Sustainable Cities and Society 134 (2025) 106927

Contents lists available at ScienceDirect

Sustainable Cities and Society

journal homepage: www.elsevier.com/locate/scs

Unveiling hidden allergenic hotspots: A fine-scale, parameter-optimized approach for spatiotemporal mapping of urban allergenicity assessments

Carolin Trost [a,b,*], Thomas Rötzer [c], Claudia Traidl-Hoffmann [a,b,d], Maria P. Plaza [a,b]

[a] Environmental Medicine - Institute of Environmental Medicine and Integrative Health, Faculty of Medicine, University of Augsburg and University Hospital of Augsburg, Augsburg, Germany
[b] Institute of Environmental Medicine, Helmholtz Center Munich, German Research Center for Environmental Health, Augsburg, Germany
[c] Chair for Strategic Landscape Planning and Management, Technical University of Munich, Freising, Germany
[d] Christine Kühne Center for Allergy Research and Education (CK-CARE), Davos, Switzerland

ARTICLE INFO

Keywords:
Allergenic hotspots
Pollen exposure
Index optimization
Urban allergenicity
Temporal variability
Seasonal risk mapping

ABSTRACT

Evaluating allergenicity in urban environments is essential for understanding risks to allergy sufferers, improving urban planning, and strengthening climate resilience. In this study, we applied a modified Urban Green Zone Allergenicity Index (I_{UGZA}) to a pilot area in Augsburg, southern Germany, to assess spatial and temporal dynamics of allergenic exposure and identify opportunities for healthier cities.

The index was adapted to local species composition, flowering periods, and sitespecific conditions, integrating tree inventory data and allometric parameters. To enhance ecological relevance, we additionally incorporated airborne pollen concentrations, temperature, and air pollution in combination with a climate impact adjustment model. Temporal dynamics were examined on seasonal, monthly, and daily scales. To explore spatial variability, the area was divided into equal sub-areas, each with I_{UGZA} calculated using GIS, followed by the spatial interpolation method Inverse Distance Weighing (IDW) to generate continuous allergenicity heatmaps.

A total of 1427 trees representing 66 species were analyzed, with approximately 35 % classified as allergenic, mainly from Betula and Corylus. The overall allergenic potential was relatively high (0.36). A sensitivity analysis revealed crown projection area as the strongest influence on allergenic potential, underscoring the role of morphological traits in allergen exposure. Allergenic peaks were observed in spring, coinciding with the flowering periods of dominant allergenic species, and temperature is the most relevant adjustment factor.

The results highlight the importance of both spatial distribution and phenological timing in influencing allergenic potential. By integrating ecological, climatic, and morphological factors, this approach provides a flexible and transferable framework for improving allergenicity assessments at neighborhood and city scales, supporting public health strategies and climate-resilient urban planning.

1. Introduction

Cities and urban areas are rapidly expanding in population and physical footprint, with 55 % of the world's 8 billion people already living in cities and projections indicating 70 % of 9.4 billion by 2050 (United Nations, 2024; UN-Habitat, 2024). This intensifies environmental and health challenges such as air pollution, urban heat, noise, water contamination, allergen exposure and mental health stressors, which are further exacerbated by climate change and threaten urban sustainability and public well-being (Puga-Bonilla et al., 2025; Niu et al., 2025; Fan et al., 2025). Numerous studies have developed models, tools, and predictive frameworks to mitigate these risks and guide the transition toward more resilient, health-supportive cities, while accounting for differing socioeconomic and environmental contexts (Kim et al., 2025; Jia et al., 2025).

Consequently, urban green spaces are becoming increasingly important for sustainability and livability (Bassen et al., 2023) due to their role in ecosystem services such as mitigating air pollution (Beckett et al., 1998; Yang et al., 2015; Islam et al., 2024; Nowak et al., 2018), reducing urban heat (Pattnaik et al., 2024; Maimaitiyiming et al., 2014), supporting biodiversity (Ives et al., 2016), and managing stormwater quality and quantity (WBGU, 2024; Coutts & Hahn, 2015; Helmreich et al., 2025). In addition, green spaces, encompassing urban, peri-urban and rural areas, as well as private gardens, have been demonstrated to

* Corresponding author.
E-mail address: carolin.trost@med.uni-augsburg.de (C. Trost).

https://doi.org/10.1016/j.scs.2025.106927
Received 22 April 2025; Received in revised form 21 October 2025; Accepted 22 October 2025
Available online 4 November 2025

promote healthy lifestyles and provide mental and physical health benefits (Organization & for Europe, 2016; Legg & Kabisch, 2024; Stas et al., 2021; Aerts et al., 2020), contributing positively to human well-being (Ekkel & de Vries, 2017; Bassen et al., 2023; WBGU, 2024; Ugle et al., 2010; Aerts et al., 2020).

However, the release of airborne pollen as part of plant reproduction may result in deteriorated air quality and negatively impact human health (Escobedo et al., 2023; Liu et al., 2023). Pollen exposure has been linked with a range of allergic conditions, including allergic rhinitis, bronchial asthma, conjunctivitis, reduced lung function, atopic dermatitis exacerbation (Simunovic et al., 2023; Traidl-Hoffmann et al., 2024; Parmes et al., 2020) and overall decreased quality of life, particularly among sensitized individuals, leading to a high global prevalence of allergic disease and a substantial socioeconomic burden (Bassen et al., 2023; Ring, 2012). Epidemiological studies have identified associations between pollen exposure and increased hospital admissions due to respiratory distress, particularly among vulnerable individuals (Simunovic et al., 2023; Annesi-Maesano et al., 2023), or in synergies with viral infections (Damialis et al., 2021; Gilles et al., 2020). Allergic individuals report greater distress than those without, which can be exacerbated by allergenic trees (Aerts et al., 2020; Stas et al., 2021). In addition, climate change-induced temperature rises and shifts in weather patterns are altering pollen dynamics, affecting pollen season's timing, duration, and intensity (Zhang & Steiner, 2022; Rojo et al., 2021; Chmielewski & Rötzer, 2001; Ranpal et al., 2024; Schramm et al., 2021), increasing pollen potency (Oh, 2022), and enabling the spread of allergenic plant species into new areas (Damialis et al., 2019; Anderegg et al., 2021; Xian et al., 2023). These changes reshape ecological and public health landscapes, highlighting the urgent need for fine-scale, spatiotemporal pollen assessments.

Effective pollen monitoring and source mapping are becoming increasingly important for public health, particularly in urban environments where tree selection is based on site suitability, ecosystem services (Otero-Durán & Torres, 2024; Buang et al., 2024), maintenance costs (Hasan et al., 2017; Buang et al., 2024), and aesthetic appeal (Schroeder, 2011; Gatrell & Jensen, 2002), often without adequate consideration of their allergenic potential. This can lead to the formation of pollen hotspots especially where allergenic, wind-pollinated species such as *Betula* sp., *Alnus* sp., *Corylus* sp., and *Fraxinus* sp. dominate streetscapes and parks (Jochner-Oette et al., 2018; Sjöman et al., 2012). These species produce abundant airborne pollen that can also travel long distances, and potentially trigger allergic reactions in sensitized individuals (Bayr et al., 2023; Ghasemifard et al., 2020), posing a substantial public health concern (Beutner et al., 2021; Eder et al., 2018). As a result, urban areas with high allergenic potential may influence mental health, behavior, and the perception of green spaces (Legg & Kabisch, 2024).

Furthermore, the interaction between urban air pollutants, such as particulate matter (PM), carbon dioxide (CO_2), and nitrogen dioxide (NO_2), with pollen allergens can modify their structure and increase pollen potency, enhancing their allergenic properties (Rauer et al., 2021) and triggering more severe immune responses (Beck et al., 2013; Motta et al., 2006). The removal of trees with a high allergenic effect is not a sustainable preventive measure as it neglects the potential risks from other species that may become problematic under changing climatic and pollution conditions (Aerts et al., 2021). Accordingly, systematic evaluation of urban vegetation is needed to assess and mitigate the potential impact of the urban allergenic plants on air quality and public health.

In recent years alternative approaches have emerged, including remote sensing techniques to forecast pollination dates, for example, using EVI for Poaceae (Devadas et al., 2018) or NDVI for *Quercus* species (González-Naharro et al., 2019). Additionally, indices such as AIROT (Pecero-Casimiro et al., 2019) assess aerobiological risk at a finer scale. Among these, the Urban Green Allergenicity Index (I_{UGZA}) offers a comprehensive framework that integrates biological, phenological, and ecological traits, theoretically offering a standardized way to quantify allergenic potential across diverse urban green areas. However, to fully understand and predict allergenic exposure, it is also necessary to not only evaluate existing indices designed to calculate the allergenic potential of urban trees, such as those proposed by Cariñanos et al. (Cariñanos et al., 2014) and Pecero-Casimiro et al. (Pecero-Casimiro et al., 2019), but also to account for local atmospheric dynamics, pollution levels, and broader climatic and meteorological factors, including temperature, precipitation and wind patterns (Cariñanos et al., 2014), which affect the dispersion and concentration of aerobiological particles.

The I_{UGZA} is a widely used tool that provides a single aggregated value per park, enabling direct comparisons between different urban green spaces (Cariñanos et al., 2014; Cariñanos et al., 2017; Cariñanos et al., 2019). It estimates allergenic potential based on the biological character-istics of plant species and their role as sources of pollen emission in urban green areas, and it is applicable to parks, gardens, woodlands, green corridors, and street trees (Cariñanos et al., 2014; Cariñanos et al., 2017). Initially developed for Mediterranean climates, the index considers factors such as potential allergenicity, species composition, and flowering periods, and its applicability in diverse climatic regions is increasingly recognized (Fernández-Alvarado & Fernández-Rodríguez, 2023; Velasco-Jiménez et al., 2020; Jochner-Oette et al., 2018). It was recently applied in a geostatistical analysis in Valencia, Spain Calatayud and Cariñanos (2024), considering the diverse flora, including subtropical and tropical species. However, indices created for the Mediterranean climate may be less accurate in temperate areas due to differences in climate, biodiversity, phenological cycles, and the sensitization rates from the local population. These factors highlight the need for adapting or developing new indices that are adjusted to the characteristics of temperate urban regions (Jochner-Oette et al., 2018). One example of such an adaptation is the index for the individual-specific allergenic potential (I_{ISA}), which is based on the I_{UGZA} and considers individual tree data instead of species-specific maximum heights (Jochner-Oette et al., 2018). While existing indices including the I_{UGZA} and I_{ISA} provide valuable insights, they are typically static and do not reflect the temporal variability of allergen exposure throughout the year. Allergenicity is not a constant factor but fluctuates with seasonal changes, plant phenology, and meteorological conditions. Therefore, a dynamic approach that integrates climatic parameters and seasonal variability is essential for a more accurate and responsive assessment of allergenic risk in urban environments.

Integrating these insights into urban planning can help reduce allergenic exposure and promote healthier environments, particularly for sensitive populations. To address this gap, we present an extended and enhanced version of the widely used I_{UGZA} index that incorporates both spatial and temporal variability, as well as dynamic climatic factors such as temperature, precipitation, and atmospheric CO_2 enrichment. While previous studies have introduced spatial or temporal components separately, our approach offers a novel integration of high-resolution species-level tree inventory, daily pollen monitoring, and climate sensitivity modeling into a unified system. Unlike traditional static indices, this method enables daily allergenicity mapping based on meteorological conditions and pollen monitoring data, offering a more responsive and realistic representation of allergenic risk in urban environments. To explore this, a case study was conducted in Westfriedhof Park, located in Augsburg, Germany. It features diverse vegetation and a temperate climate, making it a representative site for evaluating allergenic dynamics in such environments. Our aim was to analyse and refine the I_{UGZA} framework by identifying the most relevant variables and climate-related factors that influence allergenic potential. Beyond methodological innovation, our dynamic allergenicity framework has clear applications for urban policy and public health: the resulting high-resolution spatiotemporal maps and adjusted index will highlight allergenic hotspots, supporting informed tree species selection and adaptive planning for healthier allergy-resilient cities. Together, these applications help cities better respond to the growing burden of pollen-related diseases under changing environmental conditions.

2. Material and methods

To assess the spatiotemporal allergenic potential of urban green spaces, we developed a multi-step methodological framework integrating aerobiological modeling, species traits, spatial mapping, and climatic data implementation. The methodology is structured as follows: First, we introduce the study area and describe the application of the I_{UGZA} index with region-specific adjustments. Next, we outline the spatial implementation, including grid-based mapping and interpolation of allergenicity across Westfriedhof Park and surrounding neighborhoods. We then evaluate the spatial results using a global sensitivity analysis (Sobol method) to identify the most influential input parameters in the index formulation. Finally, we present the temporal extension of the I_{UGZA}, incorporating phenological, meteorological, and climate-driven variability to dynamically adjust allergenicity across time.

2.1. Study area

The study area was located in the city of Augsburg, in the southeast of Germany. Within Augsburg, the Westfriedhof Park (48°22′05.1″N 10°51′36.8″E) served as the specific study site (Fig. 1). Covering 19 ha, this urban park is surrounded by residential areas and features a diverse tree population, with 59 tree species identified at species level and 17 at genus level (Geodatenamt et al., n.d.).

Augsburg is located at an altitude of 480 m above sea level, at the transition between a dry continental climate and a humid Atlantic climate (Jäger & Werner, 2011). Its proximity to the Alps, which act as the Central European weather divide, results in relatively variable weather conditions (Gobiet & Kotlarski, 2020). For the city of Augsburg, the long-term average (1991–2020) annual precipitation sums up to 750 mm, and the average annual temperature is 9 °C, with July being the warmest month at an average temperature of 18.3 °C (DWD - Deutscher Wetterdienst, 2024). Westfriedhof Park is situated within an air corridor, where dominant southwest winds during the daytime transport air from the park into nearby residential areas, potentially influencing local air quality (GEO-NET Umweltconsulting GmbH., 2023). The relative frequencies of the genera in the park were compared with those in the city-wide municipal tree register. A Person correlation analysis revealed a strong positive relationship ($r = 0.71$, $p < 0.001$), suggesting that the park's composition closely mirrors the general tree distribution across the city. This supports the use of Westfriedhof as a suitable case study for city-level allergenicity assessment.

2.2. Implementation of the aerobiological index I_{UGZA}

The original studies and most applications of the Urban Green Zone Allergenicity Index (I_{UGZA}) developed by Cariñanos et al. (Cariñanos et al., 2014; Cariñanos et al., 2017; Cariñanos et al., 2019) have focused on cities with Mediterranean climates, where the index was first developed and tested. However, the underlying methodology could be adapted to other climatic regions by adjusting species composition and local pollen calendars.

