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Variations in urban forest allergy potential among cities and land uses

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A B S T R A C T

Tree pollen with allergenic potential in cities triggers nasal, skin, eye, and asthmatic allergic reactions in humans. Pollen is one of the most common allergy-causing inhaled substances. Tree species composition, cultivar selection and the proximity of certain trees to humans can influence allergic responses. Data from 53 cities or states from various parts of the world were used to assess the magnitude and differences in an allergy index (AI) among the sampled locations and among land uses within cities. Index values for species ranged from one (most allergy-free species) to 10 (highest allergy potential). The average index score among the cities and states was 6.3, with values ranging from 4.2 (Halifax, Nova Scotia) to 8.3 (Austin, Texas). On average, forest/open space areas had a slightly higher average index score (6.4) than commercial/industrial/transportation (6.2) and residential areas (6.1). About 2/3 of the analyzed cities had higher index scores in forest/open space than in residential areas. Forest/open space areas contributed over 40 percent of total leaf area and may influence allergenicity in cities. Cities developed within areas with naturally occurring Pinaceae (pine, spruce, fir, cedar, Douglas fir, larch) forests and/or have more Pinaceae species tended to have the lowest pollen index scores. Most leaf area tended to come from trees in index class 8. While pollen production is essential for natural regeneration and potential seed/food production, limiting tree species with high allergenic potential in areas near people can help reduce tree-related allergies. Through better understanding and quantification of urban forest allergenicity, managers can create sustainable local-scale landscapes that limit pollen exposure to humans, but also provide numerous ecosystem services and values to residents.

1. Introduction

Urban forests provide numerous benefits such as moderating climate, improving air and water quality, mitigating rainfall runoff and flooding, reducing building energy use and associated pollutant emissions, sequestering carbon, enhancing human health and social well-being and lowering noise impacts (Nowak and Dwyer, 2007). However, vegetation can also negatively affect the local environment through allergen production, and other effects such as winter shade increasing building energy use, lowered wind speed and dispersion increasing local pollutant concentrations, and invasive plants altering local biodiversity (e.g., Lyytimaki, 2017).

Allergy to tree pollen (pollinosis) is common, producing symptoms such as rhinitis, conjunctivitis, hay fever, allergic-asthma, dermatitis and even anaphylactic shock (Barral et al., 2004). Pollinosis in cities is increasing (e.g., Heinrich and Wichmann, 2004) and occurs more often in urban areas vs. rural areas (e.g., Gonzalo-Garijo et al., 2006; Bousquet et al., 2008). In addition to pollen, some tree species can cause allergic contact dermatitis (e.g., *Dalbergia* spp.) and insect dander associated with trees can also trigger allergic reactions (Moore et al., 2006). Reactions vary depending upon human sensitivities, plant species and human exposure to the species, including time of year, distance from sources and wind direction (e.g., D'Amato et al., 2007; Rojo et al., 2015). In addition, a high degree of repeated exposure to the same environment may influence the development of sensitization to the particular pollen load associated with that area (Cariñanos et al., 2002). Studies have shown that allergic diseases such as asthma, rhinitis and eczema have increased fourfold over the past 30 years, particularly in developed countries (Davies et al., 1998).

Once a pollen-allergy has been initially triggered by one species, the individual then becomes more susceptible to developing new allergies to pollen from numerous other species (Ribeiro et al., 2009; Killian and McMichael, 2017). Many food allergies and sensitivities are initially triggered by pollen-allergies (American College of Allergy, Asthma, and Immunology, 2019). About 70 percent of people diagnosed with asthma also have pollen-allergies (ACAAI, 2018).

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Urban emergency room visits for asthma have been positively associated with pollen concentrations (e.g., Lierl and Hornung, 2003; Tobias et al., 2003; Dales et al., 2004, 2008; Heguy et al., 2008; Jariwala et al., 2011). However, other studies did not find associations between pollen and emergency room visits or asthma symptoms (e.g., Delfino et al., 1996; Dales et al., 2000). Deaths from all causes are higher than average on high pollen count days (Moyer, 2000).

In Westernized countries "allergic diseases" affect 10–30 % of the population and can come from many sources (e.g., pollen, dust, molds, insects, animals, foods) (Pawankar et al., 2013). A recent Gallup study

Table 1
Information on the 53 cities and states analyzed. For state assessments, all urban areas were sampled within the state.

