Environmental Research 252 (2024) 118823

Contents lists available at ScienceDirect

Environmental Research

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

Mapping pollen allergenicity from urban trees in Valencia: A tool for green infrastructure planning

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A R T I C L E I N F O

Keywords:
Allergenic pollen emission
Allergenic urban trees
Hot spot analysis
Ecosystem disservices
Value of potential allergenicity (VPA)

A B S T R A C T

Urban trees provide many benefits to citizens but also have associated disservices such as pollen allergenicity. Pollen allergies affect 40% of the European population, a problem that will be exacerbated with climate change by lengthening the pollen season. The allergenic characteristics of the urban trees and urban parks of the city of Valencia (Spain) have been studied. The Value of Potential Allergenicity (VPA) was calculated for all species. The most abundant allergenic trees with a very high VPA were the cypresses, followed by *Platanus x hispanica* and species of genera *Morus*, *Acer* and *Fraxinus*, with a high VPA. On the contrary, *Citrus x aurantium*, *Melia azedarach*, *Washingtonia* spp., *Brachychiton* spp. and *Jacaranda mimosifolia* were among the most abundant low allergenic trees. VPA was mapped for the city and a hot spot analysis was applied to identify areas of clustering of high and low VPA values. This geostatistical analysis provides a comprehensive representation of the VPA patterns which is very useful for urban green infrastructure planning. The Index of Urban Green Zone Allergenicity (I_{UGZA}) was calculated for the main parks of the city. The subtropical and tropical flora component included many entomophilous species and the lowest share of high and very high allergenic trees in comparison with the Mediterranean and Temperate components. Overall, a diversification of tree species avoiding clusters of high VPA trees, and the prioritization of species with low VPA are good strategies to minimize allergy-related impacts of urban trees on human health.

1. Introduction

Cities cover only 2% of the planet's surface but their inhabitants use 75% of the natural resources. By 2050, 68% of the population will live in urban areas (United Nations, 2019). Urban green areas (UGAs) provide many benefits to city inhabitants. These areas sustain biodiversity, provide spaces for social interaction and leisure, improve physical and mental health of the users, and may even provide food (Pearlmutter et al., 2017). Trees remove air pollution and buffer noise, sequester carbon and mitigate climate change, attenuate the heat island effect by shadowing and through transpiration (therefore reducing energy consumption in climatization of buildings), and also avoid water runoff, reducing flooding (McDonald et al., 2016; Pearlmutter et al., 2017). Parts of these benefits can be quantified (e.g., tons of pollutants removed and associated avoided economic costs), while the impacts on well-being are more intangible (Nowak, 2021; Song et al., 2020; Pearlmutter et al., 2017). Now the importance of the UGAs and street trees in the cities is widely recognized and the rule of thumb of 3-30-300 has been recently proposed: 3 well-established trees in view from every home, school, and place of work, no less than a 30% tree canopy in every neighborhood, and no more than 300 m to the nearest public green space from every residence (Konijnendijk, 2021, 2023).

However, despite the above-mentioned unquestionable benefits, urban trees have also associated disservices, i.e., harmful effects to human health. Two of the most important are the emission of biogenic volatile organic compounds (bVOCs) and the pollen emission. bVOCs such as the isoprene are released by vegetation and contribute to the formation of ozone and other secondary pollutants, which are harmful to human health (Calfapietra et al., 2013; Sicard et al., 2022; Yuan et al., 2023). The pollen emissions from some plant species cause allergic reactions in sensitive population (Cariñanos et al., 2011; 2021). Furthermore, pollen contributes to the particulate matter (PM) component of air pollution and, when combined with air pollutants as it is the typical case of cities, its negative effects are exacerbated (Cariñanos et al., 2016;

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https://doi.org/10.1016/j.envres.2024.118823
Received 2 February 2024; Received in revised form 15 March 2024; Accepted 27 March 2024
Available online 1 April 2024

D'Amato et al., 2007; Candeias et al., 2022). In Europe, the prevalence of pollen allergy in the general population is estimated to be as high as 40% (D'Amato et al., 2007), with an economic burden of 151 billion EUR (Zuberbier et al., 2014). The magnitude of this problem is expected to increase with climate change (Lake et al., 2017; Ziska et al., 2019).

So far, cities have not considered systematically the allergenic potential of plants when selecting them for the urban green. Selection is usually based on other criteria such as their resilience and adaptability to local conditions, ease of maintenance and growth, availability in local nurseries, aesthetic values or, more recently, even their capacity to cope and mitigate air pollution, carbon fixation potential and bVOC emissions (Nowak et al., 2013; Palau Garrabou et al., 2015; Chaparro and Terradas, 2009). However, given the strong impact on human health of pollen allergies and the fact that a large part of the world population is currently living in urban areas, the inclusion of the allergenicity traits of urban vegetation should be a major issue in the urban green planning in order to limit allergenic pollen exposure to citizens and to ensure a healthy urban environment (Cariñanos and Casares-Porcel, 2011; Cariñanos et al., 2014; Sousa-Silva et al., 2021).

The allergenic potential of urban trees has been compiled in different allergenicity datasets with contrasting results in different regions of the world for some of the species, i.e. species highly allergenic in an area can be less allergenic in other areas (Sousa-Silva et al., 2021). The development of a Value of Potential Allergenicity (VPA) index has been recognized as an important step into pinpointing the potential allergenic risk that the presence of certain tree species can pose for allergic people (Sousa-Silva et al., 2021), given that this integrative index takes into account not only the allergenic potential, but also the pollen emission and the duration of the pollination period of each plant (Cariñanos et al., 2014; Cariñanos and Marinangeli, 2021). The VPA in combination with georeferenced urban tree inventories is a potentially optimal and easy-to-apply tool to represent the spatial distribution of allergenicity risks from local (streets, district, parks) to a city scale. However, only a few previous studies have provided so far maps of allergenicity risk based on the VPA (Tang et al., 2022; Escobedo et al., 2023). Furthermore, none of these studies has applied geostatistical tools such as the hot spot analysis (ESRI, 2011) with the aim of providing a detailed and statistically supported picture of the spatial clustering of high and low VPA for a target city.