To estimate the potential allergenicity in the study area Westfriedhof, we used the I_{UGZA} formula (Eq. (1)), with minor modifications, as a model. Although H_{max} is not explicitly displayed in Cariñanos et al. (2014), Cariñanos et al. (2019) and (Cariñanos et al., 2017), recalculations suggest that it is implicitly considered during the normalization step. In this study, H_{max} was incorporated accordingly in Eq. (1) to ensure clarity and completeness.

$$I_{UGZA} = \frac{1}{maxVPA \times H_{max} \times S_T} \sum_{i=1}^{k} (VPA_i \times S_i \times H_i) \quad (1)$$

Where S_T signifies the total surface area of the park in square meters, H_{max} corresponds to maximum potential canopy height under local climatic conditions, k represents the number of species, S_i indicates the surface area covered by the species i in square meters, H_i represents maximum height in meters that a tree can reach at maturity of the species i in meters, and *VPA* (Value of Potential Allergenicity) is a metric that quantifies the potential allergenicity of a given species. This value is derived from the multiplication of three distinct parameters, used to compute an allergenicity score per spatial unit:

- *ap*: intrinsic allergenic potential of the pollen for each tree taxon present in the study area, ranging from 0 to 4, and reflecting the known allergenicity of locally relevant species (i.e., the allergenic potential of species *i*).
- *dpp*: duration of pollination period that spans from 1 to 3, indicating the main pollination period of the species
- *i* in weeks.
- *ps*: pollination strategy of the species *i* that varies from 0 to 3, describing the mechanism of pollen dispersion.

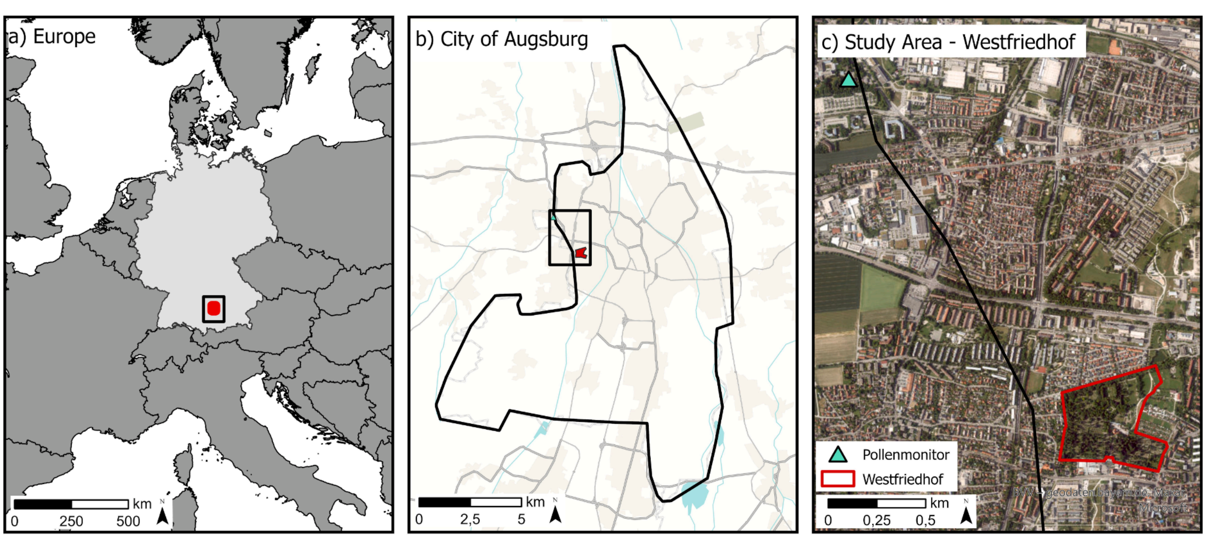


Fig. 1. Study area: Westfriedhof park, Augsburg. Maps show (a) Augsburg (red) in Germany (light grey) within Europe; (b) Westfriedhof (red) within the city boundary of Augsburg (black); (c) the pollen monitor (blue triangle) and Westfriedhof park (red) shown over a satellite basemap of the surrounding neighborhood.

In order to adapt the I_{UGZA} to temperate regions, adjustments were made to the biogeographical variables. Key modifications included refining the duration of pollination period (*dpp*), which is strongly influenced by the regional climate, and reassessing the allergenic capacity (*ap*) of specific species, since allergenicity might vary significantly by location (Magyar et al., 2022). More details about the parameters, including minor adjustments to better reflect local conditions, can be found in Section 2.3.

2.3. Description and modifications of allergenicity input variables, preprocessing and data collection

The official tree cadastre of Augsburg (Geodatenamt et al., n.d.) contains the geographical location and key characteristics of public urban trees across the city. The dataset includes detailed information on tree distribution, such as species identification (at both genus and species levels), location, Diameter at Breast Height (*DBH*), and total tree height. In the municipal tree register only public areas are partly mapped, while private gardens are not included. More on the composition and distribution of trees are provided in Section 3.1. The data from the tree cadastre were essential in the implementation of the I_{UGZA} methodology and the estimation of the crown projection area (section 2.3.d).

A comprehensive assessment of allergenic potential requires the integration of multiple data sets that account for species-specific characteristics, regional conditions, and methodological consistency. To ensure a locally relevant analysis, additional sources were incorporated and combined to derive the necessary parameters for a more accurate evaluation. In this context, the following items describe the variables, the considerations underlying their inclusion, and any modifications applied to them to better reflect conditions in temperate regions. Table 1 provides a summary of the sources consulted for determining the parameter values.

(a) Allergenicity potential - *ap*

Multiple databases describe the allergenicity of trees and plants, but they differ in purpose, scope, and location, as noted by Magyar et al. (Magyar et al., 2022). For this study, the classification of the allergy potential from Bergmann et al. (Bergmann et al., 2012) served as the primary source, as it is specific to Germany and designed for policymakers, researchers, and urban greening initiatives (Bergmann et al., 2012). To complement this, the CARE-S value for allergenicity from Magyar et al. (Magyar et al., 2022) was included into the analysis. This globally applicable index provides a standardized measure across regions, although it does not consider local factors such as flowering duration, population size, or pollen concentration. Its comparability make it a useful tool for policymakers and legislative frameworks aimed at regulating allergenic tree planting in cities. Furthermore, allergenicity values from the Ogren Plant Allergy Scale (OPALS) (Ogren, 2000) were considered, as they have been previously used by Jochner-Oette et al. (Jochner-Oette et al., 2018) in Germany in connection with the I_{UGZA}. While OPALS offers a widely recognized framework for assessing plant allergenicity, it is primarily based on U.S. data and may not fully align with German conditions due to differences in species composition, climate, and regional pollen exposure patterns. Adaptations may be necessary for its effective application in a European city (Ogren, 2000). Consequently, OPALS was only used for species lacking other references. Regarding missing species not mentioned in Magyar et al. (2022), Bergmann et al. (2012), Ogren (2000) the median of the *ap* from the given genus was calculated (**Table S1**).

Table 1
Parameter value scales and sources for I_{UGZA} calculation. Value scales assigned to parameters used in the I_{UGZA} (Urban Green Zone Allergenicity Index) calculation, considering a variety of plant characteristics and partially adjusted for our study. Relevant literature sources for each parameter are also provided.

Intrinsic parameters	Values	Sources
Intrinsic allergenic capacity of the pollen grain (*ap*)	0 = non-allergenic 1 = low allergenicity 2 = moderate allergenicity 3 = high allergenicity 4 = main allergenic species in area	(Ogren, 2000; Vicentic et al., 2017; Nowak & Ogren, 2021; Traidl-Hoffmann & Trippel, 2021)
Duration of pollination period (*dpp*)	1 = 1–4 weeks 2 = 5–8 weeks 3 = ≥ 9 weeks	(Jochner-Oette et al., 2018; Kolek et al., 2021; Ewald, 2023; Gurk & Hepp, 2024)
Pollination strategy (*ps*)	0 = non-allergic (sterile, cleistogamous or female-sex only) 1 = Entomophilous 2 = Amphiphilous 3 = Anemophilous	(Jäger & Werner, 2011; Jochner-Oette et al., 2018; Kolek et al., 2021; Ewald, 2023; Gurk & Hepp, 2024)
Maximum height that the tree can reach at maturity (H_i)	real heights from the trees achieved through the Augsburger tree cadastre	(More & White, 2005; Geodatenamt et al., n.d.)
Surface area covered by the i-species (*cpa*)	calculated based on species-specific allometric equations by height (m) and Diameter at breast height (cm)	(Pretzsch et al., 2015; Geodatenamt et al., n.d.)

(a) **Duration of pollination period** - *dpp*

The pollination period for the studied tree species was determined using airborne pollen continuously monitored by an automated pollen monitor (BAA500, Hund GmbH) located at the Institute of Environmental Medicine and Integrative Health in Augsburg (48°23′02.6″N 10°50′36.3″E), providing data every three hours, during the period 2016–2023. These observations were complemented by results from Kolek et al. (Kolek et al., 2021) and the database (Gurk & Hepp, 2024), ensuring a comprehensive and locally relevant assessment of pollen release patterns.

The duration of pollination period at genus level was calculated using the main pollen season definition by Andersen (1991). This method incorporates 95 % of the seasonal total pollen concentration, starting on the day on which 2.5 % of the annual pollen integral was documented and ending on the day on which 97.5 % of the annual pollen integral was recorded. We used Rstudio (RStudio Team, 2020), R (R Core Team, 2021) version 4.3.3. and the specific AeRobiology R package (Rojo et al., 2019) for the calculation. Since the study is conducted in a different biogeographical region than the original IUGZA, the categories for *dpp* were adjusted to temperate regions following (Jochner-Oette et al., 2018). For missing species, additional sources from Germany and Central Europe were consulted (Table 1).

(a) **Pollination strategy** - *ps*

The tree pollination strategy values were derived from literature focusing on the intrinsic biological and reproductive characteristics of tree species (Table 1). Given the assumption that species-level features remain consistent across geographical regions, sources from global literature were considered. However, for certain species where specific pollination data were unavailable, values at the genus level were used as a proxy (**Table S1**). Although previous publications (e.g., (Cariñanos et al., 2014; Cariñanos et al., 2016; Cariñanos et al., 2017)) label the variable as *pollen emission (pe)* or *type of pollination (tp)*, they consistently describe it as representing the species pollination strategy, without incorporating actual quantitative pollen measurements (e.g., pollen grains/m^3). For example, Cariñanos et al. (Cariñanos et al., 2017) state: *Pollen emission* (*pe*) refers to the species pollination strategy. This confirms that the scale reflects qualitative differences between species rather than measured emission rates. The terminology *pollination strategy* was explicitly used in later work (Cariñanos et al., 2019), and we adopt it here to avoid confusion and more accurately describe the variables conceptual basis.

(a) **Crown projection area and tree height** – *cpa,* H_{max} *&* H_i

Regarding tree surface area (Si), the original IUGZA (Eq. (1)) incorporates species-specific maximum values for height and crown width using literature-based information on the standard size attained by species during reproductive maturity. While tree height is typically provided in the tree cadastre, crown width data is often unavailable. However, this approach does not capture individual variability between trees.

To ensure consistency but also to provide a more precise and realistic representation while using the original I_{UGZA} from Cariñanos et al. (Cariñanos et al., 2017; Cariñanos et al., 2019), the real heights from the trees achieved through the Augsburger tree cadastre (Geodatenamt et al., n.d.) were used for Hi. Following (Jochner-Oette et al., 2018), H_{max} was defined as the maximum observed tree height in the study area (40 m). This change rescales absolute I_{UGZA} values but does not affect the relative ranking of sites. To achieve a more accurate canopy structure, we did not use crown width. Instead, the crown projection area (*cpa*) was calculated individually for each tree. For this, we applied the methodology of Pretzsch et al. (Pretzsch et al., 2015), which provides specific allometric equations for 22 common tree species in urban centers and parks, incorporating *DBH* to capture species-specific variations in crown shape and growth patterns, and avoiding estimated averages. For species not specified in Pretzsch et al. (2015), the crown type classification from the same genus is used if available. In the absence of such information, the species is assigned the medium crown type (Type 2) by default (**Table S1**). No crown size was sought for species with an *ap* of 0, as the I_{UGZA} is 0 for these species regardless. The parameter *DBH* was provided by the tree register of the city of Augsburg (Geodatenamt et al., n.d.). An overview of all parameters used in the index, along with the respective literature sources, is provided in Table 1.

2.4. Data analysis

2.4.1. Shannon index and tree diversity

To assess the diversity of tree species in the study area, we applied the Shannon Index (H'), a commonly used measure of biodiversity. The Shannon Index (Eq. (2)) takes into account both the richness (number of species S) and the evenness (relative abundance) of species within the urban green space:

$$H' = -\sum_{i=1}^{S} p_i \ln(p_i) \text{ with } p_i = \frac{n_i}{N} \quad (2)$$

where S is the total number of species in the community, n_i is the number of individuals of species i, N is the total number of individuals across all species, and p_i is the proportion of individuals of species i. The mapping approach followed the same procedure as for I_{UGZA}, mentioned in Section 2.4.2. Higher values of the Shannon Index indicate greater diversity, which can contribute to ecosystem stability and resilience against environmental stresses, including those associated with allergenic pollen. This information is crucial for understanding the relationship between species diversity and allergenic potential, as species diversity influences the overall pollen load and the spread of allergens throughout the city.

2.4.2. Baseline I_{UGZA} assessment

The allergenic potential was assessed using the I_{UGZA} formulation proposed by Cariñanos et al. (Cariñanos et al., 2014; Cariñanos et al., 2017) previously described with small modifications, as intended: a static, non-spatial, non-temporally resolved index. This static index integrates biological and morphological traits of tree species present in the Westfriedhof study area, including allergenic potential (*ap*), pollination strategy (*ps*), duration of the pollination period (*dpp*), crown projection area (*cpa*), and tree height H_i. The index was calculated for the entire tree population within the study area and aggregated into a single annual value representing the static allergenic load of the site. To compare allergenic traits of dominant species, a radar chart was generated based on five variables: abundance, crown size, *ps, dpp*, and intrinsic *ap*. Abundance was rescaled using min-max normalization (0–4), and crown size categorized into predefined canopy types: Type 1 (largest crowns) = 4, Types 2–3 = 2, and Type 4 = 1. Variables were standardized to ensure equal contribution to the visual comparison.

2.4.3. Mapping environmental risk

To spatially evaluate allergenic risk, the park was divided into 25 *m* × 25 *m* grid cells, enabling a fine-scale as- sessment of allergenic potential across the entire area. This resolution balances spatial granularity with computational efficiency and is appropriate for capturing localized allergenic gradients. It is also supported by empirical findings from Adams-Groom et al. (2017), who demonstrated that most pollen from isolated trees is deposited within 20–50 m of the source, with deposition beyond 50 m rapidly declining. This approach aimed to identify allergenic hotspots by integrating spatial and statistical analyses, offering a comprehensive evaluation of the allergenic potential within the park. The goal was not only to assess the overall allergenic potential but also to elucidate specific areas of heightened exposure, shedding light on the underlying factors influencing the allergenic risk.

The creation of the grid and the subsequent calculation of the I_{UGZA} within these sub-regions was developed using ArcGIS Pro (Redlands, 2011) (version 3.2.2). Firstly, to construct the input database, all relevant parameters for calculating the index were integrated from multiple sources, as detailed in Section 2.3: species-specific *ap* and *ps* were obtained from the literature; long-term *dpp* were sourced from pollen monitoring in Augsburg; and tree-specific parameters, including tree height (H_i) and *DBH* were extracted from the official tree cadastre of Augsburg. *cpa* was derived via species-specific allometric equations using the tree cadastre data (Table 1). The specific parameter values used for the calculation are provided in **Table S1**. Within each grid cell, the I_{UGZA} values are calculated to identify spatial variation. Given that not all trees flower throughout the year, the temporal component was also considered in order to determine when high allergenicity is most likely during different seasons. Additional maps were created according to the predominant seasons in temperate regions: Spring (March - May), Summer (June - August), Autumn (September- November), and Winter (December - February).