City / State	Year[a]	Area[b] (km^2)	Plots[c] (#)	Trees[d] (#)	Species[e]	LA[f] (%)	Reference[g]
Adrian, MI	2012	19	201	940	*Acer saccharum (7), Acer platanoides (8), Juglans nigra (8)*	32	
Albuquerque, NM	2013	274	199	421	*Ulmus pumila (8), Morus alba (6), Populus fremontii (5)*	50	Mikulanis (2014a)
Arlington, TX	2009	264	233	1,048	*Quercus stellata (8), Ulmus crassifolia (8), Celtis laevigata (8)*	42	City of Arlington (2009)
Atlanta, GA	1997	341	205	2,402	*Liriodendron tulipifera (4), Pinus taeda (4), Liquidambar styraciflua (7)*	32	
Austin, TX[h]	2014	790	223	2,325	*Juniperus ashei (9), Quercus virginiana (9), Ulmus crassifolia (8)*	65	Nowak et al. (2016a)
Baltimore, MD	2009	209	195	1,030	*Fagus grandifolia (7), Liriodendron tulipifera (4), Acer saccharinum (5)*	29	
Barcelona, Spain	2008	101	579	3,308	*Platanus hybrida (9), Pinus halepensis (4), Quercus ilex (8)*	51	Chaparro and Terradas (2009)
Boise, ID	2011	689	250	347	*Robinia pseudoacacia (5), Picea pungens (3), Juglans regia (8)*	22	
Boston, MA	1996	143	217	930	*Acer platanoides (8), Quercus rubra (8), Acer rubrum (5)*	47	
Calgary, Canada	2009	550	196	284	*Picea glauca (3), Populus spp. (5), Picea pungens (3)*	61	
Casper, WY	2006	55	234	235	*Populus deltoides (5), Picea pungens (3), Ulmus americana (8)*	59	Nowak et al. (2006a)
Chester, PA	2008	12	200	789	*Platanus spp. (9), Morus spp. (5), Juglans nigra (8)*	30	
Chicago, IL	2007	598	745	1,697	*Acer saccharinum (5), Acer platanoides (8), Fraxinus pennsylvanica (5)*	31	Nowak et al. (2010b)
Edmonton, AB	2009	700	307	1,884	*Picea glauca (3), Ulmus americana (8), Populus tremuloides (5)*	37	City of Edmonton (2012)
El Paso, TX	2016	410	201	279	*Pinus eldarica (4), Morus alba (6), Fraxinus berlandieriana (7)*	44	Mikulanis (2014b)
Freehold, NJ	1998	5	144	626	*Acer platanoides (8), Acer saccharinum (5), Robinia pseudoacacia (5)*	31	
Gainesville, FL	2007	122	93	1,335	*Quercus laurifolia (9), Pinus elliottii (4), Pinus taeda (4)*	37	Escobedo et al. (2009)
Golden, CO	2007	24	115	194	*Ulmus pumila (8), Elaeagnus angustifolia (9), Picea pungens (3)*	34	
Grand Rapids, MI	2016	92	201	1,058	*Acer saccharum (7), Acer platanoides (8), Acer saccharinum (5)*	30	
Halifax, Canada	2008	693	190	6,423	*Picea rubens (3), Acer rubrum (5), Abies balsamea (2)*	65	
Hartford, CT	2007	46	200	791	*Acer rubrum (5), Acer saccharinum (5), Quercus palustris (8)*	30	
Houston, TX[h]	2015	1,626	209	881	*Celtis laevigata (8), Triadica sebifera (8), Ilex vomitoria (4)*	30	Nowak et al. (2017)
Indiana[h]	2002	4,834	32	249	*Acer saccharinum (5), Quercus rubra (8), Liriodendron tulipifera (4)*	36	Nowak et al. (2007a)
Jersey City, NJ	1998	38	220	341	*Platanus hybrida (9), Acer platanoides (8), Ailanthus altissima (9)*	45	
Kansas[i]	2008/09	3,877	188	1,043	*Ulmus spp. (8), Celtis spp. (8), unknown spp.*[j]	39	Nowak et al. (2012b)
Las Cruces, NM	2013	313	205	224	*Chilopsis linearis (5), Pinus eldarica (4), Fraxinus berlandieriana (7)*	71	
Lincoln, NE	2008/09	190	178	573	*Acer saccharinum (5), Celtis spp. (8), Pinus sylvestris (4)*	30	
London, Canada	2008	349	383	2,596	*Quercus palustris (8), Acer rubrum (5), Acer saccharinum (5)*	23	
London, UK[k]	2014	236	200	319	*Platanus hybrida (9), Tilia cordata (7), Tilia x vulgaris (7)*	23	Rogers et al. (2015)
Los Angeles, CA	2007/08	1,218	348	681	*Magnolia grandiflora (5), Jacaranda mimosifolia (4), L. styraciflua (7)*	17	Nowak et al. (2011)
Milwaukee, WI	2008	251	216	1,084	*Acer platanoides (8), Acer negundo (6), Fraxinus pennsylvanica (5)*	42	
Minneapolis, MN	2004	151	110	278	*Fraxinus pennsylvanica (5), Ulmus americana (8), Acer saccharinum (5)*	51	Nowak et al. (2006b)
Moorestown, NJ	2000	38	206	1,690	*Acer rubrum (5), Liquidambar styraciflua (7), Prunus serotina (4)*	31	
Morgantown, WV	2004	22	136	1,295	*Acer saccharum (7), Prunus serotina (4), Acer rubrum (5)*	33	Nowak et al. (2012c)
Nebraska[i]	2008/09	1,901	200	941	*Celtis spp. (8), Ulmus pumila (8), Ulmus spp. (8)*	37	Nowak et al. (2012b)
New York, NY	2013	799	206	643	*Platanus hybrida (9), Acer platanoides (8), Robinia pseudoacacia (5)*	29	Nowak et al. (2018)
North Dakota[i]	2008/09	1,052	299	186	*Fraxinus spp. (7), Picea spp. (3), Populus deltoides (5)*	66	Nowak et al. (2012b)
Oakville, Canada	2005	99	372	2,391	*Acer saccharum (7), Acer platanoides (8), Acer saccharinum (5)*	28	McNeil and Vava (2006)
Omaha, NE	2008/09	299	189	1,005	*Acer saccharinum (5), unknown spp.*[j]*, Ulmus pumila (8)*	29	
Philadelphia, PA	2012	342	210	1,433	*Platanus spp. (9), Quercus rubra (8), Juglans nigra (8)*	23	Nowak et al. (2016b)
Phoenix, AZ	2017	1,347	204	263	*Pinus eldarica (4), Brachychiton occulneuem (4), Prosopis velutina (5)*	28	Mikulanis (2014c)
Roanoke, VA	2010	111	160	1,501	*Liriodendron tulipifera (4), Juglans nigra (8), Prunus serotina (4)*	22	Wiseman and King (2012)
Sacramento, CA	2007	1,307	300	637	*Quercus wislizeni (9), Platanus hybrida (9), Quercus lobata (8)*	24	Aguaron-Fuente (2012)
San Francisco, CA	2004	120	194	478	*Pinus radiata (4), Cupressus macrocarpa (10), Eucalyptus globulus (7)*	47	Nowak et al. (2007b)
Scranton, PA[l]	2006	42	182	1,798	*Quercus rubra (8), Acer platanoides (8), Acer rubrum (5)*	33	Nowak et al. (2010a)
Seattle, WA	2010/11	486	186	1,496	*Alnus rubra (9), Acer macrophyllum (8), Pseudotsuga menziesii (3)*	40	Ciecko et al. (2012)
Seoul, South Korea	2010	605	199	2,428	*Quercus mongolica (8), Robinia pseudoacacia (5), Pinus densiflora (4)*	33	
South Dakota[i]	2008/09	1,184	200	612	*Fraxinus spp. (7), Pinus ponderosa (4), Ulmus spp. (8)*	52	Nowak et al. (2012b)
Syracuse, NY	2009	65	198	1,499	*Acer platanoides (8), Acer saccharum (7), Acer negundo (6)*	29	Nowak et al. (2016c)
Tennessee[h]	2005-09	6,306	255	2,331	*Celtis spp. (8), Liriodendron tulipifera (4), Juniperus virginiana (10)*	17	Nowak et al. (2012a)
Toronto, Canada	2008	637	407	2,571	*Acer platanoides (8), Acer saccharum (7), Acer negundo (6)*	32	Nowak et al. (2013b)
Washington, DC	2004	159	201	976	*Liriodendron tulipifera (4), Fagus grandifolia (7), Quercus rubra (8)*	34	Nowak et al. (2006c)
Woodbridge, NJ	2000	60	215	1,284	*Quercus palustris (8), Acer rubrum (5), Acer saccharinum (5)*	35	