Complementarily to VPA, the Index of Urban Green Zone Allergenicity (I_{UGZA}) has been proposed to estimate the potential allergenic risk of urban green areas, typically characterizing parks and gardens (Cariñanos et al., 2014). Its calculation takes into account the VPA of the species present in the green zone but also biometric parameters of the trees such as the tree heigh at maturity and the cover of each species within the green zone, as well as the surface of the green zone. Thus, this is an area-related index that provides values for the different green areas that are comparable. Although a comparative analysis of the I_{UGZA} of parks in different cities has been provided before for 23 Mediterranean cities (Cariñanos et al., 2019), so far it has not been applied to the main parks of a single city. When estimating the allergenic risk of the urban trees in a city, both the mapping approach and the calculation of the I_{UGZA} provide relevant complementary information.

In the present study, a hot spot analysis of VPA is applied for the first time in a city to characterize allergenicity risk, representing a practical example in support of a healthier green urban planning that can be easily applied to other cities. The city of Valencia has been chosen for this purpose. It is a coastal city characterized by a Mediterranean climate with mild winters and rare frost events. This makes the city very suitable for planting, besides Temperate and Mediterranean trees as in other cities of Spain, a wide range of tropical and subtropical species (from now on (Sub-)Tropical). For this reason, Valencia is an optimal city to conduct a study of the allergenic risk of urban trees, and results of the present study are expected to provide useful information not only for many other Mediterranean cities, but also, to some extent, for tropical and subtropical urban areas.

The main objectives of the present study are: 1) To calculate the VPA for all tree species in Valencia, also taking into account the biogeographic distribution of the trees; 2) To use geostatistical tools to identify hot spot areas of allergenic species for the first time, using the VPA index; 3) To calculate the I_{UGZA} for the main parks and gardens of Valencia and its possible relationship with their typology.

The ultimate objective of the study is to provide recommendations for the selection of the most appropriate urban tree species in Mediterranean cities in order to minimize pollen allergy problems for citizens.

2. Materials and methods

2.1. Tree datasets

A dataset of 145,222 georeferenced tree species was used for the city of Valencia. Data were provided by the Valencian Municipality (downloaded on September 06, 2023) and, for its University campus, by the Polytechnic University of Valencia. This dataset mainly included the coordinates and scientific names of the species. Most of Valencia's urban trees were included in this dataset, as private gardens with trees are rare in this compact city. Admittedly, gardens or street trees in recently developed areas, as well as in the Botanical Garden, Park Central and a small part of the Jardí del Túria park, are not included in the municipal database yet, but the proportion of missing trees is small in the context of the whole city (<7%). As in this database the treatment of the taxa was not fully consistent (e.g., some taxa reported to variety level but not others, presence of synonym taxa or currently non-accepted names), all taxa were assigned to an accepted species following the Plants of the World Online of Kew Royal Botanical Gardens Database (https://powo.science.kew.org/). For simplicity, the authors of plant names are not reported here, but they can also be consulted in the Kew database. Each species was also assigned to a genus, family, order, and class, and was classified into evergreen or deciduous. The database was completed with the species distribution: mostly Temperate, (Sub-)Tropical or Mediterranean, also using the Kew Database.

2.2. Calculation of the Value of Potential Allergenicity (VPA)

The Value of Potential Allergenicity (VPA) of each species is determined based on a series of biological attributes: pollination strategy (Table S1), duration of the main pollination period, and intrinsic allergenic potency of pollen grains due to the presence of allergenic molecules (Cariñanos and Marinangeli, 2021). The product of these three parameters generates a specific Value of Potential Allergenic (VPA) of each species, which ranges between 0 and 36 (Cariñanos and Marinangeli, 2021) (Table S1). Based on the VPA values, 5 allergenicity classes have been defined (Cariñanos et al., 2014; Cariñanos and Marinangeli, 2021): Null (VPA 0), Low (VPA 1–6), Moderate (VPA 8–12), High (VPA 16–24), or Very High (VPA 27–36).

In the municipal tree inventory, a few species were dioecious, i.e., with male and female individuals, the latter not emitting pollen (thus, with VPA = 0). A VPA = 0 could be assigned to female palm tree individuals, as for these species the sex was included in the inventory. All *Gingko* trees were classified as males, as in the city female individuals are avoided due to the bad smell of their seeds (Valencia Gardening Service, com. pers.). Unfortunately, for individuals of the genera *Morus*, *Populus*, *Salix* and *Fraxinus* no information on the sex was available (Valencia Gardening Service, com. pers.), and all trees have been considered as potential pollen emitters.

2.3. Spatial distribution of the Value of Potential Allergenicity

Based on the georeferenced catalogue of tree species of the city of Valencia, a VPA value was assigned to each individual and the distribution of the VPA classes throughout the city was represented using ArcGIS Desktop Release 10.8.2 (Redlands, CA: Environmental Systems

Research Institute). Subsequently, an Optimized Hot Spot Analysis was also conducted with the same software package, considering the VPA values of each feature (tree) as the analysis field and using a distance band of 300 m around each tree (ESRI, 2024). This type of hot spot analysis is based on the Getis-Ord Gi* algorithm, the application of which provides a map of *z*-score values and their associated *p*-values. These *z*-score values represent a measure of the clustering of high (hot spots) and low values (cold spots) (ESRI, 2024). A map of the number of neighbours for each tree within the selected distance band is also provided as an output. The distance band determines which features are analysed together in order to assess local clustering. A distance band of 300 m was selected because, using this distance, the resulting hot spot patterns were easily interpretable at city level, and it is also a threshold value when assessing accessibility for people's residence to green spaces (World Health Organization, 2016; Annerstedt van den Bosch et al., 2016). For clarity, results of the hot spot analysis were subsequently interpolated using the Inverse Distance Weighted method to produce the city maps (ESRI, 2011).

