2023). The collected data should be combined with epidemiological data in integrated health- and environment information systems, using georeferencing, to inform targeted early-warning and risk-information systems.

4.1. Strengths and limitations

With our interdisciplinary approach, we were able to combine and compare objective pollen measurement data with subjective data obtained from the local questionnaire survey, which contributed to a more developed understanding of how allergenic pollen might affect park visitors and residents, and enabled us to explore how our measurements aligned with the lived experience of residents, including perceived health impairments and potential behavioural adaptation. The collection of participants' recommendations for city planning further allowed us to account for their subjective perspectives into the discussion of potential policy implications of our study results. The pollen data, through being measured both within the parks and on the roof of the university hospital building, allowed us to account for both more local and regional pollen origins. While local and *in-situ* measurements are important particularly for park visitors who want and need to know current pollen concentration levels (Hornick et al., 2022; Kasprzyk et al., 2019), as demonstrated by requests for easy access to such data in the survey, regional measurements are also essential to understand how pollen may be transmitted from other areas.

However, there were several limitations. First, the pollen trapping took place between 23rd February and 4th May 2021, while the questionnaire survey took place between 12th April and 3rd July 2021. This limits the comparability of the results across these different dates. In future studies, we recommend synchronising the dates at which the pollen data is gathered and the survey conducted, allowing for more accurate interpretations. Similarly, we also suggest measuring climatological data, such as air temperature and precipitation, as well as air pollution, directly at the sites of the pollen traps, to test if there might be potential climate or weather-related impacts on local pollen concentrations and health burden.

Second, there may have been a potential bias in survey respondents because the survey was distributed among employees in the local research centres of the city. Thus, we could assume that those particularly interested in environmental change and conservation participated in the survey to an extent beyond that representative of the general population. In addition, the survey respondents were heavily weighted towards some age brackets, lacking comparable contributions of respondents younger than 19 and older than 59 years, the latter perhaps because the survey was online. It can be assumed that the results might have differed amongst both groups. Future studies should strive for a broader coverage of city residents, as well as investigate a wide range of parks with a more expansive pollen measuring network citywide.

Furthermore, objective criteria for participants' allergy status and allergic symptoms would have been useful to compare perceived burdens with diagnosed symptoms and this is left for future research.

Finally, our underlying assumptions on the allergic potential of certain tree species are based on a study conducted in the Mediterranean region (Cariñanos & Marinangeli, 2021). Their allergenicity findings may not be valid in this present study, as *Tilia* or *Acer* may differ in their allergenicity depending on context and surrounding climate. However, to the best of our knowledge, the study by Cariñanos and Marinangeli (2021) is the most comprehensive study in this field on the allergic potentials of various species.

5. Conclusions

From the results of our interdisciplinary study combining objective and subjective data on the burden of allergenic pollen, and the contextualisation into the broader scientific literature, we conclude that differentiated urban green space planning strategies are necessary to minimize potentially negative health effects on urban residents, such as those related to allergies. This is of particular relevance since, given the current trends of climate change and urbanisation, the role of green spaces for disease prevention and health promotion will likely increase in the future. It is essential that urban green space planning minimises the risk posed to urban residents by selecting species that have low allergy potential and which are still viewed positively by those visiting the park, which requires effective collaboration with residents and expert stakeholders. Instead of avoiding planting particularly allergenic trees like *Betula* completely, we advise avoiding doing so in densely populated areas, where the greatest number of people would be affected, but planting within reason elsewhere, as plant diversity is crucial for ecosystem resilience. Providing safe urban green spaces for people with allergies, combined with improved risk information systems using existing and new approaches, could enhance opportunities for targeted behavioural adaptation, help relieve health impairments, and reduce medical treatment need. Further research is needed to support these conclusions. Future studies should, among other things, measure pollen concentrations and allergenicity in a spatially and temporally differentiated way, also include other meteorological variables and environmental stressors such as air pollution, include representative population samples, and objective measures for participants' allergy status and allergic symptoms. Comparing objective and subjective data on the burden of allergenic pollen within green spaces may reveal a detailed picture of how visitors and residents experience these spaces, and help derive targeted policy recommendations.

6. R-packages citation

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Plotme: https://github.com/yogevherz/plotme.

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Author contributions

The complete study was conceptualized by NK, SD, TH, RK and JB. SD, TH, JB, MB and RK contributed significantly to the pollen measurement part of the study. NK and OM contributed significantly to the questionnaire survey. NK prepared the initial manuscript with substantial contribution of all co-authors. Visualization of data was prepared by RK, TH and SD. NK, OM, RL, TH and SD revised the manuscript.

CRediT authorship contribution statement

Nadja Kabisch: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Thomas Hornick:** Writing – review & editing, Visualization, Methodology, Formal analysis, Data curation. **Jan Bumberger:** Writing – review & editing, Methodology, Conceptualization. **Roland Krämer:** Writing – review & editing, Visualization, Conceptualization. **Rupert Legg:** Writing – review & editing. **Oskar Masztalerz:** Writing – review & editing, Methodology, Data curation. **Maximilian Bastl:** Methodology, Data curation. **Jan C. Simon:** Writing – review & editing. **Regina Treudler:** Writing – review & editing, Methodology. **Susanne Dunker:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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