[a] Year sampled.
[b] Area sampled (city area or urban area within state).
[c] Number of plots sampled.
[d] Number of trees sampled.
[e] Top 3 dominant species based on total leaf area; species allergy index value is given in parenthesis.
[f] Percent of total population leaf area comprised by the top 3 species with the greatest leaf area.
[g] if no reference is given, data are from unpublished i-Tree analyses.
[h] 0.067 ha plots with 4 nested 13.5 m^2 microplots.
[i] 0.067 ha plots.
[j] unknown species are often standing dead trees that could not be identified, but may include some living unidentified species.
[k] inner London.
[l] urban area only.

estimates Americans with allergies at 50 percent (Bassett, 2017). Hidden direct costs of allergies include the treatment of asthma, chronic sinusitis, upper respiratory infection, nasal congestion, and sleep-disordered breathing. In ten years, diagnostics costs for allergies in the United States will be over three billion dollars annually (Med Gadget, 2020).

The closer one is to an allergenic pollinating tree, the greater their exposure. The allergy-potential of trees near homes, work, and schools are important because allergy is normally triggered by repeated heavy exposure. Close proximity can also result in much larger doses of pollen inhaled, and allergy to pollen is almost always dose-dependent (Ogren, 2015a).

Tree selection can influence exposure and urban forest designs need to consider the allergenic pollen potential of trees to optimize benefits, while minimizing pollen exposure. These designs need to consider not only species, gender, and cultivar selection, but also proximity to humans. As urban forests are constantly changing and approximately 75 % of the world's urban populations lives in forested regions with relatively high tree cover (Nowak and Greenfield, 2020), there is ample opportunity for urban forest managers to create forests that are beneficial for the majority of the world's population while minimizing exposure to allergenic plants.

Various studies have investigated the allergenic potential of urban forests. These studies often use a pollen allergy index based on local tree composition, size and associated pollen allergenicity characteristics of individual species (e.g., Cariñanos et al., 2014). A case study of Garcia Lorca Park, in Granada, Spain, found that a 44.1 % of the park's total surface area was occupied by species with moderate to elevated allergenic potential (Cariñanos et al., 2014). Analysis of urban parks in 23 Mediterranean cities reveal that ornamental native species are among the main causative agents of allergies (Cariñanos et al., 2019). Studies of 26 green areas (1−100 ha) in 24 Spanish cities reveal that the percentage of allergenic species varied between 17–67 % with a significant correlation between a pollen index value and both the number of trees and tree density (Cariñanos et al., 2017).

The goal of this paper is to analyze urban forest field data from numerous cities to quantify and compare how the allergenic capacity of urban forests vary among cities and within cities by land use type. Most of the cities are from the United States and Canada, and all cities are from the northern hemisphere. Understanding current allergenic exposure from urban forests can provide insights on how city vegetation designs could be improved to reduce allergenic exposure from urban forests.

2. Methods

2.1. City and state data

To estimate tree allergenicity in urban forests, field data from 53 cities and states were used. These data include 38 U.S. cities, 6 Canadian cities, 3 cities from other countries, and data from samples of all urban areas within 6 U.S. states (Table 1, Fig. 1). State assessments of urban areas were based on U.S. Census classification of urban land (U.S. Census Bureau, 2017) which include city, town, village and suburban areas that meet the population-based definition of urban. Data on urban forest composition in each city and state (hereafter referred to as city) were collected using random samples of 0.04 ha field plots (unless otherwise noted in Table 1) and analyzed using the i-Tree Eco model to estimate the total leaf area of each tree species (Nowak et al., 2008). The i-Tree Eco model uses local environmental variables and a random sample of field measurements of trees to estimate forest structural attributes (e.g., leaf area) and associated ecosystem services and values derived from the forest (e.g., Nowak et al., 2013a; and 2016c, Nowak and Greenfield, 2018; Nowak, 2020). The field samples provide a statistical representation of the entire tree population in a city.