2.4. Index of Urban Green Zone Allergenicity (I_{UGZA}) and park characteristics

The Index of Urban Green Zone Allergenicity (I_{UGZA}) estimates the potential allergenic risk of urban green areas. This index, which varies between 0 and 1, is calculated with the following formula (Cariñanos et al., 2014, 2019):

$$I_{UGZA} = \frac{1}{maxVPA \text{ x } S_T \text{ x } \overline{H}_i} \sum_{i=1}^{k} VPA \text{ x } S_i \text{ x } H_i$$

Where, for each of the *k* species in the park, VPA is the Value of Potential Allergenicity, S_i is the projected area covered by all trees of the species and H_i is the maximum height of a mature tree of that species. maxVPA is the maximum VPA reached in the park, S_T is the surface of the urban park, and $\overline{H}_i$ is the average of the H_i values of all trees in the park. For each species, H_i, was mainly obtained from iTree database (https://www.itreetools.org/) or, if not available, from a random sampling of >600 tree heights (as well as crown width and other parameters needed to apply iTree) carried out in 2023 in the city of Valencia (unpublished data), or from diverse online sources on forestry and urban green. A limit of 25 m for H_i was established as urban trees in the city of Valencia rarely exceed such tree height (<0.2% of the trees in the mentioned random sampling). The crown width was calculated from regressions between these mature tree heights (H_i) and the crown width, based on allometric and crown architecture data of the TALLO database (at species level if available, Jucker et al., 2022; if not, at genus level), but also from the above-mentioned sampling.

Complementarily, parks were classified according to their typology. Their area, density of trees, number of species and the Shannon Index of Diversity (Bittinger, 2020) were also calculated.

3. Results

3.1. Tree composition of the urban forest of Valencia

The city hosted 145,222 trees, with a high diversity of palms and tree species (302 different species, including hybrids), belonging to a wide range of genera (141) and families (65), overall representing 5 taxonomical classes. The most abundant tree in the city was the bitter orange (*Citrus x aurantium*, with 11,832 individuals), followed by the London plane (*Platanus x hispanica*, 10,591 individuals), the Chinaberry tree (*Melia azedarach*, 7795 individuals), the Mediterranean hackberry (*Celtis australis,* 7166 individuals) and two palm trees, the Mexican fan palm (*Washingtonia robusta*, 6195 individuals) and the date palm (*Phoenix dactilyfera*, 5921 individuals) (Table 1). The white mulberry (*Morus alba*, 5173 individuals), the Jacaranda (*Jacaranda mimosifolia*, 5084 individuals), the ash-leafed maple (*Acer negundo*, 4756 individuals), the Kurrajong (*Brachychiton populneus*, 5433 individuals), and the Mediterranean cypress (*Cupressus sempervirens*, 3937 individuals) were also among the most abundant species (Table 1). If the distribution in genera is analysed (Fig. 1), the most represented genus was *Citrus*, (12,687 trees, 9%), *Platanus* (10,660 tree, 7%), palm trees of the genera *Phoenix* (8567 trees, 6%) and *Washingtonia* (7597 trees, 5%), *Melia* (7795 trees, 5%), and *Celtis*, *Morus*, *Ligustrum*, *Pinus* and *Acer*, with 7555 (5%), 6157 (4%), 5988 (4%), 5859 trees (4%) and 5789 (4%), respectively. The percentage of tree individuals in the other genera was ≤4%. Further information on the diversity of families and classes is presented in Fig. S1.

Regarding the biogeographic distribution of the tree species, the flora of the city had a similar share of Temperate and (Sub-)Tropical trees (59,595 and 65,491 individuals, 41% and 45% of the total trees, respectively), and less trees had a distribution centred in the Mediterranean area (20,136 individuals, 14% of the total). While among species with a Temperate distribution the deciduous leaf traits dominated, the opposite was true for (Sub-)Tropical species, and a more similar share

Table 1
List of tree species with more than 1000 individuals in the city of Valencia.

Species	Common name	Number of trees
Citrus x aurantium	Bitter orange	11,832
Platanus x hispanica	London plane	10,591
Melia azedarach	Chinaberry tree	7795
Celtis australis	Mediterranean hackberry	7166
Washingtonia robusta	Mexican fan palm	6195
Phoenix dactylifera	Date palm	5921
Ligustrum japonicum	Japanese privet	5273
Morus alba	White mulberry	5173
Jacaranda mimosifolia	Jacaranda	5084
Acer negundo	Ash-leafed maple	4756
Brachychiton populneus	Kurrajong	4533
Cupressus sempervirens	Mediterranean cypress	3937
Cercis siliquastrum	Judas tree	3756
Tipuana tipu	Tipu	2849
Styphnolobium japonicum	Japanese pagoda tree	2589
Pinus pinea	Stone pine	2531
Phoenix canariensis	Canary Island date palm	2515
Pinus halepensis	Aleppo pine	2504
Prunus cerasifera	Cherry plum	2431
Ficus benjamina	Weeping fig	1909
Grevillea robusta	Silk oak	1834
Chamaerops humilis	Mediterranean fan palm	1469
Robinia pseudoacacia	Black locust	1450
Washingtonia filifera	California fan palm	1402
Ulmus pumila	Siberian elm	1370
Populus alba	White poplar	1294
Quercus ilex	Holm oak	1249
Olea europaea	Olive	1245
Fraxinus ornus	Manna ash	1206
Trachycarpus fortunei	Windmill palm	1063

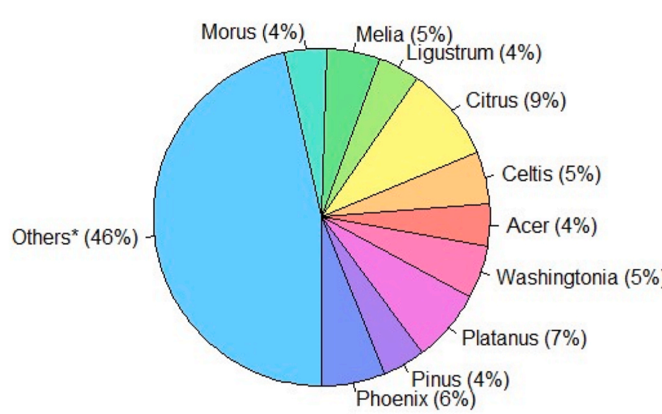

Fig. 1. Percentage of individual trees per genus in the city of Valencia in 2023.

was observed for Mediterranean species (Table 2). Among the most important Temperate species in terms of number of individuals, *Platanus x hispanica*, *Acer negundo*, *Ligustrum japonicum* or *Morus alba* can be cited. The (Sub-)Tropical group was well represented, including abundant species such as *Citrus x aurantium*, *Melia azedarach*, *Jacaranda mimosifolia*, *Phoenix* spp., *Brachychiton* spp., or *Ficus* spp. Characteristic trees of the Mediterranean component are *Celtis australis*, *Quercus ilex*, *Chamaerops humilis*, *Fraxinus ornus* or *Ceratonia siliqua*, among others.