After calculating the I_{UGZA} values, the Interpolation method *Inverse Distance Weighting* (IDW) was used to estimate the values at unsampled locations between the grid points. Several interpolation methods were considered, but ap- proaches such as kriging, spline, kernel density estimation, and trend surface analysis were unsuitable for city-level applications, given the unevenly distributed data and the artificial structure of urban tree plantings. For consistency across scales, IDW was applied to both neighborhood- and park-level analyses, producing heat maps that effectively highlight areas of high allergenic potential, thereby providing a clear visual representation of risk zones.

2.4.4. Identifying key drivers of index variability

Variance-based sensitivity analysis (also known as Sobol sensitivity analysis) was applied to the computational model underlying the I_{UGZA} to identify the most influential factors driving allergenic potential in urban green spaces, including crown projection area, species-specific allergenicity scores, tree density, and flowering period overlap (see Section 2.3). Unlike the spatial interpolation used to visualize allergenicity patterns via IDW, the sensitivity analysis was performed independently of spatial data, focusing solely on quantifying the influence of individual input factors on the model output. This methodological distinction reflects a dual purpose: spatial interpolation supports visualization and hotspot detection, while sensitivity analysis informs model robustness of I_{UGZA} results under parameter uncertainty. The Sobol method, implemented in R (R Core Team, 2021) (Version 4.3.3) with the *sensitivity* (Pujol et al., 2015) and *randtoolbox* (Dutang et al., 2024) packages, is a global variance decomposition technique for assessing the contribution of individual input parameters on the model output variability. The analysis produced first-order indices (direct effects) and total-order indices (including interactions), providing insight into which factors most strongly affect the I_{UGZA} output regardless of location. The analysis considers both first-order indices, which measure the direct effect of individual parameters, and total-order indices, which account for interactions with other parameters. This analysis allows the identification of the most critical model parameters for optimising the index.

2.4.5. Incorporating temporal dynamics in the urban allergenicity index

To improve the accuracy and temporal relevance of the I_{UGZA}, we propose a set of modifications that transform it into a dynamic, time-sensitive index. Specifically, we introduce three complementary approaches: (1) a seasonal weighting factor, (2) pollination intensity derived from daily pollen concentration data in the city, and (3) a climate impact adjustment using daily temperature, precipitation and CO_2 values. The selection of one approach over another will depend on the desired level of temporal detail and data availability.

All temporal allergenicity calculations in this study are based on daily airborne pollen concentration data recorded by the BAA500 automatic pollen monitor (Hund GmbH) located within 2 km of the study area. Daily concentration values (in pollen grains/m^3) were extracted for the 16 pollen taxa recorded between 2018 and 2023. These taxa include both arboreal and herbaceous species, representing the dominant contributors to Augsburg urban allergenicity (Kolek et al., 2021). The **Figure S1** in Supplementary Material shows the daily pollen concentrations and relative abundance for the 16 taxa. While the park's full tree inventory comprised 59 species, only 16 dominant and allergenic taxa were used in the temporal pollen modeling due to their availability and suitability for phenological curve fitting. Species with limited pollen dispersal may be underrepresented in atmospheric measurements, but the spatial I_{UGZA} index fully accounts for their allergenic potential through species-specific allergenicity scores and local abundance.

(a) **Seasonal Weighting Factor (Wt)**. To better represent pollen allergenicity risk throughout the year, a seasonal weighting factor (Eq. (3)) can be introduced to modulate the static I_{UGZA} base (Eq. (1)):

$$IUGZA_t = IUGZA_{base} \times W_t \text{ with } W_t = \frac{\overline{P}_m}{\max(\overline{P}_m)} \tag{3}$$

where: $IUGZA_t$ represents the time-resolved allergenicity index at time period t, and W_t is a normalized weighting factor (ranging from 0 to 1) based on the observed total airborne pollen concentration across all taxa for that period recorded by the volumetric sampler. W_t is calculated at the monthly resolution by dividing the average total pollen concentration for each month P_m by the maximum monthly average observed during the pollen season. Rather than assuming a constant allergenicity risk throughout the year ($IUGZA_{base}$), this factor allows the index to reflect seasonal dynamics based on actual pollen measurements. While monthly resolution was used in this study, based on daily pollen data aggregated to monthly averages, the same approach can be adapted to other temporal resolutions, including seasonal or weekly, depending on data availability and the desired level of detail. It provides a simple yet effective method to incorporate temporal variability into the I_{UGZA} without the need for complex flowering phenology models.

(b) **Pollination Intensity Parameter (PI)**. To dynamically model the daily variation in pollen allergenicity, we developed a species-specific Pollination Intensity parameter (PI_t) which is based on Gaussian distributions that have been fitted to the phenological data derived from the local pollen calendar. The pollen concentration dataset includes daily pollen concentrations (pollen grains/m^3) for the six full flowering seasons (from 2018 to 2023). For each of the dominant taxa in the area (>0.5 % relative abundance and accounted for >90 % of the total (Kolek et al., 2021)), we extracted flowering phenology from the AeRobiology package (Rojo et al., 2019) using the 95 % pollen season definition ((Andersen, 1991; Nilsson & Persson, 1981)). This generated two key metrics:

- μ the day of peak pollen release
- σ the temporal length of the flowering season

Assuming a symmetric bell-shaped distribution of pollen concentration around the peak flowering day, we modeled daily pollination intensity using the Gaussian function (Eq. (4)), as in previous studies (Kasprzyk, 2011; Li et al., 2022). To ensure consistency across years, all temporal analyses were standardized to a 365-day calendar:

$$PI_{s,t} = A_s \times \exp\left(\frac{(t-\mu_s)^2}{2\sigma_s^2}\right) \tag{4}$$

where: PI_S, t denotes the pollination intensity of species s on day t (ranging from 1 to 365); A_s is the peak intensity (normalized to 1), indicating the maximum pollination intensity during the flowering season per species s; μ_S and σ_S are species-specific parameters derived from phenological averages, corresponding to the mean and the standard deviation of the distribution, respectively (**Table S2**). To adjust for differences in species abundance, the intensity curve of each species was weighted according to its contribution to the local allergenic load, relative abundance (in [%]). These weighted daily curves were then aggregated across all species to calculate the total daily pollination intensity (Eq. (5)):

$$PI_t^{total} = \sum_{s=1}^{S} w_s \times PI_{s,t} \tag{5}$$

where w_s is the abundance-based weight for species s.

The aggregated PI values were then normalized to a 0–1 scale to represent the relative allergenic burden over the year. This normalized intensity was then used to scale a baseline I_{UGZA} value ($IUGZA_{base}$), resulting in a temporally dynamic allergenicity index (Eq. (6)) given by:

$$IUGZA_t = IUGZA_{base} \times \frac{PI_t^{total}}{max\left(PI_t^{total}\right)} \tag{6}$$

where $IUGZA_t$ reflects the daily allergenic potential, adjusted by the species-specific pollination intensity. This approach captures short-term fluctuations in pollen release across the flowering period, rather than assuming a constant emission rate. While Gaussian functions were used to model pollination dynamics in this study, the method is flexible and can incorporate alternative curve shapes (e.g., sigmoid or skewed distributions) when justified by phenological data. Importantly, this and the previous formulation can also be extended beyond tree species to include non-arboreal pollen sources, such as grasses and herbaceous plants, allowing for a more complete assessment of allergenic exposure in urban green spaces. By reflecting intra-annual variation, the model supports daily-scale allergenicity assessments and improves temporal resolution in risk estimation. While both the Pollination Intensity (PI) and the Seasonal Weighting Factor (Wt) rely on pollen-related data, including con- tributions from non-tree species such as grasses and herbs, they serve distinct functions. PI is a species-specific, model-based estimate derived from phenological curves (e.g., Gaussian distribution), while Wt is an empirical scaling factor based on observed total pollen concentrations, capturing real-time variability. All computations were carried out in R (version 4.3), using the AeRobiology (Rojo et al., 2019) and dplyr packages.

(c) **Climate Impact Adjustment (CIA)**. To account for meteorological variability and long-term CO_2 enrichment in airborne pollen emissions, we developed a Climatic Impact Adjustment (CIA) factor applied to the I_{UGZA} temporal index (Section 2.4.5.b). Since climate change is expected to significantly alter flowering timing, pollen production and allergenicity (Zhang & Steiner, 2022), incorporating this factor improves the biological realism and temporal respon- siveness of allergenicity assessments. The CIA factor captures short-term meteorological influences (temperature and precipitation), long-term CO_2 trends, and seasonal phenological patterns, computed as (Eq. (7)):

$$CIA_t = \left[1 + \alpha \times \overline{T}_t^* + \beta \times P_t^*\right] \times CO_2^{factor} \quad (7)$$

where $\overline{T}_t^*$ is the standardized average temperature over the current and previous day, P_t^* is standardized daily precipitation, and CO_2^{factor} represents the long-term influence of elevated CO2 on pollen allergenicity. The model- derived meteorological sensitivity coefficients, α and β, for temperature and precipitation on pollen concentration are estimated using a multiple linear regression model (OLS), with log-transformed daily pollen concentration as the response variable. This regression was trained on six years of observational data (2018 - 2023) that included daily pollen counts, meteorological variables, and atmospheric CO_2 concentrations. The resulting coefficients were then applied to calculate the daily-adjusted allergenic index for the year 2023 as a representative example of temporal resolution. Although the CIA was derived from total daily pollen concentrations (rather than species-specific values), its application is modulated by the temporally weighted $IUGZA_t$ or PI, which already accounts for phenological timing via species-level flowering windows. This means the CIA is only impactful during active pollination periods. Model details, diagnostics, and coefficients are provided in Supplementary Methods. The CIA value was then applied multiplicatively to the daily I_{UGZA} index as (Eq. (8)):

$$IUGZA_t^{adjusted} = IUGZA_t \times CIA_t \quad (8)$$

This approach offers a straightforward and adaptable implementation of the CIA factor, requiring only commonly available meteorological variables (temperature and precipitation). However, the model can be extended to include additional climate drivers (e.g., humidity, wind, solar radiation) or tailored to specific datasets and regional phenological patterns to improve accuracy and contextual relevance. In this study, the historical and recent climate data, including daily CO_2 concentrations, precipitation and daily average temperature, were ob- tained from the Copernicus Climate Data Store (CDS). Specifically, we used atmospheric CO_2 data derived from satellite observations (Service, C.C.C., 2018) and ERA5-Land hourly reanalysis data (Hersbach et al., 2023), aggregated to daily resolution and georeferenced to the pollen monitoring site in Augsburg to ensure spatial consistency and minimize interpolation errors. Reanalysis data were preferred over local station data due to their spatial completeness, temporal conti- nuity, and ability to capture urban-scale climatic conditions, which is particularly important given the occasional gaps and peripheral location of the nearest meteorological station. The integration of temporal resolution into the index, including the development of the Climate Impact Adjustment (CIA), as well as the estimation of the meteorological sensitivity coefficients (α and β), was implemented in Python (version 3.11).

3. Results

3.1. Tree inventory and species diversity

The Augsburg tree inventory has 66.718 trees mapped in public areas in Augsburg city, covering a wide range of urban environments and with a high diversity (224 different species, 87 genera) spread across its 146.93 km^2. The dataset includes trees from public parks, street alignments, and other municipal areas. However, private gardens are not included, and certain public areas remain only partially mapped, particularly clusters of trees in peripheral zones or less managed green spaces. While park and street trees are generally well covered, gaps remain in areas with dense groupings or informal plantings. The most common tree species in Augsburg's public areas are *Acer* sp. followed by *Tilia* sp. and *Fraxinus* sp. (**Figure S2a**). The city has 12 official parks along with numerous green areas, including cemeteries, playgrounds, other maintained open spaces and greenery surrounding rivers and lakes, covering a total green area of 6.12 km^2. This results in a high proportion of green area in the municipality with 20.31 m^2 per inhabitant (Green Spaces Office of the City of Augsburg, https://www.augsburg.de/umwelt-soziales/ umwelt/stadtgruen/gruenanlagen-und-freizeitbereiche).

Westfriedhof contains a total of 1.427 trees (42 Genus, 67 species), with an average tree density of 74.7 trees per hectare. The trees are evenly distributed across the study area, except for a northeastern section characterized by an open space with sparse tree cover. Additionally, the park features scattered bushes and pathways structures, although only trees are included in the inventory. For comparison, the broader city of Augsburg has an average density of 4.5 trees per hectare. This underscores the higher vegetation concentration in structured green spaces like Westfriedhof compared to the more heterogeneous urban matrix. This number is based on the official tree cadaster, which records only public trees; consequently, the actual density of trees in the city is likely somewhat higher, although precise data are not available. The most allergenic tree species in the study area (*Betula* sp., *Corylus* sp., *Fagus* sp., *Carpinus* sp., and *Fraxinus* sp.) accounted for 35 % of the trees in the park (Fig. 2**a**), which are spread throughout it. However, larger groups can be seen in the centre and in the southwest side of the park. The most abundant species are *Tilia* sp., *Acer* sp., and *Fagus* sp. (Fig. 2**a**). The Fig. 2**b** revealed that certain species, such as *Betula pendula* and *Carpinus betulus*, exhibit high scores across multiple allergenicity related parameters, particularly in *ap* and *ps*. These species also rank among the most abundant in the urban tree inventory, amplifying their overall contribution to allergenic exposure. Conversely, species like *Tilia cordata*, despite high abundance, scored lower in *ap* and *ps*, suggesting a relatively lower allergenic impact. A similar pattern was observed at the city level (**Figure S2b**) where the most abundant species, such as *Tilia cordata* and *Acer platanoides*, exhibited relatively lower scores across the allergenicity parameters.

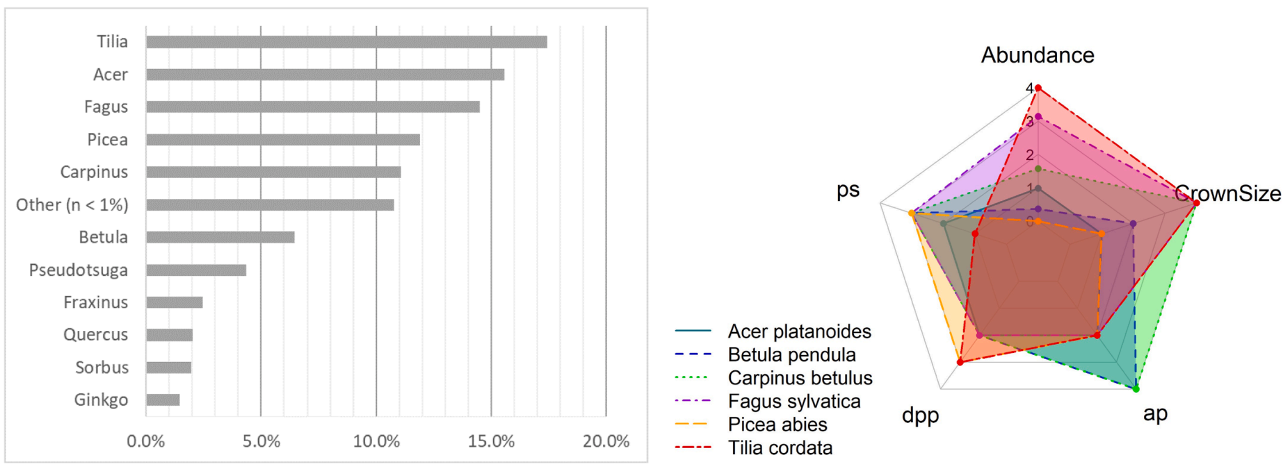
The park has a highly diverse species composition, with a Shannon-Index of 2.89 and an Evenness of 0.75. The 25 $m \times 25$ m grid cells for higher resolution made areas with lower biodiversity (green) and higher biodiversity (red) visible. The northeast part of the study area, as well as in the north and some small patches in between, has a low biodiversity with values between 0 and 0.5, while most of the park has a medium to high biodiversity, with some hotspots in the south, west, and north of the park (**Figure S3**).