Within each field plot, all trees with a diameter at breast height (dbh at 1.37 m) of at least 2.54 cm were measured as to species, dbh, total height, crown height, crown width, dieback and percent crown missing (Nowak, 2020). From the crown measurements, tree leaf area was estimated using the following equation from Nowak (1996).

$$\ln Y = -4.3309 + 0.2942H + 0.7312D + 5.7217S + -0.0148C$$

where Y is leaf area (m^2) H is crown height (m), D is average crown diameter (m), S is the average shading factor for the individual species

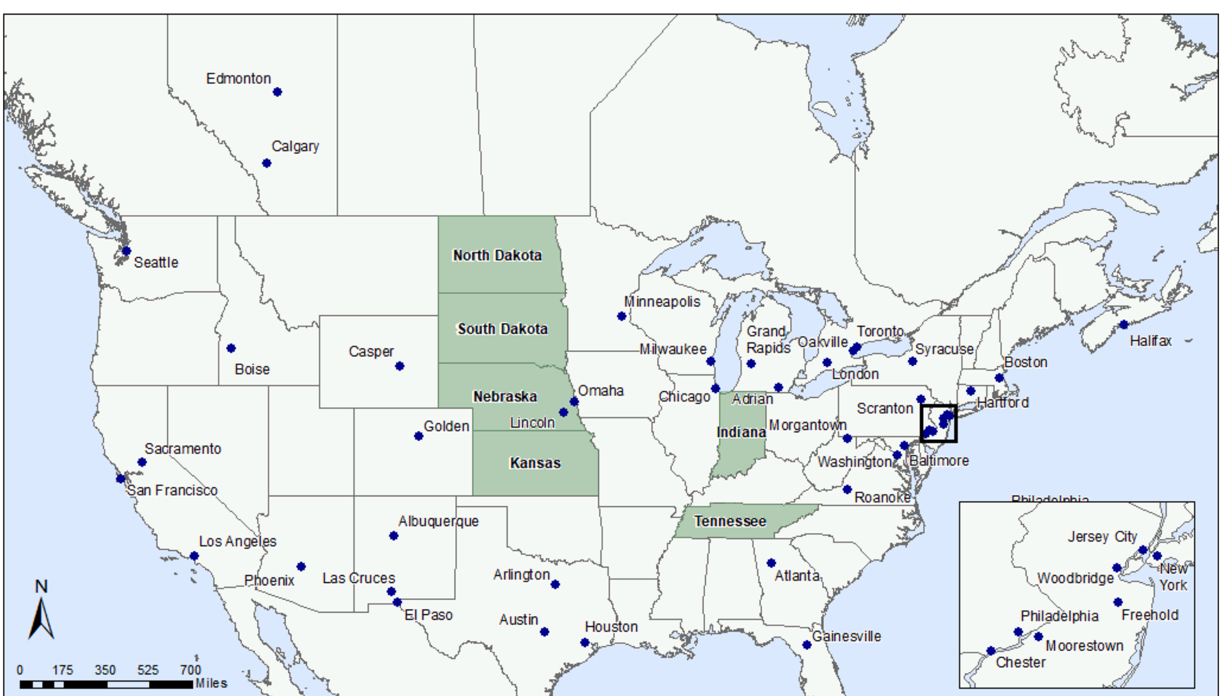

Fig. 1. Location of cities and state urban areas sampled in North America. Highlighted states indicate that the entire urban area in the state was sampled. Non-North American cities (Barcelona, Spain; London, UK; Seoul, South Korea) are not shown.

(percent light intensity intercepted by foliated tree crowns) and C is based on the outer surface area of the tree crown (πD(H + D)/2). Population and species leaf area were estimated based on processes detailed in Nowak (2020).

As allergenicity of the urban forest is based on species attributes and size, leaf area was used as the indicator of tree size as tree pollen and contact allergies will be dependent upon leaf area (e.g., dead trees may be large, but do not produce pollen). In many cities, each plot was classified as to its dominant land use. If land use information was collected, data were subdivided by the following land use classes: Residential (single and multi-family), Forest/Open Space (including recreational areas, parks, cemeteries, golf courses), Commercial/ Industrial/ Transportation, and Other (e.g., agriculture and grass, institutional, other developed areas) (e.g., State of New Jersey, 2007).

2.2. Allergy index

Tree species allergic potential was based on an OPALS® scale from 1 to 10 (Ogren, 2000; Allergy Free Gardening, 2020), with 1 being the most allergy-free selections and 10 being species or cultivars with highest allergy potential (Supp. Table 1). The allergy scale considers length of pollination and all plant-related allergies including allergies to pollen, insect dander, odors and plant contact. A greater weight was given to inhalant pollen allergies. While insect dander, odors and plant contact are considered, they have a relatively minimal impact on tree species as these factors are more important in annuals, perennials, groundcovers and shrubs. However, some tree and shrub species will include these other allergens, thus the index is an allergy index, not a pollen index per se.

The species allergy potential (AP: 1–10) was weighted by species leaf area to calculate an allergy index (AI):

$$AI_x = \sum_{i=0}^{n} (AP_i \times LA_{ix}) \div LA_x$$

Where AIx = allergy index in class x (city or land use), APi = allergy potential of species i (1–10), LAix = leaf area (m^2) of species i in class x, and LAx = total leaf area (m^2) in class x. This index was calculated for all cities (Table 1) and by land use if land use was analyzed in the city.

For dioecious species, male and females were assumed to be 50 percent each. However, as people in urban areas may plant more male selections to avoid fruit or seed nuisance and clean-up, a high-male scenario was also analyzed assuming that 80 percent of the dioecious species were male. This extra scenario was calculated to see the potential impact on the index score if more male trees are selected. This high-male allergy index (HMAI) was calculated the same as the AI, except that the allergy potential of the species (APi) was weighted as 80 percent male within the species (AI weights dioecious species as 50 percent male).