Overall, the tree flora of Valencia city was characterized by a relatively high diversity of species, with an important (Sub-)Tropical component, and a similar share between deciduous and evergreen plants (Table 2).

3.2. Urban forest composition based on the Value of Potential Allergenicity of tree species

All tree species present in the city were classified according to their Value of Potential Allergenicity (VPA) (Table S1). In the city, few trees were classified in the category of not allergenic (2244 individuals, 2%, VPA = 0), the majority exhibited low VPA (70,429 individuals, 48%, VPA = 1–6), and 32,653 (22%, VPA = 8–12), 33,428 (23%, VPA = 16–24) and 6468 tree individuals (4%, VPA = 27–36) presented moderate, high and very high VPA, respectively (Fig. 2).

Three uncommon species in the city showed no potential allergenicity, *Chitalpa tashkentensis*, *Cydonia oblonga*, and *Dracaena draco*, as well as female individuals of palm trees (Fig. 3). Some of the most planted trees in the city, belonging to the genera *Citrus* (mainly *Citrus x aurantium*), *Melia*, *Washingtona, Brachychiton*, *Jacaranda*, *Cercis*, *Tipuana, Ficus*, *Prunus* or *Tilia* had low VPA (Fig. 3). Palm trees of genus *Phoenix*, had a moderate VPA, a class also shared by trees belonging to the genera *Celtis*, *Ligustrum* and *Pinus* (mainly *P. halepenis* and *P. pinea*) (Fig. 3). The genera including more individuals with a high VPA were *Platanus* (mainly *Platanus x hispanica*), *Morus*, *Acer*, *Fraxinus*, *Populus*, *Ulmus*, *Quercus* and *Olea*. Finally, the most abundant species with a very high VPA were those of genus *Cupressus*, but this VPA class included other species of the *Cupresaceae* such as *Juniperus* spp. or *Thuja* spp.; *Casuariana equisetifolia* and *Morus nigra* also belong here. In general, the species of the same genus tended to have similar VPA, although this was not always the case (Table S1). For example, *Fraxinus excelsior* and *F. pennsylvanica* are more allergenic than the other species of the genus because they are anemophilous, therefore releasing larger amounts of pollen. The same holds true for *Acer negundo* (VPA class high), in comparison with other congeneric species (VPA class moderate), and *Morus nigra* (VPA class very high) is more allergenic than *Morus alba* (VPA class high) (Table S1).

The percentage of species belonging to each of the five VPA classes was also analysed considering their biogeographic distributions (i.e., (Sub-)Tropical, Mediterranean, and Temperate) (Fig. 4). Interestingly, for species with a (Sub-)Tropical distribution, only 12% of them showed "High" or "Very High" VPA. Comparatively, the percentage of species with such high or very high allergenicity was much higher in Mediterranean species (30%) and specially in Temperate species (35%). Consistently, 71% of the (Sub-)Tropical species were characterized by a Low or Null VPA class, in comparison with a 39% in Mediterranean species and 46% in Temperate species. Part of these differences in VPA are related to the pollination strategy, which contributes to the VPA calculation. In the city, 50% of the tree species were entomophilous,

Table 2
Number of trees and their percentage in classes according to their distribution and leaf traits.

	Temperate	(Sub-)Tropical	Mediterranean	*Total*
Deciduous	46,239 (32%)	20,068 (14%)	8724 (6%)	*75,031 (52%)*
Evergreen	13,356 (9%)	45,423 (31%)	11,412 (8%)	*70,191 (48%)*
Total	*59,595 (41%)*	*65,491 (45%)*	*20,136 (14%)*	

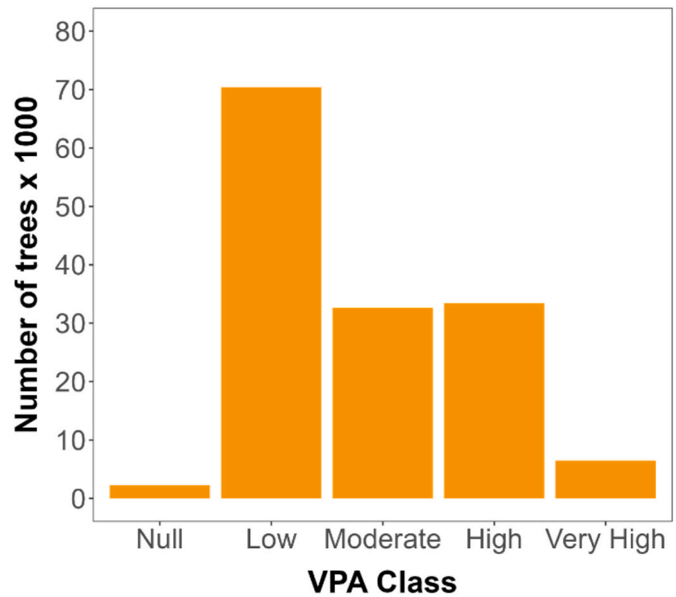

Fig. 2. Number of trees per classes of potential allergenicity (VPA) in the city of Valencia. VPA Classes: Null (VPA = 0), Low (VPA = 1–6), Moderate (VPA = 8–12), High (VPA = 16–24), and Very High (VPA = 27–36).