3.2. Static allergenicity assessment using IUGZA

When calculating the I_{UGZA} value for the entire park, based solely on the tree population, a value of 0.36 was obtained. According to Cariñanos *et al.* (Cariñanos et al., 2019), a value above 0.3 indicates a high allergenic potentialand a notable baseline risk throughout the year.

3.3. Spatial distribution of allergen exposure in Westfriedhof park

The application of the methodology produced a map that represented the values of the I_{UGZA} index. The use of a color ramp was employed, establishing green tones for low exposure values and red tones for high exposure values. Fig. 3 shows the exposure I_{UGZA} values in the grids. Each cell represents the I_{UGZA} value of its centroid, representing values of 0 (not exposed) or in the range of 0.1 to 1 (slightly to strongly exposed). The spatial resolution in the 25 $m \times 25$ m grid reveals that, particularly in the middle of the park but also distributed throughout the park, small patches with the high I_{UGZA} values of 0.7 - 1 can be observed, indication a high allergenic potential in these locations. The northeastern area, which has fewer trees (**Figure S4** in



(a) Species composition in Westfriedhof landscape (b) Allergenicity-related parameter

Fig. 2. Species abundance and allergenicity profiles in Westfriedhof (a) Bar chart illustrating the relative abundance of tree species (%) in the study area, highlighting the dominant species contributing to the overall urban forest structure. (a) Radar plot comparing allergenicity-related parameters for the most abundant tree species in the study area's urban tree inventory. Each axis represents a key factor influencing allergenicity, including intrinsic allergenic potential (*ap*), pollination duration (*dpp*), pollination strategy (*ps*), abundance and crown size. All parameters are displayed on a unified 0–4 range scale, with the exception of *dpp* and *ps*, which retain their original 0–3 ranges.

Supplementary Material) showed, as expected, a lower allergenic potential with values ranging from 0 to at most 0.2. The rest of the park exhibited mixed allergenicity risk (Fig. 3).

3.4. Neighborhood-level assessment of pollen exposure

The I_{UGZA} was applied on a neighborhood scale to assess the allergenic potential of urban districts. This approach allowed for the identification of local allergenic hotspots across the urban landscape and provided a broader under- standing of allergenic exposure risks, and informed targeted urban planning strategies. The analysis revealed significant variation in allergenicity risk across different districts, with some areas showing high allergenic potential due to the presence and accumulation of specific tree species, while others had a lower risk, suggesting a mitigating effect of diverse vegetation. For comparison, the area around the Westfriedhof cemetery, consisting of many residential areas and other larger green spaces (Fig. 4), and the old town of Augsburg, with fewer trees and closely spaced houses (Fig. 5), were considered.

Across both neighborhoods, allergenicity values predominantly range above 0 and below 0.1. Isolated patches with moderate allergenicity levels (0.1 to 0.5) are visible in both areas (Figs. 4 and 5). The highest and most spatially concentrated allergenicity is observed in the Westfriedhof, which contains the densest clustering of trees, including a high density of *Carpinus* sp. and *Betula* sp. (Fig. 4). In contrast, other areas exhibit lower allergenicity, likely influenced by the presence of tree species with lower allergenic potential and a generally low density of both mapped and unmapped trees (Figs. 4 and 5). Supplementary **Figures S5** and **S6** show which tree genera are present and how they are spatially distributed. Species such as *Carpinus* sp., *Betula* sp. *and Corylus sp*. were the primary contributors to allergenicity risk in the city, particularly in urban parks near residential areas, like the study area Westfriedhof in the east. These species, characterized by short long pollination periods but high peaks and allergenicity potential, were found in areas with elevated I_{UGZA} scores.

3.5. Sensitivity analysis

The results from the sensitivity analysis revealed that the parameter *cpa* has the strongest influence on the aller- genicity index variance, with a First Order Index of 0.6118 and Total Index of 0.6953, explaining more than 60% of the variance. The relatively narrow confidence intervals suggest that the value is robust and reliable (Table 2).

The second most influential parameter was *ap*, which explained about 18 % of the variance in the output (First Order Index = 0.1791). For the total index, the value increases to 0.3463, meaning that 34.6 % of the variance can be directly or indirectly attributed to *ap*. In contrast, the parameters *ps* and *dpp* showed a minor influence on the variance of the output. The parameter *ps* shows a first-order index of 0.1356 (13.56 %) with a large confidence interval, indicating some uncertainties. Its influence on the overall indices is very low, accounting for only 6.3 % of the variance. The parameter *dpp* exhibits a very low index both in the first-order and overall indices, suggesting that *dpp* has no significant influence. These findings highlight the key role of the crown area projection *cpa* and the species-specific allergenicity in calculating the I_{UGZA}.

3.6. Temporal risk assessment

We applied the Pollination Intensity PI_t parameter based on daily pollen release data throughout the year for the most abundant species in the study area. In parallel, the Seasonal Weighting Factor W_t was calculated based on monthly and seasonal pollen concentration data. Both metrics were incorporated into the urban allergenicity index to capture temporal and spatial variations in allergenic potential (Table 3, Fig. 6). The species-specific parameters used to model pollination intensity using a Gaussian distribution are provided in supplementary **Table S2**. The results highlight distinct peaks in allergenicity periods coinciding with the major pollination phases of key species (**Figure S7**), such as *Betula* (April-May) and *Corylus* (February-March), as illustrated spatially in Fig. 6.

The temporal adjustment of the I_{UGZA} index using the Pollination Intensity ($P\ I$) and the Seasonal Weighting Factor (Wt) approaches revealed notable differences in allergenic potential over time. As shown in Table 3, the Wt-based model produced I_{UGZA} values ranging from 0.002 to 0.360, with a mean of 0.057 and a standard deviation of 0.101, reflecting a high degree of temporal variability and several low-activity days. The $P\ I$-based method exhibited slightly higher average values (mean = 0.148), with a narrower range (0.019 to 0.360) and comparable variability (SD = 0.104), suggesting more consistently elevated allergenic conditions across the season.

In contrast, the *CIA*-adjusted model, which incorporates the effects of temperature, precipitation and long-term atmospheric CO_2, yielded a

Fig. 3. Annual **I_{UGZA} distribution in Westfriedhof.** Spatial distribution of allergenic potential in the Westfriedhof area, calculated using the I_{UGZA} on a 25 $m \times$ 25 m grid. Values were interpolated across the area using the Inverse Distance Weighting (IDW) method to visualize estimated allergenicity for the entire year.

wider range of I_{UGZA} values (0.014 to 0.447) and similar variability (SD = 0.112). This approach was the only one to produce values exceeding the static baseline (0.36), resulting in a maximum increase of 24.1 % during periods of elevated temperature and low or zero precipitation levels. The CIA model also exhibited a substantial relative decrease from peak to minimum values (97.8 %), reflecting its ability to capture both high and low allergenic conditions under changing environmental influences. While the largest relative drop (99.1 %) was observed in the Wt-based approach, this likely reflects its seasonal rather than daily resolution, which limits its responsiveness to short-term fluctuations.

Fig. 6 shows that the spring season contains the higher allergenicity grids of the park compared with the static approach, indicating that the overall high allergic potential of trees is mainly due to spring-flowering taxa such as *Betula* sp., *Fagus* sp. and *Carpinus* sp. The allergenicity risk is not determined solely by the allergenic potential of the species, as the sensitivity analysis has demonstrated, but also by other key parameters, most notably the *cpa*. Consequently, species with larger size or higher frequency, such as *Fagus* sp., can contribute significantly to elevated I_{UGZA} values in certain zones. The spatial and temporal decomposition of the I_{UGZA} index reveals hot spots with a high allergenic potential, but also areas of low risk. However, these do not always correspond to the species composition. It can be seen that some areas in the park have a high number of highly allergenic birch trees, but the overall I_{UGZA} value remains low, ranging between 0.001 and 0.2. The areas with high I_{UGZA} values (above 0.3) consist of species with high allergenic potential, primarily *Carpinus* sp., but also *Fagus* sp.

Fig. 7 displays the daily-adjusted I_{UGZA} for the Westfriedhof site, calculated using the *PI* and the monthly weighting factor W_t approaches. As expected, allergenicity peaked during the flowering phases of dominant taxa and dropped to near zero during off-season months. These temporal dynamics highlight the substantial intra-annual variation in allergenic potential. A comparison of static versus temporal I_{UGZA} values showed that species with shorter but intense pollen release periods had disproportionately high allergenic impacts during peak months. In contrast, species with extended flowering duration contributed to a more consistent baseline allergenicity.

3.7. *Impact of climate factors on allergenicity*

The Climate Impact Adjustment (CIA) model computed as a

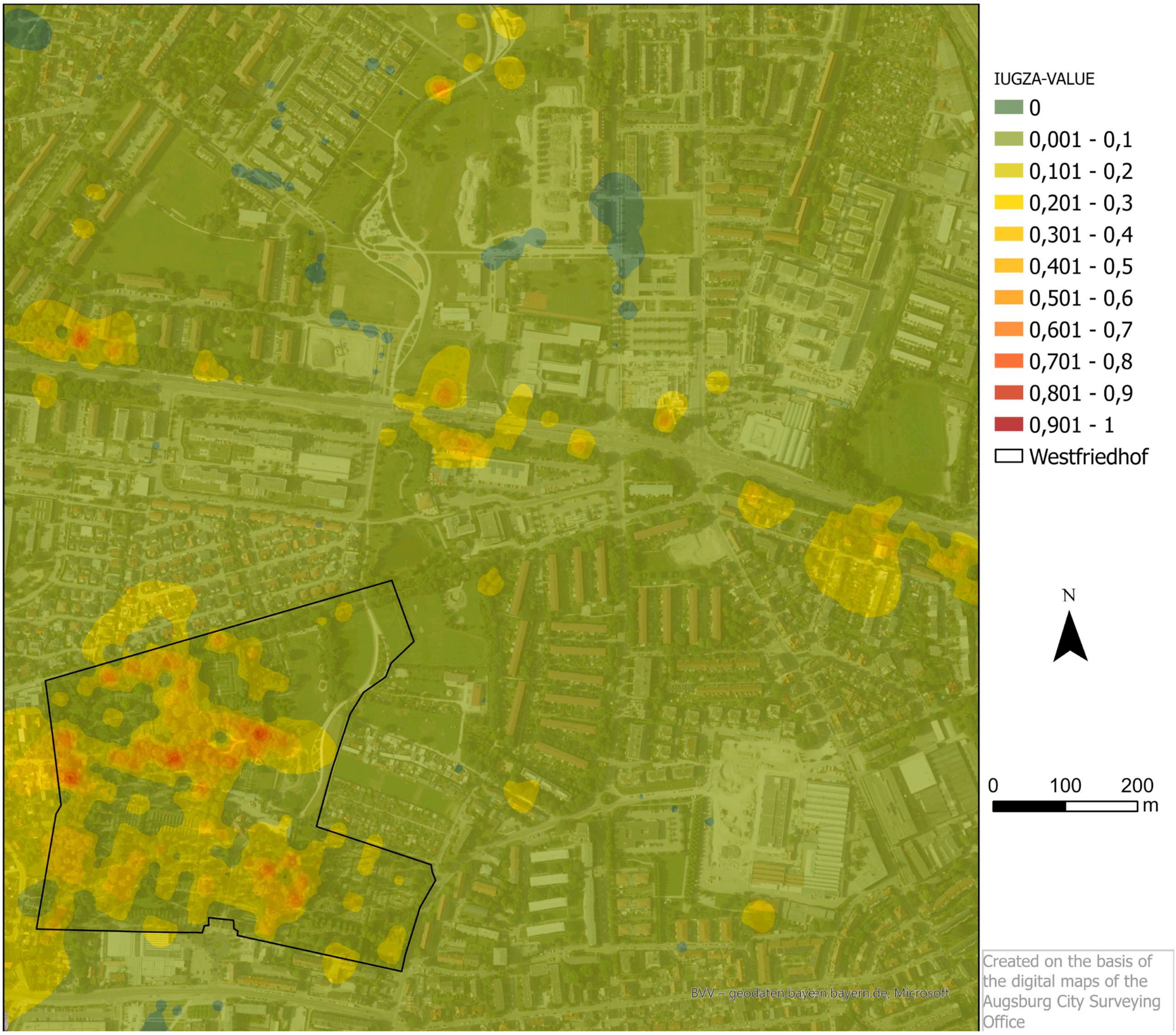


Fig. 4. Annual I_{UGZA} distribution in residential area around Westfriedhof. Estimated allergenic potential in the residential area surrounding Westfriedhof (outlined in black), calculated using the I_{UGZA} on a 25 *m* × 25 m grid size. Interpolation was performed using the Inverse Distance Weighting (IDW) method to represent annual allergenicity patterns.

multiplicative correction to the I_{UGZA} index, integrates short-term meteorological variability and long-term atmospheric CO_2 trends to dynamically modulate airborne aller- genic potential. Scaling co-efficients for temperature ($\alpha = 0.1948$) and precipitation ($\beta = -0.1579$) were derived from standardized multiple linear regression (see **Tables S3** and **S4** in Supplementary Methods). During the 2023 pollen season in Augsburg, daily average temperatures ranged from 12.3 °C to 25.8 °C (mean: 19.5 °C), while total annual precipitation was 872.2 mm. Rainfall (>1 mm) occurred on 33 % of days, with peak monthly averages in August (5.48 mm), July (4.74 mm), and November (4.61 mm), indicating a seasonal pattern. CO_2 concentrations varied between 295.8 ppm and 452.5 ppm (mean: 411.4 ppm). The resulting CIA values ranged from 0.929 to 1.048, with a mean of 1.010 and a standard deviation of 0.219, indicating relatively stable modulation of allergenicity by climatic conditions over time (Table 4).

Among the components, temperature contributed most significantly to CIA variability, with values ranging from −0.584 to 0.437 (mean = 0.166, SD = 0.195)), while precipitation ranged from −1.815 to 0.066 (SD = 0.158). CO_2 con- tributed a consistent factor of 1.006, based on the seasonal mean concentration of 411.5 ppm. On average, temperature accounted for approximately 16.5 %, precipitation for 9.0 %, and CO_2 for 0.57 %. These results (Table 4) highlight the dominant role of temperature in shaping short-term allergenic risk, while reinforcing the importance of considering long-term CO_2 increases in future projections.

The adjusted model incorporating combined temperature, precipitation, and CO_2 data, increased the I_{UGZA} values by up to 24.0 % compared to the static baseline, extending the allergenic season and intensifying risk during already active pollination periods (Table 4), indicating a measurable impact of climate-related variables on allergenic potential.