The AI and HMAI index scores can range between 1 (all species with an AP = 1) and 10 (all species with an AP = 10). The allergy index scores were also combined into low, medium and high index classes for display purposes: Low = classes 1–3; Medium = classes 4–7; High = classes 8−10.

The AI is similar in concept to allergenic index given in Cariñanos et al. (2014). However, there differences between these indices. The AI uses a 10-point species rating weighted by species leaf area to produce index values between 1 and 10. The Cariñanos et al. (2014) index combines a 5-point allergenic potential, 4-point pollen emission, and 3-point pollination period rating with crown volume to estimate an allegenicity index with values between 0 and a variable maximum value based on local composition.

3. Results

3.1. City and state index values

Overall, 803 tree and shrub species or genera were sampled among the 53 cities. The average distribution among cities reveals that most of the urban forest (51.3 %) had medium allergy scores, followed by high allergy scores (39.1 %) and low allergy scores (8.4 %). Average allergy index scores ranged from a low of 4.2 in Halifax, NS to 8.3 in Austin, TX. Over 85 percent of Austin's urban forest was in the high allergy class. Cities with the highest proportion of their urban forest in the low allergy class were all in Canada: Halifax, NS (50.3 %), Calgary, AB (42.5 %) and Edmonton, AB (26.7 %) (Table 2). The high-male index increased the

Table 2
Percent leaf area among allergy classes and average allergy index scores among cities.

	Percent Leaf Area					
City	L[a]	M[b]	H[c]	Unk[d]	AI[e]	HMAI[f]
Austin, TX	2.9	11.7	85.2	0.2	8.3	8.4
Arlington, TX	0.7	20.9	78.0	0.4	7.7	7.9
Jersey City, NJ	2.6	37.2	60.1	0.0	7.2	7.5
Kansas	1.8	29.7	57.5	11.0	7.1	7.5
Sacramento, CA	6.6	35.4	57.9	0.0	7.1	7.4
Houston, TX	1.8	33.8	63.7	0.7	7.0	7.5
Philadelphia, PA	1.5	50.0	48.5	0.0	6.9	7.2
Nebraska	4.8	36.2	53.6	5.4	6.8	7.1
London, UK	5.7	53.4	40.4	0.5	6.8	7.1
Barcelona, Spain	4.0	38.9	53.4	3.6	6.8	6.9
Milwaukee, WI	3.8	50.0	46.1	0.0	6.7	7.4
Tennessee	1.6	51.0	47.3	0.2	6.6	7.0
London, ON, Canada	6.0	49.2	44.4	0.4	6.6	6.6
Albuquerque, NM	0.5	53.7	45.8	0.0	6.6	7.2
New York, NY	8.1	42.2	49.6	0.1	6.6	6.9
Chester, PA	5.1	48.3	46.6	0.0	6.6	6.8
Boston, MA	9.2	38.7	52.1	0.0	6.6	6.9
Grand Rapids MI	6.8	50.4	42.8	0.0	6.6	7.1
Omaha, NE	3.3	49.0	38.9	8.8	6.5	7.0
Washington, DC	1.4	55.5	43.0	0.0	6.5	6.8
Adrian, MI	8.5	49.4	42.1	0.0	6.4	6.9
Chicago, IL	3.0	58.4	37.8	0.8	6.4	7.1
Los Angeles, CA	8.3	52.4	36.3	3.0	6.4	6.6
San Francisco, CA	7.3	56.5	33.5	2.7	6.4	6.4
Freehold, NJ	4.9	49.7	45.4	0.1	6.4	6.8
Seattle, WA	20.9	25.9	53.0	0.1	6.4	6.4
Toronto, ON, Canada	8.2	56.7	34.7	0.4	6.3	6.8
Oakville, ON, Canada	11.1	52.4	36.3	0.2	6.3	6.7
Gainesville, FL	3.4	54.1	41.5	0.9	6.3	6.5
Syracuse, NY	11.4	49.4	39.2	0.0	6.3	6.7
Woodbridge, NJ	2.0	64.8	33.1	0.1	6.3	6.9
Roanoke, VA	3.3	52.8	43.9	0.0	6.3	6.5
Minneapolis, MN	4.5	55.0	40.3	0.3	6.2	7.1
Baltimore, MD	7.1	58.0	34.9	0.0	6.2	6.6
Morgantown, WV	6.2	66.0	27.7	0.1	6.1	6.6
Hartford, CT	6.1	61.7	32.1	0.1	6.1	6.8
Indiana	4.3	54.0	37.6	4.2	6.1	6.8
Atlanta, GA	1.2	64.8	33.6	0.4	6.0	6.2
Lincoln, NE	8.0	55.4	30.7	5.9	6.0	6.5
Golden, CO	12.4	48.8	38.6	0.2	6.0	6.5
Scranton, PA	13.5	46.0	40.6	0.0	6.0	6.5
South Dakota	5.5	75.4	17.1	2.0	6.0	6.3
Seoul, South Korea	6.1	60.2	33.3	0.4	6.0	6.1
El Paso, TX	6.6	68.7	24.6	0.1	5.9	6.4
Moorestown, NJ	3.6	69.8	26.5	0.1	5.9	6.4
North Dakota	20.5	62.3	17.3	0.0	5.7	6.3
Boise, ID	14.3	59.1	26.6	0.0	5.6	6.1
Phoenix, AZ	9.0	63.9	18.4	8.7	5.5	5.9
Las Cruces, NM	0.9	87.8	11.4	0.0	5.3	5.4
Edmonton, AB, Canada	26.7	54.9	18.2	0.2	5.2	5.8
Casper, WY	24.5	58.3	17.0	0.2	4.9	5.9
Calgary, AB, Canada	42.5	46.5	11.1	0.0	4.6	5.2
Halifax, NS, Canada	50.3	44.8	4.9	0.0	4.2	4.7
Average	8.4	51.3	39.1	1.2	6.3	6.7

[a] Low allergy scores (1–3) for AI.
[b] Medium allergy scores (4–7) for AI.
[c] High allergy scores (8–10) for AI.
[d] Unknown allergy scores (not rated).
[e] Average allergy index score for city.
[f] High male allergy index score; average index score with dioecious species assumed as 80 % male.

average allergy index by 0.4 (6.4 %) with greatest increases occurring in Casper, WY (+1.0, 20.4 %) and Minneapolis, MN (+0.9, 14.5 %) (Table 2).