44% anemophilous and 6% amphiphilic. 66% of the (Sub-)Tropical species were entomophilous, against only 40% and 36% of the Temperate and Mediterranean species, respectively (Fig. S2). On the contrary, the largest share of anemophilous species (52% and 61%, respectively) was found in Temperate and Mediterranean species (Fig. S2).

3.3. Spatial distribution of the Value of Potential Allergenicity

After mapping all VPA in the city using the georeferenced tree inventory dataset (Fig. S2), an analysis based on hot and cold spots (Optimized Hot Spot Analysis) was subsequently performed. This analysis provides a *z*-score (Fig. 5A) and the number of neighbours (Fig. 5B) per feature (i.e., neighbours for each tree in a radius of 300 m), that can be interpolated to produce maps. In Fig. 5A, different areas of the city show high *z*-score values, representing zones where there is a clustering of trees with high VPA values, while the areas with a clustering of trees with low VPA values are the cold spots. The chance of having an allergenicity hot spot in a park or garden is higher, given the larger abundance and clustering of trees (compare Fig. 5A and B). Several hot spots were not associated with parks but to streets planted with allergenic species (A-C, E) and there is a special case of a cemetery (D), with abundant cypresses. In some hot spots, high allergenic species were distributed inside parks but also in the surrounding streets, enlarging the hot spot area (e.g., 2, 6 and 9).

A few species had the greatest importance in determining the hot spots. *Cupressus* spp., *Platanus x hispanica*, *Acer negundo*, *Morus* spp. and *Populus* spp. were the most abundant trees with high VPA values in the hot spot areas, with the former two having a strong influence. *Cupressus* sp. are highly allergenic trees that were especially abundant in hot spots D (Municipal cemetery), but also locally in some parks (5), while some individuals were also present in most of the other hot spots. *Platanus x hispanica* was responsible of several allergenicity hot spots, especially along boulevard and broad streets, such is the case of zones A, B, C and E, and also in streets around Parks 2 and 3. *Acer negundo* is a very common species in the city, contributing to the allergenicity in streets and parks, as in hot spots A, E, and Park 2 and surrounding streets. Similarly, *Morus* species are locally frequent in streets and parks, especially in zones A, B and E and Parks 3, 5 and 7. Mediterranean species such as *Olea europaea* or *Quercus ilex* were relatively important among allergenic species in

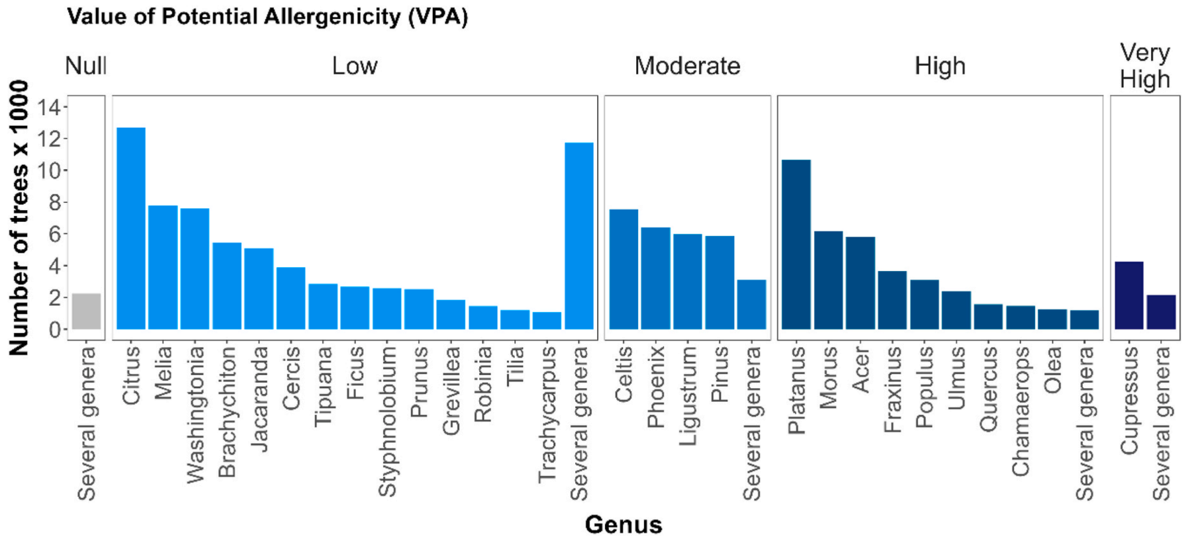

Fig. 3. Number of trees per genera and classes of potential allergenicity (VPA) in the city of Valencia. The genera considered individually are only those with >1000 trees. See Fig. 2 caption for the definition of VPA Classes.

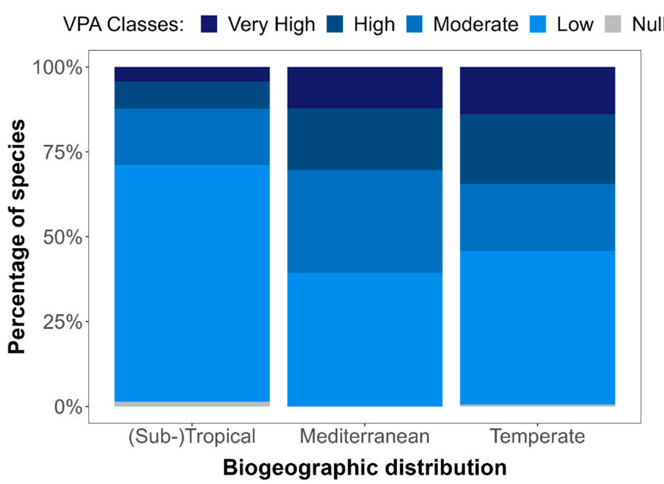

Fig. 4. Percentage of species classified according to their biogeographic distribution and VPA Class.

parts of hot spots 5, 7 and 9 (Jardí del Túria, Jardins del Real and Parc de la Rambleta). Poplar species, which are anemophilous, are relatively abundant in naturalized parks with riparian vegetation (e.g., Parc de la Rambleta and Parc de Capçalera, Nr 9 and 4, respectively). On the other hand, cold spots occur mainly in streets lined with species of genera *Citrus*, *Melia*, *Washingtonia*, *Brachychiton*, *Jacaranda* or *Tipuana*, very common in the city.