4. Discussion

Understanding the spatial dynamics of allergenic risk in urban green spaces is essential for evidence-based land- scape planning and public health mitigation. While urban trees provide critical ecosystem services, including air purification, cooling, and mental health benefits, their pollen emissions can also negatively affect respiratory health and well-being, particularly among sensitized individuals (Aerts et al., 2020;

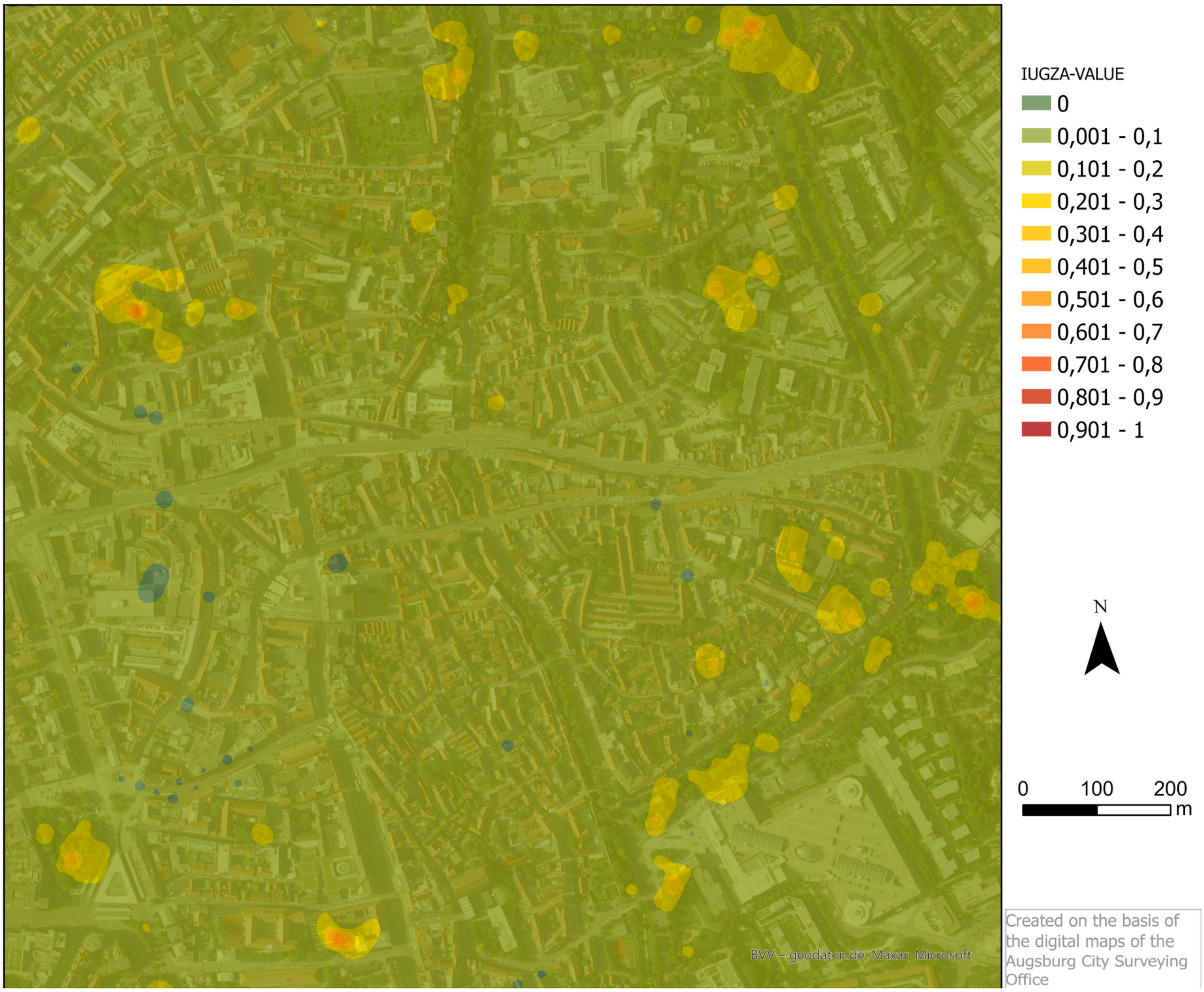


Fig. 5. Annual I_{UGZA} distribution in the old town of Augsburg. Estimated allergenic potential in the old town of Augsburg, calculated using the I_{UGZA} on a 25 *m* × 25 m grid size. Interpolation was performed using the Inverse Distance Weighting (IDW) method to represent annual allergenicity patterns.

Table 2
Sensitivity analysis of I_{UGZA} parameters. Results of the Sobol sensitivity analysis for the I_{UGZA}, showing first-order and total-effect indices for four key parameters: allergenicity potential (*ap*), pollination strategy (*ps*), duration of the pollination period (*dpp*), and crown projection area (*cpa*).

Parameter	Original	Bias	Std. Error	Confidence Interval
First Order Indices				
X1 (ap)	0.1791	−0.0013	0.0299	0.1237 – 0.2381
X2 (ps)	0.1356	−0.0005	0.0305	0.0732 – 0.1946
X3 (dpp)	0.0607	−0.0006	0.0204	0.0204 – 0.0973
X4 (cpa)	**0.6118**	−0.0036	0.0358	0.5496 – 0.6784
Total Indices				
Parameter	Original	Bias	Std. Error	Confidence Interval
X1 (ap)	**0.3463**	0.0005	0.0303	0.2841 – 0.4073
X2 (ps)	0.0629	0.0007	0.0157	0.0365 – 0.0861
X3 (dpp)	0.0660	0.0004	0.0139	0.0465 – 0.0872
X4 (cpa)	**0.6953**	−0.0043	0.0490	0.6117 – 0.7744

Table 3
Adjusted I_{UGZA} summary statistics. Overview of I_{UGZA} values adjusted using three dynamic approaches: Seasonal Weighting Factor (W_t), Pollination Intensity (*P I*) and Climate Impact Adjustment (*CIA*). The static baseline I_{UGZA} was set at 0.36 for comparison.

Metric	W_t-based	PI-based	CIA-adjusted
Static Baseline I_{UGZA}	0.360	0.360	0.360
Minimum I_{UGZA}	0.002	0.019	0.014
Maximum I_{UGZA}	0.360	0.360	0.447
Mean I_{UGZA}	0.057	0.148	0.153
Standard Deviation	0.101	0.104	0.112
Relative Decrease from Max to Min (%)	99.07	94.7	97.8
Max Increase from Baseline (%)	0	0	24.1

Annesi-Maesano et al., 2023; Beckett et al., 1998; Islam et al., 2024; Maimaitiyiming et al., 2014; Pattnaik et al., 2024; Simunovic et al., 2023; Stas et al., 2021; Yang et al., 2015). The application of I_{UGZA} to assess the potential allergenicity of green infrastructure in a pilot area in southern Germany, combining spatial analysis with sensitivity testing, provides valuable insights into how urban green spaces contribute to allergenic exposure in temperate climates. Few studies have applied I_{UGZA} in a spatial context; however, these efforts have primarily focused on species-level traits (Fernández-Alvarado & Fernández-Rodríguez, 2023) or a geographical analysis of VPA (Calatayud & Cariñanos, 2024). While VPA includes factors such as allergenic potential and pollination intensity, it does not fully capture the complexity of real exposure in urban settings (Calatayud & Cariñanos, 2024). Specifically, parameters like tree height, crown volume, and spatial distribution may significantly influence the dispersion and concentration of airborne pollen,

Fig. 6. Seasonal I_{UGZA} maps in Westfriedhof. Spatial distribution of allergenic potential in the Westfriedhof area across the four meteorological seasons: winter (top left, December to February), spring (top right, March to May), summer (bottom left, June to August), and autumn (bottom right, September to November). All maps are based on I_{UGZA} values calculated at a 25 $m \times 25$ m spatial resolution.

which our findings confirm as key determinants of allergenic risk. According to I_{UGZA} methodology described by Cariñanos et al. (Cariñanos et al., 2019), the overall value of allergenic potential was found relatively high (0.36) in the study area, after adjusting certain parameters to reflect local site characteristics. An elevated risk was expected due to the dominance of highly allergenic trees, such as *Betula* sp., *Carpinus* sp. and *Fraxinus* sp. which together account for over 30 % of the total tree population, even though most individual species present moderate allergenicity scores. Previous I_{UGZA} studies (Cariñanos et al., 2014; Cariñanos et al., 2017) highlighted tree species whose pollen grains are classified as allergenic and the existence of single-species stands as the two primary contributors influencing the allergenicity risk. However, our spatial analysis, representing one of the first high-resolution grid--based implementation of I_{UGZA}, offers a novel and detailed approach to identifying local allergenicity spatial dynamics, revealing that low I_{UGZA} values were observed in certain areas, where monospecific allergenic trees were predominant. Dividing the study area into smaller subregions further illuminated spatial variability: it showed zones contributing disproportionately to the overall allergenic potential, as well as areas of relatively low risk. Interestingly, while some regions with a high presence of known allergenic trees (e.g., *Betula* spp.) (Asam et al., 2015) exhibited high I_{UGZA} scores, others with similar tree compositions showed values between 0.1 and 0.2. This discrepancy suggests that other factors than intrinsic allergenicity potential, such as spatial distribution or morphological characteristics of trees, play a decisive role in determining localized allergenic exposure.

This assumption is confirmed by our findings in the sensitivity analysis. The crown projection area *cpa* defined in I_{UGZA} as the surface of the park covered by species i (S_i), appeared to be the most influential factor, with a total index variability of 69.5 %. In comparison, allergenic potential accounted for only 34.6 %, which may explain the differences between areas dominated by *Carpinus* sp. trees and those with *Betula* sp. Although hornbeam tree (*Carpinus* sp.) are classified as large-sized species (Pretzsch et al., 2015) and exhibits a wider crown size than birch tree, the tree size alone does not neces- sarily reflect pollen emission (Katz et al., 2020) or tree age (McCarthy & Weetman, 2006;

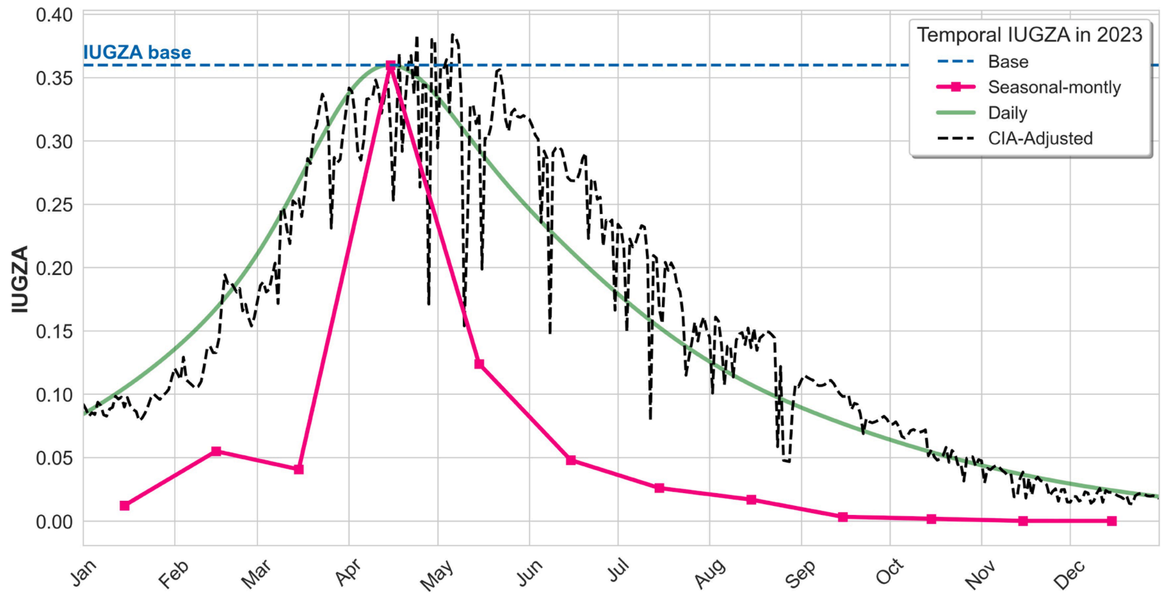


Fig. 7. Dynamic I_{UGZA} variation in 2023-Westfriedhof. Estimated allergenic potential in the Westfriedhof area for 2023, incorporating the Seasonal Weighting Factor (*Wt*), derived from monthly and seasonal pollen concentration data (pink line - monthly resolution) and the Pollination Intensity (*P I*) parameter-based on daily pollen release data from dominant local taxa (green line - daily resolution). The daily climate adapted variation of the I_{UGZA} is shown, integrating short-term meteorological effects and long-term CO_2 effects via the Climate Impact Adjustment (*CIA*) factor (black dashed line - CIA-adjusted).

Table 4

CIA Factor and Component Statistics. Descriptive statistics for the Climate Impact Adjustment (*CIA*) factor and its underlying components temperature, precipitation, and CO_2 during the main pollen season in Augsburg, Germany. Scaling coefficients were derived from regression analysis to quantify their influence on allergenic potential.

Metric	CIA	Temperature Contribution	Precipitation Contribution	CO_2 Contribution
Minimum	0.511	−0.584	−1.815	1.006
Maximum	1.502	0.437	0.066	(based on average CO_2: 411.5 ppm)
Mean	1.010	0.166	0.091	0.57
Standard Deviation	0.219	0.195	0.158	
% contribution to CIA	–	16.53	9.05	

Kuuluvainen et al., 2002; Korning & Balslev, 1994), both of which can significantly influence allergenic exposure. This raises a critical question of using the crown projection area as a proxy for allergenic risk. Incorporating parameters such as tree age and pollen production would enhance the accuracy of allergenicity assessments by providing a more realistic representation of exposure scenarios. In practice, however, this is often challenging due to data availability, as these variables are difficult to obtain or require complex field measurements and specialized procedures (Katz et al., 2020; Kuuluvainen et al., 2002).

Another limitation lies in the theoretical assumptions of the I_{UGZA} calculation, which assesses the allergenic potential of a park under the hypothetical scenario that all trees reach maturity, flower simultaneously, and have uniform allometric crown characteristics (Cariñanos et al., 2014; Cariñanos et al., 2017). Although this theoretical framework provides an interpretable parameter that facilitates comparisons between different parks, it may oversimplify complex biological processes and may not accurately reflect the actual conditions of allergen exposure experienced by individuals in a given area. The I_{ISA} index offers an improvement by incorporating tree-specific attributes such as actual tree height, crown dimensions, and maturity status (Jochner-Oette et al., 2018). However, while it produces more realistic values than simpler approaches, it is labour-intensive, not easily reproducible, and it remains static, providing only a single aggregated value per park. In contrast, our approach relies on *DBH* and tree height, data commonly available in urban tree cadastres, combined with allometric equations to estimate crown size, enabling reproducible and spatially explicit analysis.