3.2. Index values by land use and allergy class

In comparing allergy index values among land use classes, the Forest/Open space land use (average AI = 6.4) had the highest index values, followed by Commercial-Industrial-Transportation (AI = 6.2) and Residential (AI = 6.1) (Table 3). About 2/3 of the cities sampled had lower AI values in residential areas compared with forest/open space areas (Supp. Table 1). The greatest difference between residential and forest/open space land occurred in the Southwestern United States. Residential AI values in Las Cruces, NM were +1.3 compared to forest/open land and −2.2 in Phoenix, AZ. In Las Cruces, 5.7 percent of the leaf area in forest/open space areas was in the High AI class compared to 24.3 percent in residential areas. In Phoenix, 40.2 percent of the leaf area in forest/open areas was in the High AI class compared to 14.5 percent in residential areas.

Only Residential and Other land uses had greater than 10 percent of its leaf area in the lowest allergy class. Among the land use classes, the proportion of total leaf area was greatest on Forest/Open space (42.1 percent), followed by Residential (33.0 percent), Commercial/Industrial/Transportation (12.5 percent) and Other (12.4 percent). Individual city results by land uses are provided in Supplemental Table 2.

Most species were in the allergy classes of 8 and 4, but most leaf area was in allergy classes 8 and 5 (Fig. 2). Thus, trees in class 8 tend to dominate potential allergy production. Common species in allergy class 8 include hackberry (*Celtis* spp.), oak (*Quercus* spp.) and elm (*Ulmus* spp.). In the United States, two of the top five species in terms of leaf area were from allergy class 8; in Canada, one of the top five species; in Seoul, two of the top five species, and in London UK and Barcelona, two of the top five species (plus one species in class 9). Thus, allergy potential from trees in class 8 were common throughout all areas sampled. Relatively few trees were found in allergy classes 1–3, which include such species as fir (*Abies* spp.), spruce (*Picea* spp.), hemlocks (*Tsuga* spp.) and Douglas-fir (*Pseudotsuga* spp). These Pinaceae genera were relatively uncommon with only eight cities (15.1 percent) having a species from these genera among the top three species in leaf area (Table 1). The cities with two of their top three species among these genera (Calgary and Halifax) had the lowest average allergy index values. Shifting from a 50 percent male population (AI) to 80 male population among dioecious species (HMAI) only increased the average allergy index by 6 percent (Table 2).

4. Discussion

As 75 percent of urban areas globally are found within forest biomes (Nowak and Greenfield, 2020), and natural forests are integral parts of urban systems (e.g., Nowak et al., 2013a), the natural forest species composition will have an impact on allergy potential within city systems. As found in this paper's sample of cities and a previous study (Nowak and Greenfield, 2018), two land uses tend to comprise about 75 percent of total leaf area in cities: natural forest/vacant areas and residential land. In grassland and desert biomes, natural forests have less of an impact and residential leaf area becomes more dominant (Nowak and Greenfield, 2018).

The natural environment influences the forest composition in all cities, with the native forest having a relatively substantial influence in some cities (e.g., Austin, Calgary, Halifax, Las Cruces). In Austin (highest AI of 8.3), native ashe juniper (*Juniperus ashei*) contributed over 40 percent of the city's total leaf area, with over 75 percent of this leaf area from forested/natural areas. In Halifax (lowest AI of 4.2), native red spruce (*Picea rubrens*) and balsam fir (*Abies balsamea*) also contributed over 40 % of the city's total leaf area. In Mediterranean cities, some native species (e.g., Oleaceae, Cupressaceae, Fagaceae, and *Platanus hispanica*) are among the main causative agents of allergy in the population (Cariñanos et al., 2019). Thus, native species and forests can have a major influence on allergy potential as they can comprise a large proportion of the overall forest composition. Future research could further investigate the role of native/remnant vegetation influences on pollen loads in cities throughout the world.

The impact of native vegetation will vary by region. In some cities the native forest has higher allergy potential than trees planted by the local population; in other cities it is lower (e.g., Rojo et al., 2016). Local native forest composition influences the local allergy potential, as does the tree species that are planted by residents. The results from this study are based heavily on results from North America, particularly the United States, but exhibit a wide range in average allergy values (AI ranges from 4.2–8.3; Table 2). Results are dependent upon local forest composition and future studies could investigate more cities, particularly in the southern hemisphere, to better understand variations in urban forest composition (e.g., Yang et al., 2015) and the varying influence of native vegetation vs planted species impacts on allergy potentials.

Past tree pollen studies have focused on allergy indices for smaller areas within cities (e.g., (Cariñanos et al., 2014, 2017, 2019) revealing the importance of species composition on allergy potentials within these areas. Citywide data on allergy indices provide additional important information related to variations in allergy potential across the urban landscape and illustrate how land use and native vs. planted species can influence allergies within cities. Studies in Australia and New Zealand have also illustrated the importance of geographic location and land use on airborne pollen in urban areas (Haberle et al., 2014). This information can help in developing urban landscapes that can reduce allergy exposures to residents. Mapping of allergenic potentials (e.g., McInnes et al., 2017) and airborne pollen measurements (e.g., Kasprzyk et al., 2019) can also add important information related to pollen exposure.