3.4. *Urban Green Zone Allergenicity index (I_{UGZA}) of the main parks or Valencia*

The I_{UGZA} was also calculated for the most important green areas of the city (Table 3). The largest green area of the city is the Jardí del Túria (5 in Fig. 5), a long park in the old riverbed of Turia river crossing the city, followed by the Campus of the Polytechnic University of Valencia (3 in Fig. 5). The typology of the studied parks is different (Table 3). Jardins del Real (7 in Fig. 5) is a historic garden, while the others parks have a more modern design including sport and municipal facilities (1, 2, 5, 6 and 8 in Fig. 5). In Rambleta (9 in Fig. 5) and Capçalera Parks (4 in Fig. 5), trees reproduce a riparian forest. Universitat Politècnica (3 in Fig. 5) is a University Campus, with a predominance of lawn zones covered by trees.

The results show a range of I_{UGZA} between 0.10 and >1, with large variations among parks. The largest values were observed in Parc de la Rambleta (I_{UGZA} >1), Parc de Marxalenes ($I_{UGZA} = 0.70$) and Parc de Capçalera ($I_{UGZA} = 0.38$). All the other parks except Univ. Politècnica ($I_{UGZA} = 0.10$) showed values in the range 0.3–0.36. Neither the size of the parks, the number of species nor the Shannon Index of Diversity explained a significant part of the variance of the I_{UGZA} among parks ($R^2 < 0.15$, $p > 0.1$).

4. Discussion

The results of the analysis of the tree flora of the city of Valencia show a high diversity of species, encompassing many genera and families. This high diversity of trees (302 species) that can grow in this urban environment is related to its geographic situation in the Mediterranean and its proximity to the sea, which determine its mild winters. Summer is hot and frost events are very rare (hardiness zone 10a, −1.1 °C to −1.7 °C), allowing the grow of many thermophilus species including tropical and subtropical species (45% of the total). In comparison, for example, cities like Bogotá have 228 different species but including shrubs besides trees and palms (Escobedo et al., 2023), and the main cities from European Nordic countries hosted only 27–133 different tree species per city (Sjöman et al., 2012).

Results of the calculation of VPA show that only 23% of the species have a high VPA and 4% a very high one, and that the most abundant VPA class is that of low allergenicity. The massive plantation of orange trees in the streets, considered an iconic tree of the Valencian region, as well as many individuals of the subtropical or tropical component belonging to genera *Melia*, *Washingtonia*, *Brachychiton*, *Jacaranda*, *Cercis* or *Tipuana* partly explain the high percentage of individuals with low VPA. Interestingly, as shown in this study, many tropical and subtropical plants have large flowers to attract insects and therefore are entomophilous, a type of pollination that releases much less pollen that anemophilous species, determining lower VPA values. The most problematic species in the city in terms of allergenicity in the city are the cypresses (*Cupressus* spp.), with a very high VPA class. With a lower but still high VPA, the following species must be mentioned: *Platanus x hispanica*, *Morus* spp., *Acer* spp. (especially *Acer negundo*), *Fraxinus* spp., and *Populus* spp., in order or abundance. Cypresses are symbolic plants that have been planted especially in parks, gardens and in cemeteries. Their release of pollen is high and cover a large period, from September to April, being responsible of many of the allergies observed in winter

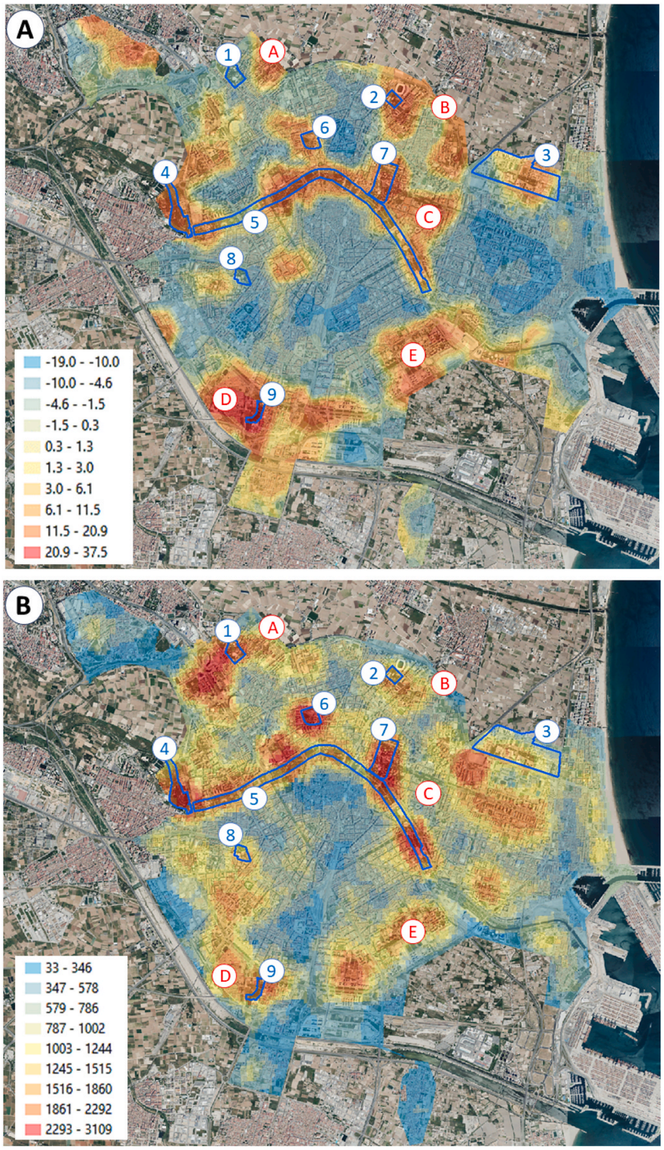

Fig. 5. A) Spatial representation of the VPA hot and cold spots in the city of Valencia (*z*-scores). The higher (or lower) the *z*-score values, the higher the spatial clustering of high (or low) values is. A *z*-score near zero indicates no apparent spatial clustering. For both maps, main parks of the city are highlighted with a blue line and labelled with numbers (see their names in Table 3). Hot spots not in parks are labelled with letters. B) Number of neighbours per tree within a 300 m radius as calculated by the Optimized Hot Spot Analysis, representing areas with different clustering of trees.