Despite certain limitations, the I_{UGZA} index remains a valuable tool for evaluating the allergenic potential of urban green spaces (Fernández-Alvarado & Fernández-Rodríguez, 2023; Sabariego et al., 2021), as it integrates species composition and allergenic potential into a single metric useful for comparative assessments and urban planning decisions (Calatayud & Cariñanos, 2024; Ciani et al., 2021). Such applications can have significant, long-lasting consequences for citywide pollen production (Katz et al., 2024). In the context of our study, I_{UGZA} offered a robust starting point for quantifying allergenicity at a fine spatial scale, while allowing us to explore potential methodological improve- ments. Its modular structure allowed for the incorporation of locally adapted parameters, such as site-specific pollen intensity curves and flowering periods, making it particularly well suited for application in diverse ecological settings (Jochner-Oette et al., 2018; Velasco--Jiménez et al., 2020; Aerts et al., 2021). By building on the existing I_{UGZA} framework, we were able to make use of its strengths while addressing key limitations, resulting in a more locally tailored and responsive assessment of allergen exposure.

As a standardized tool, I_{UGZA} relies on consistent and transparent methodology to enable meaningful comparisons across urban green spaces. Variations in results often stem from differences in the underlying parameter databases. As noted by Magyar et al. (2022), different databases provide different allergenicity values depending on their purpose. This means that the use of data from multiple sources can potentially compromise the accuracy of allergenicity assessments (Magyar et al., 2022). While our cross-comparison of multiple databases revealed no major discrepancies for species present in more than one source, validation was unfeasible for species listed in only a single database. Additionally, databases differ in focus; some rely on plant-based biological characteristics, while others incorporate epidemiological data, which may vary by region (Magyar et al., 2022). A further significant limitation is the lack of transparency in some systems, where methodologies and reference sources are not clearly documented, making it difficult to assess their reliability (Magyar et al., 2022). To address these issues, standardized systems with verifiable and transparent methodologies are needed. The CARE-S index (Magyar et al., 2022) offers a promising alternative, combining intrinsic allergenic potential with clear documentation and global applicability. In the present study, we attempted to improve the robustness of I_{UGZA} by carefully curating and harmonizing allergenicity parameters derived from multiple sources, allowing for greater clarity and comparability in assessments across different urban parks.

On the other hand, temporal variability in allergenicity has not been thoroughly incorporated into allergenicity indicators. Most allergenicity indices have traditionally provided static (Zong et al., 2020; Jochner-Oette et al., 2018), annual, or purely spatial assessments (Krwanji et al., 2025) that focus on the overall allergenic potential of vegetation in urban spaces without factoring in seasonal or temporal variations (Suanno et al., 2021; Cariñanos et al., 2014; Pecero-Casimiro et al., 2019). While these approaches offer valuable baseline insights, they may overlook short-term dynam- ics in pollen exposure. As a result, static assessment may underestimate peak exposure periods and fail to capture critical fluctuations, thereby limiting the effectiveness of targeted mitigation strategies and real-time public health responses. Integrating temporal dynamics into allergenicity assessments is becoming increasingly relevant, particularly in light of climate change. Shifting flowering periods, altered pollen production, and changing dispersal patterns, driven by factors such as temperature extremes and altered precipitation regimes, are reshaping pollen exposure risks (Baumbach et al., 2017; Schramm et al., 2021). Furthermore, pollination seasons vary widely across Europe, from over 220 days in the Mediterranean to around 120 days in northern Scandinavia (Chmielewski & Rötzer, 2001), pointing out the need for regionally adaptable and time-sensitive allergenicity models. Many studies have explored pollen forecasting models and the seasonal dynamics of allergenicity (Makra et al., 2024; Picornell et al., 2024; Kolek et al., 2021).

However, these efforts rarely consider the I_{UGZA} or similar allergenicity indices, which remain underrepresented in the literature, particularly those in combination with spatial modeling and city-scale implementation, as applied in our study. Notably, a recent study (Zahradníková et al., 2024) introduced a temporal component by modifying the VPA parameter within the I_{UGZA} framework, marking an important step toward dynamic allergenicity assessments. To build upon this, we adapted the index further to enable high-resolution temporal modeling and to more accurately reflect local conditions. By incorporating seasonal weighting, species-specific pollination intensity, and climate-based adjustments, our imple- mentation of the I_{UGZA} model revealed clear seasonal patterns in allergenic risk, with spring emerging as the period of highest allergenic potential in the study area. This seasonal peak is primarily attributed to the dominance of highly allergenic tree species such as *Betula* sp., *Fagus* sp., and *Carpinus* sp., which collectively contributed to elevated I_{UGZA} values during their flowering periods. When comparing static and temporally adjusted I_{UGZA} scores, species with short and intense pollination windows showed disproportionately high allergenic impacts during their peak months, whereas species with longer flowering periods contributed to a more consistent allergenicity baseline throughout the season. This emphasizes the need to consider phenological dynamics when assessing allergenic exposure to ensure accurate risk evaluation and effective intervention timing. Although Gaussian models may not perfectly capture the pollen season of all species, they provide a practical solution in data-scarce contexts. When real pollen data are available, as in our W_t implementation, they offer a more accurate representation of allergenic exposure. Together, these methods allow for flexible modeling across varying data availability scenarios.

To further enhance realism, we incorporated climate responsiveness into the index through the Climate Impact Adjustment (CIA) model, which modulates allergenicity based on short-term effect of daily temperature and precipi- tation and long-term influence of CO_2 levels. Temperature and precipitation emerged as key drivers of CIA variability, with precipitation acting mainly through its washout effect, temporarily reducing airborne allergen concentrations following rainfall events. CO_2 contribution was limited to approximately 0.6 %, partly attributed to the relatively low levels of air pollution in Augsburg, where CO_2 concentrations did not vary substantially across the pollen season. Although CO_2 had a minor influence, its cumulative effects over longer periods or in future climate scenarios may still be relevant. We acknowledge that the CIA model uses total pollen concentrations and not species-specific responses to climate. Whilst this may obscure differential sensitivities, the CIA is only applied during active flowering periods already captured by the temporally weighted $IUGZA_t$. This safeguards against overestimating climate impacts outside species-specific pollination windows. Future improvements could explore species-level climate response functions to refine this approach. Overall, the inclusion of temporal and climatic parameters enhanced the ecological relevance of the I_{UGZA} index, offering a more refined understanding of allergenic risk in urban environments. While previous studies have begun to explore the integration of temporal factors into allergenicity models (Zahradníková et al., 2024), to our knowledge, the method introduced here represents one of the first efforts to combine temporal variation with a spatially explicit implementation of the I_{UGZA} framework. Incorporating short-term temporal dynamics and long-term meteorological variables allows for the identification of critical exposure windows that static indices cannot capture. This advancement is particularly crucial in urban areas, where many biological and environmental factors co-occur, such as overlapping flowering periods of different species (Iwanycki Ahlstrand et al., 2023), emerging non-native species (Werchan et al., 2024) or coincidental presence of fungal spores (Myszkowska et al., 2023), leading to compounded allergenic exposure.

Finally, applying the I_{UGZA} index beyond the scale of a single park to the entire urban area or at neighborhood level introduced several challenges, primarily related to data limitations. Municipal tree registers, the basis of the analysis, are often incomplete or outdated, lacking essential information such as recent maintenance status or updated records for individual trees. Furthermore, it is important to note that municipal tree inventories do not cover data on shrubs, grasses, herbaceous plants, or other non-tree vegetation, many of them recognised as significant allergen sources. Consequently, the actual allergenic potential in the study area may be underestimated. Moreover, private garden trees are typically excluded from official inventories, further reducing the comprehensiveness of the dataset. These limitations constrained the accuracy of allergenicity assessments at the city-wide level. To overcome current limitations in urban-scale allergenicity assessment, the integration of real-time pollen sampling, as done in this study, and high-resolution 3D vegetation mapping, could significantly enhance future applications of the I_{UGZA} index. Impor- tantly, by incorporating observed pollen concentrations, our approach enables the inclusion of allergenic contributions from grasses and herbaceous plants, based on their actual presence in the airborne pollen load. These advancements would allow for a more accurate representation of actual allergenic exposure and support the development of refined spatial models that account for pollen dispersion dynamics in complex urban environments. In our dynamic extension, flowering timing is captured by the species-specific PI function, so the pollination duration parameter no longer determines timing but contributes to species weighting within the annual risk framework. We retained *dpp* to preserve compatibility with the original I_{UGZA}, though this may overweight long-flowering species and reduce relevance in dynamic contexts. Future research should explore revised formulations that remove or adapt the *dpp* component in temporally resolved contexts, while also developing tiered versions of the model that rely on proxy data, such as remote sensing-derived canopy metrics or modeled pollen levels, to improve scalability in data-limited settings without compromising methodological robustness.

By incorporating both temporal and spatial resolution into a widely recognized urban allergenicity framework, this study provides a more realistic representation of allergenic exposure risk over time. This work presents one of the first high-resolution applications of the I_{UGZA} index grounded in real-world tree inventory, meteorological factors and daily pollen concentration data. Its focus on a Central European urban context makes it a valuable case study for temperate regions, while its adaptable methodology lays the groundwork for broader applications. Such assessments are essential for informing dynamic interventions, ranging from vegetation management to timely health alerts. Furthermore, as cities expand and invest in new urban green infrastructure, integrating allergenicity risk assessments into planning processes becomes increasingly important. This ensures that green spaces deliver maximum health benefits without unintended consequences for allergy-sensitive populations, especially in the context of a changing climate that may increase exposure risks.

5. Conclusion

This study highlights the value of enhancing the I_{UGZA} index through spatial, temporal, and climate-sensitive adjustments to better assess allergenic risk in urban green spaces. By applying the index in a selected pilot area and integrating a sensitivity analysis, we identified the crown projection area as a key driver of allergenic exposure, having a greater influence than the intrinsic allergenic potential of species. Refinements to the study design that accounted for phenological patterns and local climate conditions revealed clear seasonal peaks in allergenicity, especially in spring, and emphasized the importance of genera such as *Betula* and *Carpinus*. Despite limitations in data completeness and theoretical assumptions, I_{UGZA} continues to serve as a practical and adaptable tool for comparative assessment. The temporal extension and other modifications provide a more detailed and realistic picture of exposure, and lay the groundwork for allergenicity mapping at broader urban scales. These findings support more targeted urban planning, dynamic risk management, and stronger public health responses in the face of climate change and rising pollen-related sensitivities.

Funding

This work was carried out within the research training group Urban Green Infrastructure, funded by the German Research Foundation under grant 437788427 – RTG 2679. This study was also partly financed by the IMPACCT project (01LN2202A) of the German Ministry of Federal Ministry of Research, Technology and Space (BMFTR).

CRediT authorship contribution statement

Carolin Trost: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Thomas Rötzer:** Writing – review & editing, Supervision, Funding acquisition. **Claudia Traidl-Hoffmann:** Writing – review & editing, Supervision, Funding acquisition. **Maria P. Plaza:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Carolin Trost reports financial support was provided by German Research Foundation. Maria P. Plaza reports financial support was provided by Federal Ministry of Education and Research. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scs.2025.106927.

Data availability

The authors do not have permission to share data.

References

Adams-Groom, B., Skjøth, C. A., Baker, M., & Welch, T. E. (2017). Modelled and observed surface soil pollen deposition distance curves for isolated trees of carpinus betulus, cedrus atlantica, juglans nigra and platanus acerifolia. *Aerobiologia, 33*, 407–416. https://doi.org/10.1007/s10453-017-9479-1

Aerts, R., Bruffaerts, N., Somers, B., Demoury, C., Plusquin, M., Nawrot, T. S., & Hendrickx, M. (2021). Tree pollen allergy risks and changes across scenarios in urban green spaces in brussels, belgium. *Landscape and Urban Planning, 207*, Article 104001. https://doi.org/10.1016/j.landurbplan. 2020.104001

Aerts, R., Stas, M., Vanlessen, N., Hendrickx, M., Bruffaerts, N., Hoebeke, L., Dendoncker, N., Dujardin, S., Saenen, N. D., Van Nieuwen- huyse, A., Aerts, J. M., Van Orshoven, J., Nawrot, T. S., & Somers, B. (2020). Residential green space and seasonal distress in a cohort of tree pollen allergy patients. *International Journal of Hygiene and Environmental Health, 223*, 71–79. https://doi.org/10.1016/j.ijheh.2019.10.004. URL https://www.sciencedirect.com/science/article/pii/S1438463919304390.

Anderegg, W. R. L., Abatzoglou, J. T., Anderegg, L. D. L., Bielory, L., Kinney, P. L., & Ziska, L. (2021). Anthropogenic climate change is worsening north american pollen seasons. *Proceedings of the National Academy of Sciences, 118*, Article e2013284118. https://doi.org/10.1073/pnas.2013284118

Andersen, T. B. (1991). A model to predict the beginning of the pollen season. *Grana, 30*, 269–275. https://doi.org/10.1080/00173139109427810

Annesi-Maesano, I., Cecchi, L., Biagioni, B., Chung, K. F., Clot, B., Collaud Coen, M., D'Amato, G., Damialis, A., Dominguez-Ortega, J., Galán, C., et al. (2023). Is exposure to pollen a risk factor for moderate and severe asthma exacerbations? *Allergy, 78*, 2121–2147. https://doi.org/10.1111/all.15724

Asam, C., Hofer, H., Wolf, M., Aglas, L., & Wallner, M. (2015). Tree pollen allergens-an update from a molecular perspective. *Allergy, 70*, 1201–1211. https://doi.org/10.1111/all.12696

Bassen, A., Drewes, J.E., Fischer, M., Gabrysch, S., Hornidge, A.K., Pittel, K., Pörtner, H. O., Schlacke, S., Traidl-Hoffmann, C., Weidenkaff, A., et al., 2023. Gesund leben auf einer gesunden erde. URL: https://issuu.com/wbgu/docs/wbgu_hg2023.

Baumbach, L., Siegmund, J. F., Mittermeier, M., & Donner, R. V. (2017). Impacts of temperature extremes on european vegetation during the growing season. *Biogeosciences (Online), 14*, 4891–4903. https://doi.org/10.5194/bg-14-4891-2017. publisher: Copernicus GmbH.

Bayr, D., Plaza, M. P., Gilles, S., Kolek, F., Leier-Wirtz, V., Traidl-Hoffmann, C., & Damialis, A. (2023). Pollen long-distance transport associated with symptoms in pollen allergics on the german alps: An old story with a new ending? *Science of the Total Environment, 881*, Article 163310. https://doi.org/10.1016/j.scitotenv.2023.163310

Beck, I., Jochner, S., Gilles, S., McIntyre, M., Buters, J. T., Schmidt-Weber, C., Behrendt, H., Ring, J., Menzel, A., & Traidl-Hoffmann, C. (2013). High environmental ozone levels lead to enhanced allergenicity of birch pollen. *PloS one, 8*, Article e80147. https://doi.org/10.1371/journal.pone.0080147

Beckett, K. P., Freer-Smith, P. H., & Taylor, G. (1998). Urban woodlands: Their role in reducing the effects of particulate pollution. *Environmental Pollution, 99*, 347–360. https://doi.org/10.1016/S0269-7491(98)00016-5

Bergmann, K. C., Zuberbier, T., Augustin, J., Mücke, H. G., & Straff, W. (2012). Climate change and pollen allergy: Cities and municipalities should take people suffering from pollen allergy into account when planting in public spaces. *Allergo Journal : Interdisziplinare Zeitschrift fur Allergologie und Umweltmedizin : Organ der Deutschen Gesellschaft fur Allergie- und Immunitatsforschung, 21*, 103–107. URL https://www.pollenstiftung.de/fileadmin/user_upload/documents/Article_Allergo_Journal_2_2012.pdf.