While native forests influence pollen exposure and allergy potential in cities, it is the more managed landscapes around homes that will likely have the greatest impact on pollen exposure and allergy potential to humans due to their close proximity to residents. In residential areas, a greater proportion of trees are planted as compared to influx through natural regeneration. In the United States and Canada, only about 1/3 of the urban forest is planted. However, in residential areas about 75 percent of the forest composition comes from tree planting (Nowak, 2012). Thus, decisions on species planted in residential areas can have important implications for resident allergenic reactions.

Studies show that pollen exposure is often different between urban and rural areas. While there is more total pollen in rural areas, urban areas often have more pollen from higher allergenic species: oak, birch, plane, cypress, olive, (male) juniper, (male) Podocarpus, (male) Taxus, and (male) mulberry trees (Bosch-Cano et al., 2011; Ogren, 2015a). Among the 53 cities studied, high allergy scores (39.1 % of leaf area) were more than four times greater than low allergy scores (8.4 %).

Planning and designs in urban areas need to consider limiting an

Table 3
Average percent leaf area among allergy classes and allergy index scores by land use.

Land Use	L[a]	M[b]	H[c]	Unk[d]	AI[e]	HMAI[f]
Comm/Ind/Trans[g]	5.5	60.1	34.0	0.5	6.2	6.7
Forest/Open space	3.3	57.0	38.3	1.4	6.4	6.9
Other	11.8	51.7	35.9	0.6	6.0	6.4
Residential	11.9	49.5	37.7	0.9	6.1	6.5

[a] Low allergy scores (1–3) for AI.
[b] Medium allergy scores (4–7) for AI.
[c] High allergy scores (8–10) for AI.
[d] Unknown allergy scores (not rated).
[e] Average allergy index score for city.
[f] High male allergy index score; average index score with dioecious species assumed as 80 % male.
[g] Commercial/Industrial/Transportation.

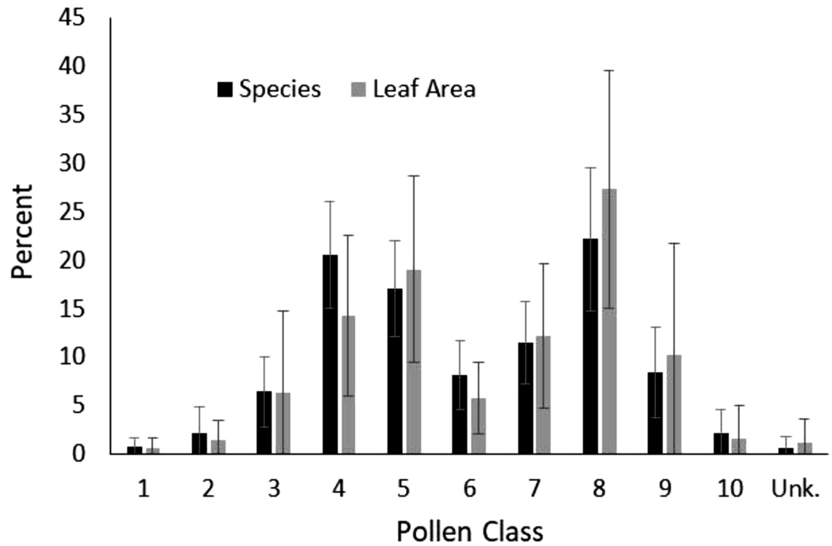

Fig. 2. Comparison of species vs leaf area distribution among cities for AI. Species distribution is based on proportion of total species richness among all cities. Error bar indicates the standard deviation of average proportion.

overabundance of high allergen species, introduction of new species with potential new allergens, use of female instead of male pollen-producing individuals in dioecious species, and management of invasive species that can increase pollen allergens (e.g., Cariñanos and Casares-Porcel, 2011). While the use of female plants could reduce pollen allergies, shifting from a 50 percent male population to 80 male population among dioecious species in the cities sampled, only increased the average allergy index by 6 percent (Table 2). However, as actual allergy exposure is often local, anyone susceptible to allergic-asthma or pollen-allergies will have less allergenic pollen-exposure with more female trees in their own landscapes. These trees shed no pollen and can also trap and remove airborne pollen (of their own species) from the surrounding air (Bassett, 2017; Ogren, 2015b).

Many coniferous genera tend to have low allergen potentials (e.g., *Abies*, *Cedrus, Larix, Picea, Pseudotsuga, Tsuga*), but other non-coniferous genera also contain species with index scores less than four (e.g., *Amelanchier*, *Arbutus*, *Diospyros*, *Ficus*, *Melia*, *Persea*, *Prunus*, *Washingtonia*). Many genera also contain species with index scores of four or five (e.g., *Citrus, Cornus, Crataegus, Jacaranda, Liriodendron, Magnolia, Malus, Metasequoia, Pinus, Pyrus, Sophora,* and *Sorbus*).

Most conifers are in plant families related to pine, yew, or cypress. Cypress and its close relatives (Japanese Cedar, Junipers) tend to be more allergenic. Junipers are dioecious and males produce large amounts of allergenic pollen. Pine, and its relatives (spruce, fir, cedar, hemlock) tend to have larger pollen grains, and grains with a protective waxy surface. Pine and its relatives tend to be less allergenic. Yew and its close relatives (*Podocarpus* spp.) are all dioecious (separate-sexed) and only males produce abundant pollen that is both allergenic and cytotoxic (Ogren, 2015a).

Cities developed within areas with native Pinaceae forests will likely have lower allergenic exposure than cities developed in other forest types. For cities developed in grassland and desert areas, species and cultivar selection and planting will likely have a greater influence on allergen exposure than cities developed in forested regions.