(De Linares et al., 2021; Charpin et al., 2005). Also important is *Platanus x hispanica*, a tree that has been widely planted in parks, boulevards and wide streets, given its good adaptation to urban environments, fast-growing characteristics and tall size, providing abundant foliage and shadow. The abundance of the London plane in Mediterranean cities has been inferred among the factors prompting new allergies to population (Alcázar et al., 2004). Its flowering period is however shorter than that of the cypresses, mainly centred in March and April, as it is the case of *Morus* spp. and *Acer* spp. (pollinic calendar of Ajuntament de València, 2024). *Fraxinus* and *Poplar* species are less abundant, although they can be locally dominant, and release pollen during a longer period, from February to May. Mediterranean high allergenic plants such as holm oaks (*Quercus ilex*) and olive trees are not very abundant but can emit a relatively high amount of pollen grains for three months, from April to June (pollinic calendar of Ajuntament de València, 2024; Gómez-Casero et al., 2007; Picornell et al., 2023). Pollen emission can be influenced by the particular urban environmental conditions, where the heat island effect can affect both the intensity and duration of the flowering period of the different species (Gisler, 2021; Cariñanos and Marinangeli, 2021). Additionally, the overlap in the flowering periods of these tree species, with that of some herbaceous species such as grasses, can have an aggravating effect on the symptoms suffered by allergic people, in which polysensitization to various pollen allergens is more and more frequent (D'Amato et al., 2023; Yalcin et al., 2023). Unfortunately, at present there are no other city-scale studies reporting the percentage of trees assigned to the different VPA classes, to directly compare with our results. Using different allergenicity indices (but not VPA), Sousa-Silva et al. (2021) calculated the percentage of trees belonging to different allergenicity classes for the cities of Barcelona, Montreal, New York City, Paris and Vancouver, reporting important discrepancies in these percentages depending on the index used. If a mean of the Pollen.com and Réseau National de Surveillance Aérobiologique (RNSA) indices (RNSA, 2016) (the most comparable to VPA) are considered, the range of percentage of trees with low allergenicity (the most comparable class) for these cities is 39%–45%, below the 52% of Valencia (VPA classes null and low). Pending of directly comparable studies applying the VPA index for the whole city tree inventory, we hypothesize that the overall picture of the pollen allergy from urban trees in the city of Valencia in comparison with other non-coastal Spanish and European temperate cities is potentially more favourable to the former, due to the high diversity of species and its important share of entomophilous species. Furthermore, for high allergic patients, it is recommended to move to coastal areas during the flowering periods of some allergenic plants such as the olive. The high humidity of the city, on the other hand, has also a positive effect, as it favours pollen deposition (Sicard et al., 2021).

Mapping the VPA values of the trees for the whole city provides a visual representation of the distribution of the trees with different allergenic potentials in the city. However, a hot spot analysis as conducted in the present study for the first time to VPA, is much more efficient in providing a comprehensive representation of the VPA patterns of allergenic risk in the city (compare Fig. 5A with Figs. S3 and S4).

Table 3
Characteristics of the main parks of the city of Valencia (density of trees, number of species and Shannon Index of Diversity), and value of the Urban Green Zone Allergenicity Index (I_{UGZA}).

Code[a]	Park	Type	Area (m^2)	Density (trees/ha)	Number species	Shannon	I_{UGZA}
1	Parc de Benicalap	Modern	80,793	142	76	3.38	0.33
2	Parc d'Orriols	Modern	45,759	108	23	2.39	0.31
3	Univ. Politècnica	Campus	659,304	39.7	106	3.84	0.10
4	Parc de Capçalera	Riparian	163,746	186	26	2.4	0.38
5	Jardí del Túria	Modern	804,536	112	101	3.58	0.36
6	Parc de Marxalenes	Modern	77,238	201	53	3.18	0.70
7	Jardins del Real	Historic	190,890	138	157	4.05	0.30
8	Parc de l'Oest	Modern	50,622	128	51	3.38	0.30
9	Parc de la Rambleta	Riparian	49,306	221	30	2.75	>1

[a] See Fig. 5 for situation of the parks in the city.

As expected, some hot spots coincide with parks or gardens where there is a higher density of trees. A remarkable hot spot was observed in the southwest of the city, in the Municipal Cemetery, with a high density of cypresses. Also, streets with extensive alignments of allergenic trees appear as hot spot areas. This is very evident in the case of boulevards or streets planted with rows of *Platanus x hispanica* and to a lower extent with *Morus* spp., *Acer* spp. or *Fraxinus* spp. This map should be used in green urban planning to avoid the introduction of trees with high VPA especially in the hot spot areas and, when replacement of individual trees be necessary, select species with a low VPA. Based on this risk maps, if there are trees whose expansion should be limited, this is the case of the cypresses and the London plane. Furthermore, the latter is currently affected by an increasing number of pest and pathogens that can reduce the vitality of trees. In addition, it has also been proven that *Platanus* pollen can establish cross reactions with the pollen types of *Olea*, grasses, and Cupressaceae, all of them major allergens not only in the Mediterranean region, but worldwide in the case of grasses (Tubby and Pérez-Sierra, 2015; Cariñanos et al., 2020). The widely planted *Acer negundo* should also be limited, as it is a highly allergenic anemophilous plant and there are other alternatives in the genus with low allergenicity such as *Acer pseudoplatanus*, *Acer campestre* or *Acer monspessulanum,* which is a drought-tolerant Mediterranean species.