Beutner, C., Werchan, B., Forkel, S., Gupta, S., Fuchs, T., Schoen, M. P., Geier, J., & Buhl, T. (2021). Sensitization rates to common inhaled allergens in germany - increase and change patterns over the last 20 years. *Journal der Deutschen Dermatologischen Gesellschaft = Journal of the German Society of Dermatology: JDDG, 19*, 37–44. https://doi.org/10.1111/ddg.14312

Buang, S., Maulan, S., Tahir, O., & Simangunsong, N. I. (2024). Trends in tree species selection for urban street planting: A thematic review. *Environment-Behaviour Proceedings Journal, 9*, 101–113. https://doi.org/10.21834/e-bpj.v9i30.6195

Calatayud, V., & Cariñanos, P. (2024). Mapping pollen allergenicity from urban trees in valencia: A tool for green infrastructure planning. *Environmental Research, 252*, Article 118823. https://doi.org/10.1016/j.envres.2024.118823

Cariñanos, P., Adinolfi, C., Díaz de la Guardia, C., De Linares, C., & Casares-Porcel, M. (2016). Characterization of allergen emission sources in urban areas. *Journal of Environmental Quality, 45*, 244–252. https://doi.org/10.2134/jeq2015.02.0075

Cariñanos, P., Casares-Porcel, M., Díaz de la Guardia, C., Aira, M. J., Belmonte, J., Boi, M., Elvira-Rendueles, B., De Linares, C., Fernández- Rodriguez, S., Maya-Manzano, J. M., Pérez-Badía, R., Rodriguez-de la Cruz, D., Rodríguez-Rajo, F. J., Rojo-Úbeda, J., Romero-Zarco, C., Sánchez-Reyes, E., Sánchez-Sánchez, J., Tormo-Molina, R., & Vega Maray, A. M. (2017). Assessing allergenicity in urban parks: A nature-based solution to reduce the impact on public health. *Environmental Research, 155*, 219–227. https://doi.org/10.1016/j.envres.2017.02.015

Cariñanos, P., Casares-Porcel, M., & Quesada-Rubio, J. M. (2014). Estimating the allergenic potential of urban green spaces: A case-study in granada, spain. *Landscape and Urban Planning, 123*, 134–144. https://doi.org/10.1016/j.landurbplan.2013.12.009

Cariñanos, Grilo, Pinho, Casares-Porcel, Branquinho, Acil, Andreucci, Anjos, Bianco, Brini, Calaza-Martínez, Calvo, Carrari, Castro, Chiesura, Correia, Gonçalves, Gonçalves, Mexia, Mirabile, Paoletti, Santos-Reis, & Semenzato, Vilhar (2019). Estimation of the allergenic potential of urban trees and urban parks: Towards the healthy design of urban green spaces of the future. *International Journal of Environmental Research and Public Health, 16*, 1357. https://doi.org/10.3390/ijerph16081357

Chmielewski, F. M., & Rötzer, T. (2001). Response of tree phenology to climate change across Europe. *Agricultural and Forest Meteorology, 108*, 101–112. https://doi.org/10.1016/S0168-1923(01)00233-7

Ciani, F., DellOlmo, L., Foggi, B., & Lippi, M. M. (2021). The effect of urban green areas on pollen concentrations at ground level: A study in the city of Forence (Italy). *Urban Forestry & Urban Greening, 60*, Article 127045. https://doi.org/10.1016/j.ufug.2021.127045

Coutts, C., & Hahn, M. (2015). Green infrastructure, ecosystem services, and human health. *International Journal of Environmental Research and Public Health, 12*, 9768–9798. https://doi.org/10.3390/ijerph120809768

Damialis, A., Gilles, S., Sofiev, M., Sofieva, V., Kolek, F., Bayr, D., Plaza, M. P., Leier-Wirtz, V., Kaschuba, S., Ziska, L. H., et al. (2021). Higher airborne pollen concentrations correlated with increased sars-cov-2 infection rates, as evidenced from 31 countries across the globe. *Proceedings of the National Academy of Sciences, 118*, Article e2019034118. https://doi.org/10.1073/pnas.2019034118

Damialis, A., Traidl-Hoffmann, C., & Treudler, R. (2019). Climate change and pollen allergies, in: Biodiversity and health in the face of climate change. *Springer International Publishing*, 47–66. https://doi.org/10.1007/978-3-030-02318-8

Devadas, R., Huete, A. R., Vicendese, D., Erbas, B., Beggs, P. J., Medek, D., Haberle, S. G., Newnham, R. M., Johnston, F. H., Jaggard, A. K., Campbell, B., Burton, P. K., Katelaris, C. H., Newbigin, E., Thibaudon, M., & Davies, J. M. (2018). Dynamic ecological observations from satellites inform aerobiology of allergenic grass pollen. *Science of The Total Environment, 633*, 441–451. https://doi.org/10.1016/j.scitotenv.2018.03.191

Dutang, C., Savicky, P., Chalabi, Y., Wuertz, D., Knuth, D., Matsumoto, M., Saito, M., & Dutang, M. C. (2024). Package randtoolbox. URL https://cran.r-project.org/web/packages/randtoolbox/randtoolbox.pdf.

DWD - Deutscher Wetterdienst, 2024. Wetter und Klima - Deutscher Wetterdienst - Augsburg. URL: https://www.dwd.de/DE/leistungen/klimadatendeutschland/mittelwerte/temp_9120_SV_html.html;jsessionid=66B3F2E0B3098E7A8A88FCA6E8597B94.live31083?view=nasPublication&nn=16102.

Eder, K., Gellrich, D., Meßmer, C., Canis, M., & Gröger, M. (2018). Component resolved analysis of ash pollen allergy in bavaria. Allergy. *Asthma & Clinical Immunology, 14*, 76. https://doi.org/10.1186/s13223-018-0291-4

Ekkel, E. D., & de Vries, S. (2017). Nearby green space and human health: Evaluating accessibility metrics. *Landscape and Urban Planning, 157*, 214–220. https://doi.org/10.1016/j.landurbplan.2016.06.008

Escobedo, F. J., Dobbs, C., Tovar, Y., & Cariñanos, P. (2023). Neotropical urban forest allergenicity and ecosystem disservices can affect vulnerable neighborhoods in bogota, colombia. *Sustainable Cities and Society, 89*, Article 104343. https://doi.org/10.1016/j.scs.2022.104343

Ewald, J. (2023). Fitschen-gehölzflora: Ein buch zum bestimmen der in mitteleuropa wild wachsenden und angepflanzten bäume und sträucher. 14., überarbeitete und erweiterte auflage. schmidt, p.a., schulz, b. & aas, g. (hrsg.). *Tuexenia, 43*, 391–392.

Fan, G., Yu, Y., Gao, M., Sharifi, A., Pathak, M., Zhang, K., de Arróyabe Hernáez, P.F., Deng, Q., 2025. One climate, one urban, one health. doi:10.1016/j.scs.2025.106619.

Fernández-Alvarado, J. F., & Fernández-Rodríguez, S. (2023). Environmental risk assessment based on the allergenicity of urban green infrastructure: Case study of an urban park. *Sustainable Cities and Society, 94*, Article 104532. https://doi.org/10.1016/j.scs.2023.104532

Gatrell, J. D., & Jensen, R. R. (2002). Growth through greening: Developing and assessing alternative economic development programmes. *Applied Geography, 22*, 331–350. https://doi.org/10.1016/S0143-6228(02)00049-8

GEO-NET Umweltconsulting GmbH., 2023. Stadtklimaanalyse Augsburg: Endbericht. Technical report. Stadt Augsburg, referat für Nachhaltigkeit, Umwelt, Klima und Gesundheit.

Ghasemifard, H., Ghada, W., Estrella, N., Lüpke, M., Oteros, J., Traidl-Hoffmann, C., Damialis, A., Buters, J., & Menzel, A. (2020). High post-season alnus pollen loads successfully identified as long-range transport of an alpine species. *Atmospheric Environment, 231*, Article 117453. https://doi.org/10.1016/j.atmosenv.2020.117453

Gilles, S., Blume, C., Wimmer, M., Damialis, A., Meulenbroek, L., Gökkaya, M., Bergougnan, C., Eisenbart, S., Sundell, N., Lindh, M., et al. (2020). Pollen exposure weakens innate defense against respiratory viruses. *Allergy, 75*, 576–587. https://doi.org/10.1111/all.14047

Gobiet, A., & Kotlarski, S. (2020). Future climate change in the european alps. *Oxford research encyclopedia of climate science*. Oxford University Press. https://doi.org/10.1093/acrefore/9780190228620.013.767

González-Naharro, R., Quirós, E., Fernández-Rodríguez, S., Silva-Palacios, I., Maya-Manzano, J. M., Tormo-Molina, R., Pecero-Casimiro, R., Monroy-Colin, A., & Gonzalo-Garijo, Á. (2019). Relationship of NDVI and oak (quercus) pollen including a predictive model in the SW mediterranean region. *Science of The Total Environment, 676*, 407–419. https://doi.org/10.1016/j.scitotenv.2019.04.213

Gurk, C., Hepp, C., 2024. Online-datenbank für bäume und sträucher. URL: https://www.baumkunde.de/. (in German) (last access 16.08.2025).

Hasan, R., Othman, N., & Ismail, F. (2017). Tree species selection in street planting: It's relationship with issues in urban area. *Environment- Behaviour Proceedings Journal, 2*, 185–194. https://doi.org/10.21834/e-bpj.v2i6.951. number: 6.

Helmreich, B., Deeb, M., Eben, P., Egerer, M., Kollmann, J., Schulz, S., Pauleit, S., Weisser, W. W., & Schloter, M. (2025). Converting infiltration swales to sustainable urban drainage systems can improve water management and biodiversity. *Frontiers in Environmental Science, 12*, Article 1524239. https://doi.org/10.3389/fenvs.2024.1524239. publisher: Frontiers.

Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., Nicolas, J., Peubey, C., Radu, R., Rozum, I., et al., 2023. Era5 hourly data on single levels from 1940 to present, copernicus climate change service (c3s) climate data store (cds)[data set].

Islam, A., Pattnaik, N., Moula, M. M., Rötzer, T., Pauleit, S., & Rahman, M. A. (2024). Impact of urban green spaces on air quality: A study of PM10 reduction across diverse climates. *Science of The Total Environment, 955*, Article 176770. https://doi.org/10.1016/j.scitotenv.2024.176770

Ives, C. D., Lentini, P. E., Threlfall, C. G., Ikin, K., Shanahan, D. F., Garrard, G. E., Bekessy, S. A., Fuller, R. A., Mumaw, L., Rayner, L., Rowe, R., Valentine, L. E., & Kendal, D. (2016). Cities are hotspots for threatened species. *Global Ecology and Biogeography, 25*, 117–126. https://doi.org/10.1111/geb.12404

Iwanycki Ahlstrand, N., Elvery, H. M., & Primack, R. B. (2023). Grass flowering times determined using herbarium specimens for modeling grass pollen under a warming climate. *Science of The Total Environment, 885*, Article 163824. https://doi.org/10.1016/j.scitotenv.2023.163824. URL https://www.sciencedirect.com/science/article/pii/S0048969723024452.

Jäger, E. J., & Werner, K. (2011). *Rothmaler-exkursionsflora von Deutschland*. Springer. URL https://link.springer.com/content/pdf/10.1007/978-3-662-49708-1.pdf.

Jia, N., Li, Y., Jiang, Z., Su, R., Lan, X., Zhang, K., Song, W., Zhao, R., Xia, Z., Song, Y., et al. (2025). Climate change, social environment, health, and urban inequality: Developing a novel adaptive evaluation framework. *Sustainable Cities and Society*. , Article 106443. https://doi.org/10.1016/j. scs.2025.106443

Jochner-Oette, S., Stitz, T., Jetschni, J., & Cariñanos, P. (2018). The influence of individual-specific plant parameters and species composition on the allergenic potential of urban green spaces. *Forests, 9*, 284. https://doi.org/10.3390/f9060284

Kasprzyk, I. (2011). *Time-series analysis of pollen seasons in Rzeszów (SE Poland) in 1997-2005 with reference to phenology*. Wydawnictwo Uniwersytetu Rzeszowskiego.

Katz, D. S., Robinson, G. S., Ellis, A., & Nowak, D. J. (2024). The effects of tree planting on allergenic pollen production in new york city. *Urban Forestry & Urban Greening, 92*, Article 128208. https://doi.org/10.1016/j.ufug.2024.128208

Katz, D. S. W., Morris, J. R., & Batterman, S. A. (2020). Pollen production for 13 urban north american tree species: Allometric equations for tree trunk diameter and crown area. *Aerobiologia, 36*, 401–415. https://doi.org/10.1007/s10453-020-09638-8

Kim, J., Lee, G., Park, S., & Kang, J. (2025). Mitigating urban heat island effects through leadership in energy and environmental design evaluation and blue-green infrastructure: Applying the hazard capacity factor design model for urban thermal resilience. *Sustainable Cities and Society, 124*, Article 106306. https://doi.org/10.1016/j.scs.2025.106306

Kolek, F., Plaza, M. P., Charalampopoulos, A., Traidl-Hoffmann, C., & Damialis, A. (2021). Biodiversity, abundance, seasonal and diurnal airborne pollen distribution patterns at two different heights in augsburg, germany. *Atmospheric Environment, 267*, Article 118774. https://doi.org/10.1016/j.atmosenv.2021.118774

Korning, J., & Balslev, H. (1994). Growth rates and mortality patterns of tropical lowland tree species and the relation to forest structure in amazonian ecuador. *Journal of Tropical Ecology, 10*, 151–166. https://doi.org/10.1017/S026646740000780X

Krwanji, D., Hopkins, A., Lemson, K., & Hanson, M. (2025). Interactive mapping of allergenic urban street trees in australia. *Urban Forestry & Urban Greening, 105*, Article 128718. https://doi.org/10.1016/j.ufug.2025.128718

Kuuluvainen, T., Mäki, J., Karjalainen, L., & Lehtonen, H. (2002). Tree age distributions in old-growth forest sites in vienansalo wilderness, eastern fennoscandia. *Silva Fennica, 36*. URL https://www.silvafennica.fi/article/556.

Legg, R., & Kabisch, N. (2024). The effects of allergenic pollen in green space on mental health, behaviour and perceptions: A systematic review. *Urban Forestry & Urban Greening, 92*, Article 128204. https://doi.org/10.1016/j.ufug.2024.128204

Li, L., Hao, D., Li, X., Chen, M., Zhou, Y., Jurgens, D., Asrar, G., & Sapkota, A. (2022). Satellite-based phenology products and in-situ pollen dynamics: A comparative assessment. *Environmental research, 204*, Article 111937.