While residential and other managed land uses tend to, on average, have slightly lower AI values than forest/open space areas, specific planning and designs can continue to reduce human exposure to allergens and lower AI values in areas where people reside or congregate. Species composition and tree size are important determinants in allergen exposure. However, while a vegetation index was the strongest predictor of pollen concentrations (Hjort et al., 2016), tree density and configurations can also affect pollen loads. Factors such as species-specific pollen production, crown shape, sun/shade habitat, and stand density can affect pollen loads and dispersion (Kasprzyk et al., 2019).

Allergenicity of a tree species is only one factor among many that needs to be considered in choosing tree species to plant. Tree species could also be selected that maximize desired benefits (e.g., air pollution removal, air temperature reduction, carbon sequestration). To optimize benefits, tree species need to survive and remain healthy over many years while producing minimal monetary (e.g., maintenance) and environmental (e.g., pollen) costs. Tree species selections should be adapted to local site conditions and be designed to address local environmental issues (e.g., Churkina et al., 2015; Vogt et al., 2017). Large, long-lived species tend to produce the most net benefits (e.g., Nowak et al., 2002). However, minimizing potential costs associated with tree species are also important considerations. Allergies is one of these species' costs that need to be considered and weighed against the benefits provided by tree species. Large trees can produce relatively large amounts of benefits but can also have relatively high allergenicity. Where possible, large tree species with low allergenic potentials could be used to reduce allergy costs while maintaining benefits.

The ability to affect changes in allergenicity through tree planting are generally limited to more managed land uses. Forest/open space areas (>40 percent of the leaf area in the sample) will likely be most influenced by natural regeneration, including invasive species. As most managed areas are near higher concentrations of people, species selection in these areas will more directly affect future benefits to humans as well as pollen and other associated costs. Future planting decisions should consider both positive and negative species attributes to provide optimal net benefits for current and future generations.

Forest/open space areas can be managed to change/reduce pollen loads. For example, in the rural southwestern United States, cutting of dominant dioecious *Juniperus* species has focused more on cutting female trees as many of the tree cutters have developed strong allergies to *Juniperus* pollen due to repeated long-term exposure (Ratner, Paul MD, allergist, pers. comm., San Antonio, TX, June 2017). In Texas, allergy to the pollen from the numerous males of the common native *Juniperus ashei* is widespread and commonly known as 'cedar fever.' Management activities to selective reduce male species could reduce pollen loads and exposure.

Data from these city analyses provide insights into allergenicity among various cities and among land uses within cities. Allergic impacts are estimated based on plant size (leaf area) and an index of allergenicity. This index procedure allows for relative comparisons among areas, but does not estimate actual pollen loads or consequent impacts on human health. However, it is well-documented that certain species of pollen are far more allergenic than others. Some of the most commonly used, and most allergenic species, on a grain-per-grain basis are male *Acer negundo*, *Olea europaea*, *Betula* spp., male *Morus* spp., and *Cupressus* spp. (Ogren, 2015a). More research is needed to estimate actual pollen emissions by species and species-specific effects on human health. In addition, more research related to field exposure to pollen (e.g., Cariñanos et al., 2015; Kasprzyk et al., 2019) relative plant parameters (e.g., species, size, distance) could help improve our understanding of plant impacts on allergies and provide information for better landscape designs to reduce plant allergen exposure.

The cities analyzed are not based on a random sample of cities, so interpolation to larger populations should be viewed with this limitation. The sample is skewed towards U.S. cities, as that is where most of the comprehensive city analyses have been conducted. More city analyses can help provide information in a local context, but also add to a global database of city analyses to help ascertain more regional influences on allergenicity and urban forest ecosystem services. The current index is based on the OPALS allergy rating, which has the most taxa analyzed among current allergy indices, but other allergy indices could produce different values (Sousa-Silva et al., 2021).

To help people collect data on urban forests across the world, the free i-Tree Eco program can be used (www.itreetools.org). In the United States, the USDA Forest Service Forest Inventory and Analysis' urban forest inventory program is also measuring urban forest data annually and uses i-Tree to assess current stock and changes in structure, services and values through time. Currently 40 cities are being monitored as part of the urban FIA program with more cities being added each year (Edgar et al., 2021). Increased number of and more comprehensive assessments will lead to better quantification of urban forest costs and benefits, both locally and globally.

Landscape managers can use plant allergy-potential as an important factor in tree selection. Other actions that could help reduce high allergy exposure include: a) adding allergy potential information on tree sale's tags, b) enhancing education on pollen dispersal and the importance of proximity, c) incorporating protective measures to prevent removal of existing female trees; d) developing pollen-control statutes-ordinances, and e) enhancing production and sale of female or allergy-friendly / allergy-free tree cultivars and species by tree nurseries. Actions to reduce pollen exposure in urban areas can have substantial health impacts.

5. Conclusion

Overall, the natural forest composition of a region can have a substantial influence on allergen exposure in a city, with cities developed in Pinaceae forests tending to have the lowest overall allergy index scores. However, at the local scale, particularly in residential areas, tree species/cultivar selection, male vs. female tree and planting location will influence allergy exposure. Reducing male trees can reduce pollen exposure while selection of females can also help reduce pollen by trapping and removing pollen. The choices made in these landscape designs will influence human health related to allergen exposure due to their close proximity to people.

Disclaimer

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Author statement

David Nowak: Conceptualization, Methodology, Formal analysis, Investigation, Writing - Original Draft, Writing - Review & Editing; Thomas Ogren: Conceptualization, Methodology, Investigation, Formal analysis, Writing - Review & Editing

Declaration of Competing Interest

The second author is an author of a book on trees and pollen that is for sale. Data from this book were used in the publication.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ufug.2021.127224.

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