The I_{UGZA} calculated for the parks yield contrasting results. As the I_{UGZA} takes into account the area of the park, parks with more infrastructure (e.g., sport facilities, recreational areas for children, university buildings and facilities in the case of a campus) may show a lower density of trees, which may result in lower I_{UGZA} values. This is the case of the Universitat Politècnica, in which the whole Campus has been considered as a green area. The highest I_{UGZA} values was observed in Parc de la Rambleta, a park with a natural structure resembling a dense riparian forest with poplar and elms among the most common species. As the species characteristic of this habitat are anemophilous, they produce large amounts of pollen, resulting in high I_{UGZA} values (in this case over the range of 1, which is indicative of a dense canopy of allergenic trees). Most of the parks exceeded the threshold of 0.3 for the I_{UGZA}, indicative of a relatively high proportion and density of allergenic species (Cariñanos et al., 2019). Therefore, allergic persons should preferably avoid staying for long periods or practice sports in these parks during the flowering months of the plants.

Results of the I_{UGZA} values can also be compared with those of the hot spot analysis. They are not fully coincident, as the I_{UGZA} refers to the whole park, but hot spot analysis provides information on the spatial distribution of the VPA within each park and furthermore takes into account the allergenicity of the trees surrounding the park too. Therefore, both analyses are complementary. While the I_{UGZA} is a recommended tool for planning new parks, the hot spot analysis provides spatially explicit details of the potential allergenicity of existing green infrastructures in the context of their surrounding area and relative to the whole city.

In recent years, Europe has launched a plan for the renaturalization of the cities. The EU Green Infrastructure Strategy aims to preserve, restore and enhance green infrastructure to help stop the loss of biodiversity and enable ecosystems to deliver their services to people. In this context, native vegetation is important to ensure connectivity with surrounding vegetation, e.g., creating green corridors for the fauna, and should be prioritized (e.g., Ortega et al., 2023). However, given that pollen release by vegetation and the emission of bVOCs, which fosters tropospheric ozone formation (Calfapietra et al., 2013; Sicard et al., 2022), can have a significant impact on human health, it is also relevant to include these two variables in the process of plant selection. For the case of Valencia, established over an alluvial plain, riparian species of the genera *Populus*, *Salix* or *Ulmus* are part of the native vegetation, and their plantation makes sense to restore riparian habitats, which may host a rich fauna. However, given the high allergenic potential of this type of trees in combination with a high bVOC emission, especially of poplar and willows (Chaparro and Terradas, 2009; Yuan et al., 2023), it is recommending that planting these species outside these target areas is not promoted. Naturalization of areas of the coastal front with a coastal pine formation would have a lower allergenic impact. Aleppo pine has a moderate VPA and some of the associated species of this type of formation show low or moderate allergenic values, e.g., species of *Phillyrea*, *Pistacia*, *Crataegus* or *Rhamnus*. More problematic in terms of allergenicity is the typical Mediterranean vegetation dominated by holm oak or olive, which are highly allergenic; on the contrary *Ceratonia siliqua* has a low VPA. Mediterranean vegetation is a good option in terms of resilience to future climatic conditions, but species of the genera *Crataegus*, *Viburnum*, *Phyllirea* or *Pistacia* or *Arbutus unedo* or *Ceratonia siliqua* should be preferred to the holm oak or the olive tree. Thus, when restoration of a habitat or connectivity are not the main matters of concern, as it is the case of gardens or street vegetation, we believe that (Sub-)Tropical trees can play an important role in coastal Mediterranean cities, as it is already the case. Besides, a number of (Sub-)Tropical species combine relatively low bVOC emissions with a low VPA (e.g., Chaparro and Terradas, 2009), and some of them are well-adapted to the dry and hot conditions expected in the future (Palau Garrabou et al., 2015). The list of species and associated VPA values (Table S1) provided in the present paper is expected to be useful not only for Valencia but for other cities in selecting the less allergenic tree species for urban green and, if suitable, in guiding the selection of a higher proportion of trees with a lower allergenicity among the native species in renaturalization plans. Obviously, attention should also be paid to shrubs, forbs and grasses, out of the scope of the present study.

Finally, and as a general recommendation, an increase of heterogeneity in the urban trees help to avoid concentration of problems in given areas, but not only in relation to allergenicity. A higher diversity contributed to diluting the load of pollen of allergenic trees but also may protect against respiratory allergies through greater and more diverse microbial exposure which is vital for the development of the immune system (Haahtela, 2019). On the other hand, a diverse area will be less prone to the spreading of pests and diseases and if a general dieback of a given species occurs due to adverse meteorological conditions, not all trees in the area will be affected. This scenario is already happening due to climate change, with alignments of heat sensitive species such as *Tilia* for example being stressed and losing leaves during summer (Vainio et al., 2017). Special attention should also be paid to the allergenic potential of new species to be introduced in the future as they can induce new sensitisations (Cariñanos and Casares-Porcel, 2011) and to cross-reactivity between related taxa (Weber, 2003). The increase in cross-allergies that can occur between pollen panallergens and fruits such as apples, bananas, kiwis, melons, peaches, and vegetables is also a matter of concern (Miralles et al., 2002; Cariñanos et al., 2019).

5. Conclusions

There is an urgent need for a science-based approach to guide urban green planning in connection to public health. With this aim, the investigation of the hot spots of allergenic risk as shown in the present study offer an easy to apply tool for urban green planners and practitioners. Also, the characterization of the allergenic potential of the different urban species through the VPA as compiled in this study is expected to provide guidance for a smart tree selection minimizing allergic reactions on sensitive population. Further investigation is needed to better understand the trade-offs between ecosystem services and disservices in order to maximize the benefits that urban vegetation offer, with the final aim of achieving more sustainable, resilient and health cities.

CRediT authorship contribution statement

Vicent Calatayud: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Paloma Cariñanos: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Acknowledgements

V.C. thanks projects URBFLUX (PID2021-125941OB-I00), funded by MCIN/AEI/10.13039/501100011033 and "ERDF A way of making Europe" and EVER (Programa PROMETEO 2022; Generalitat Valenciana). P.C. thanks the University of Granada Plan Propio project Pre-GREENMITIGATION3 (PP2022.PP.34) and by Grant C-EXP-167-UGR23 funded by Consejeria de Universidad, Investigación e Innovación and by the ERDF Andalusian Program 2021–2027.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2024.118823.

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