Liu, W., Liu, K., Cai, J., Ma, S., Yang, M., Yang, Q., & Yuan, Y. (2023). Associations between residential greenness and asthma and allergic rhinitis in children: A systematic review and meta-analysis. *Sustainable Cities and Society, 94*, Article 104566. https://doi.org/10.1016/j.scs.2023.104566

Magyar, D., Páldy, A., Szigeti, T., & Orlóci, L. (2022). A regulation-oriented approach for allergenicity categorization of plants. *Urban Forestry & Urban Greening, 70*, Article 127530. https://doi.org/10.1016/j.ufug.2022.127530

Maimaitiyiming, M., Ghulam, A., Tiyip, T., Pla, F., Latorre-Carmona, P., Halik, Ü., Sawut, M., & Caetano, M. (2014). Effects of green space spatial pattern on land surface temperature: Implications for sustainable urban planning and climate change

adaptation. *ISPRS Journal of Photogrammetry and Remote Sensing, 89*, 59–66. https://doi.org/10.1016/j.isprsjprs.2013.12.010
Makra, L., Coviello, L., Gobbi, A., Jurman, G., Furlanello, C., Brunato, M., Ziska, L. H., Hess, J. J., Damialis, A., Plaza, M. P., et al. (2024). Forecasting daily total pollen concentrations on a global scale. *Allergy, 79*, 2173–2185. https://doi.org/10.1111/all.16227
McCarthy, J. W., & Weetman, G. (2006). *Age and size structure of gap-dynamic, old-growth boreal forest stands in newfoundland*. Silva Fennica. URL http://www.metla.fi/silvafennica/full/sf40/sf402209.pdf.
More, D., & White, J. (2005). *Die kosmos-enzyklopädie der bäume: 2100 arten und sorten*. Kosmos.
Motta, A. C., Marliere, M., Peltre, G., Sterenberg, P. A., & Lacroix, G. (2006). Traffic-related air pollutants induce the release of allergen- containing cytoplasmic granules from grass pollen. *International Archives of Allergy and Immunology, 139*, 294–298. https://doi.org/10.1159/000091600
Myszkowska, D., Bogawski, P., Piotrowicz, K., Bosiacka, B., Grinn-Gofro, A., Berger, U. E., Bonini, M., Ceriotti, V., Charalampopoulos, A., Galán, C., Gedda, B., Ianovici, N., Kloster, M., Oliver, G., Pashley, C. H., Pätsi, S., Pérez-Badia, R., Puc, M., Rodinkova, V., Skjøth, C. A., Thibaudon, M., Vokou, D., & Damialis, A. (2023). Co-exposure to highly allergenic airborne pollen and fungal spores in europe. *Science of The Total Environment, 905*, Article 167285. https://doi.org/10.1016/j.scitotenv.2023.167285
Nilsson, S., & Persson, S. (1981). Tree pollen spectra in the stockholm region (sweden), 1973–1980. *Grana, 20*, 179–182.
Niu, Z., Zhang, L., Zhang, X., Lu, C., Wang, T., Zheng, X., Norback, D., Wang, J., Xu, Y., Wei, J., et al. (2025). Association between air temperature exposure and childhood rhinitis risk, and the mediating role of ambient o3: A multi-city study of 40,103 chinese preschool children. *Sustainable Cities and Society, 119*, Article 106122. https://doi.org/10.1016/j.scs.2024.106122
Nowak, D. J., Hirabayashi, S., Doyle, M., McGovern, M., & Pasher, J. (2018). Air pollution removal by urban forests in canada and its effect on air quality and human health. *Urban Forestry & Urban Greening, 29*, 40–48. https://doi.org/10.1016/j.ufug.2017.10.019
Nowak, D. J., & Ogren, T. L. (2021). Variations in urban forest allergy potential among cities and land uses. *Urban Forestry & Urban Greening, 63*, Article 127224. https://doi.org/10.1016/j.ufug.2021.127224
Ogren, T. L. (2000). Allergy-free gardening: The revolutionary guide to healthy landscaping. *Electronic Green Journal, 1*. https://doi.org/10.5070/G311310411. publisher: Ten Speed Press Berkeley, CA.
Oh, J. W. (2022). Pollen allergy in a changing planetary environment. *Allergy, asthma & immunology research, 14*, 168. https://doi.org/10.4168/aair. 2022.14.2.168
Organization, W.H., for Europe, R.O., 2016. Urban green spaces and health. URL: https://iris.who.int/handle/10665/345751.
Otero-Durán, L., & Torres, A. (2024). Trees and sidewalks: Toward an infrastructure protection approach. *Frontiers in Sustainable Cities, 6*. https://doi.org/10.3389/frsc.2024.1336472. publisher: Frontiers.
Parmes, E., Pesce, G., Sabel, C. E., Baldacci, S., Bono, R., Brescianini, S., D'Ippolito, C., Hanke, W., Horvat, M., Liedes, H., Maio, S., Marchetti, P., Marcon, A., Medda, E., Molinier, M., Panunzi, S., Pärkkä, J., Polaska, K., Prud'homme, J., Ricci, P., Tratnik, J. S., Squillacioti, G., Stazi, M. A., Maesano, C. N., & Annesi-Maesano, I. (2020). Influence of residential land cover on childhood allergic and respiratory symptoms and diseases: Evidence from 9 european cohorts. *Environmental Research, 183*, Article 108953. https://doi.org/10.1016/j.envres.2019.108953
Pattnaik, N., Honold, M., Franceschi, E., Moser-Reischl, A., Rötzer, T., Pretzsch, H., Pauleit, S., & Rahman, M. A. (2024). Growth and cooling potential of urban trees across different levels of imperviousness. *Journal of Environmental Management, 361*, Article 121242. https://doi.org/10.1016/j. jenvman.2024.121242
Pecero-Casimiro, R., Fernández-Rodríguez, S., Tormo-Molina, R., Monroy-Colin, A., Silva-Palacios, I., Cortes-Perez, J. P., Gonzalo-Garijo, Á., & Maya-Manzano, J. M. (2019). Urban aerobiological risk mapping of ornamental trees using a new index based on LiDAR and kriging: A case study of plane trees. *Science of the Total Environment, 693*, Article 133576. https://doi.org/10.1016/j.scitotenv.2019.07.382
Picornell, A., Hurtado, S., Antequera-Gómez, M. L., Barba-González, C., Ruiz-Mata, R., de Gálvez-Montañez, E., Recio, M., del Mar Trigo, M., Aldana-Montes, J. F., & Navas-Delgado, I. (2024). A deep learning lstm-based approach for forecasting annual pollen curves: Olea and urticaceae pollen types as a case study. *Computers in Biology and Medicine, 168*, Article 107706. https://doi.org/10.1016/j.compbiomed.2023.107706
Pretzsch, H., Biber, P., Uhl, E., Dahlhausen, J., Rötzer, T., Caldentey, J., Koike, T., van Con, T., Chavanne, A., Seifert, T., Toit, B.d., Farnden, C., & Pauleit, S. (2015). Crown size and growing space requirement of common tree species in urban centres, parks, and forests. *Urban Forestry & Urban Greening, 14*, 466–479. https://doi.org/10.1016/j.ufug.2015.04.006
Puga-Bonilla, M., Hidalgo-Garcia, D., Rezapouraghdam, H., & Bolivar, F. J. L. (2025). Risk of mortality and disease attributable to the heat stress index and its variability during heat waves: An observational study on the city of madrid. *Sustainable Cities and Society, 121*, Article 106189. https://doi.org/10.1016/j.scs.2025.106189
Pujol, G., Iooss, B., Iooss, M.B., DiceDesign, S., 2015. Package sensitivity. URL: https://cran.r-project.org/web/packages/sensitivity/sensitivity.pdf.
R Core Team. (2021). *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing. URL https://www.R-project.org/.
Ranpal, S., von Bargen, S., Gilles, S., Luschkova, D., Landgraf, M., Bogawski, P., Traidl-Hoffmann, C., Büttner, C., Damialis, A., Fritsch, M., & Jochner-Oette, S. (2024). Continental-scale evaluation of downy birch pollen production: Estimating the impacts of global change. *Environmental Research, 252*, Article 119114. https://doi.org/10.1016/j.envres.2024.119114
Rauer, D., Gilles, S., Wimmer, M., Frank, U., Mueller, C., Musiol, S., Vafadari, B., Aglas, L., Ferreira, F., Schmitt-Kopplin, P., et al. (2021). Ragweed plants grown under elevated co2 levels produce pollen which elicit stronger allergic lung inflammation. *Allergy, 76*, 1718–1730. https://doi.org/10.1111/all.14618
Redlands, C.E.S.R.I., 2011. Arcgis desktop: Release 10.
Ring, J. (2012). Davos declaration: Allergy as a global problem. *Allergy, 67*. https://doi.org/10.1111/j.1398-9995.2011.02770.x
Rojo, J., Oteros, J., Picornell, A., Maya-Manzano, J. M., Damialis, A., Zink, K., Werchan, M., Werchan, B., Smith, M., Menzel, A., et al. (2021). Effects of future climate change on birch abundance and their pollen load. *Global Change Biology, 27*, 5934–5949. https://doi.org/10.1111/gcb.15824
Rojo, J., Picornell, A., & Oteros, J. (2019). Aerobiology: The computational tool for biological data in the air. *Methods in Ecology and Evolution, 10*, 1371–1376. https://doi.org/10.1111/2041-210X.13203
RStudio Team. (2020). *RStudio: Integrated development environment for R. RStudio*. Boston, MA: PBC. URL http://www.rstudio.com/.
Sabariego, S., García-Ventura, C., & Cariñanos, P. (2021). Estimating the allergenic potential of urban green areas in the city of madrid (spain). *Aerobiologia, 37*, 561–573. https://doi.org/10.1007/s10453-021-09705-8
Schramm, P. J., Brown, C., Saha, S., Conlon, K., Manangan, A., Bell, J., & Hess, J. (2021). A systematic review of the effects of temperature and precipitation on pollen concentrations and season timing, and implications for human health. *International journal of biometeorology, 65*, 1615–1628.
Schroeder, H. W. (2011). Does beauty still matter? Experiential and utilitarian values of urban trees. In *Trees, people and the built environment. Proceedings of the Urban Trees Research Conference* (pp. 159–165). Institute of Chartered Foresters. URL https://research.fs.usda.gov/treesearch/41349.
Service, C.C.C., 2018. Climate data store: Carbon dioxide data from 2002 to present derived from satellite observations. URL: https://cds.climate.copernicus.eu, doi:10.24381/cds.f74805c8. accessed on 29-03-2025.
Simunovic, M., Boyle, J., Erbas, B., Baker, P., & Davies, J. M. (2023). Airborne grass pollen and thunderstorms influence emergency department asthma presentations in a subtropical climate. *Environmental Research, 236*, Article 116754. https://doi.org/10.1016/j.envres.2023.116754
Sjöman, H., östberg, J., & Bühler, O. (2012). Diversity and distribution of the urban tree population in ten major nordic cities. *Urban Forestry & Urban Greening, 11*, 31–39. https://doi.org/10.1016/j.ufug.2011.09.004
Stadt Augsburg Geodatenamt, Amt für Grünordnung, Naturschutz und Friedhofswesen, n.d. Baumkataster aus den digitalen kartenwerken des geodatenamtes augsburgs und des amtes für grünordnung, naturschutz und friedhoswesen. URL: https://www.augsburg.de/umwelt-soziales/umwelt/stadtgruen/baeume-schuetzen/digitales-baumkataster.
Stas, M., Aerts, R., Hendrickx, M., Dendoncker, N., Dujardin, S., Linard, C., Nawrot, T. S., Van Nieuwenhuyse, A., Aerts, J. M., Van Orshoven, J., & Somers, B. (2021). Residential green space types, allergy symptoms and mental health in a cohort of tree pollen allergy patients. *Landscape and Urban Planning, 210*, Article 104070. https://doi.org/10.1016/j.landurbplan.2021.104070
Suanno, C., Aloisi, I., Parrotta, L., Fernández-González, D., & Del Duca, S. (2021). Allergenic risk assessment of urban parks: Towards a standard index. *Environmental Research, 200*, Article 111436. https://doi.org/10.1016/j.envres.2021.111436
Traidl-Hoffmann, C., Afghani, J., Akdis, C. A., Akdis, M., Aydin, H., Bärenfaller, K., Behrendt, H., Bieber, T., Bigliardi, P., Bigliardi-Qi, M., et al. (2024). Navigating the evolving landscape of atopic dermatitis: Challenges and future opportunities: The 4th davos declaration. *Allergy, 79*, 2605–2624. https://doi.org/10.1111/all.16247
Traidl-Hoffmann, C., & Trippel, K. (2021). *Überhitzt: Die folgen des klimawandels für unsere gesundheit. Was wir tun können*. Duden.
Ugle, P., Rao, S., & Ramachandra, T. (2010). Carbon sequestration potential of urban trees. *Proceedings of the Lake, 22*. URL https://www.researchgate.net/profile/Prachi-Ugle-Pimpalkhute/publication/318471008_Carbon_Sequestration_Potential_of_Urban_Trees/links/596d10bfa6fdcc03edb6c28c/Carbon-Sequestration-Potential-of-Urban-Trees.pdf?ref=sparrow.
UN-Habitat, 2024. World cities report 2024: Cities and climate action. URL: https://unhabitat.org/sites/default/files/2024/11/wcr2024_-_full_report.pdf. accessed: 24 March 2025.
United Nations, 2024. World population prospects 2024: Summary of results. URL: https://www.unpopulation.org. accessed: 25 March 2025.
Velasco-Jiménez, M. J., Alcázar, P., Cariñanos, P., & Galán, C. (2020). Allergenicity of the urban green areas in the city of córdoba (spain). *Urban Forestry & Urban Greening, 49*, Article 126600. https://doi.org/10.1016/j.ufug.2020.126600
Vicentic, S., Kanjevac, B., Petrovic, J., Krstic, M., Babic, V., & Stavretovic, N. (2017). Analysis of dendroflora on the green areas of some kindergartens in belgrade (serbia). *Agriculture and Forestry, 63*. https://doi.org/10.17707/AgricultForest.63.2.12
WBGU, 2024. Water in a heated world. URL: https://www.wbgu.de/en/publications/publication/water.
Werchan, M., Werchan, B., Bogawski, P., Mousavi, F., Metz, M., & Bergmann, K. C. (2024). An emerging aeroallergen in europe: Tree-of-heaven (ailanthus altissima [mill.] swingle) inventory and pollen concentrations–taking a metropolitan region in germany as an example. *Science of The Total Environment, 930*, Article 172519. https://doi.org/10.1016/j.scitotenv.2024.172519
Xian, X., Zhao, H., Wang, R., Huang, H., Chen, B., Zhang, G., Liu, W., & Wan, F. (2023). Climate change has increased the global threats posed by three ragweeds (ambrosia l.) in the anthropocene. *Science of The Total Environment, 859*, Article 160252. https://doi.org/10.1016/j.scitotenv.2022.160252

Yang, J., Chang, Y., & Yan, P. (2015). Ranking the suitability of common urban tree species for controlling PM2.5 pollution. *Atmospheric Pollution Research, 6*, 267–277. https://doi.org/10.5094/APR.2015.031

Zahradníková, E., Rendeková, A., & Ščevková, J. (2024). Temporal variation of allergenic potential in urban parks during the vegetation period: A case study from bratislava, slovakia. *Environmental Science and Pollution Research, 31*, 2026–2041. https://doi.org/10.1007/s11356-023-31137-9

Zhang, Y., & Steiner, A. L. (2022). Projected climate-driven changes in pollen emission season length and magnitude over the continental united states. *Nature Communications, 13*, 1234. https://doi.org/10.1038/s41467-022-28764-0

Zong, H., Yao, M., Tang, Y., & Chen, H. (2020). Assessing the composition, diversity, and allergenic risk of street trees in qingyang district of chengdu city. *Urban Forestry & Urban Greening, 54*, Article 126747. https://doi.org/10.1016/j.ufug.2020.126747