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The effects of tree planting on allergenic pollen production in New York City

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ABSTRACT

Planting low-pollen trees could reduce aeroallergen exposure in cities, but the effects of historical tree planting on contemporary airborne pollen exposure remains largely unexplored. Whether tree selection decisions can effectively reduce airborne pollen will depend in part on which taxa are the most important sources of allergenic pollen and the extent to which they are intentionally planted vs. unplanted (i.e., recruiting naturally). Here, we use airborne pollen measurements to examine which taxa are of allergenic importance in New York City (NYC), and then combine two tree surveys with allometric equations to determine pollen production for several taxa. Future changes in pollen production as a function of growth, mortality, and recruitment are then simulated using i-Tree Eco Forecast. The most important producers of allergenic pollen in NYC are *Quercus, Platanus, Morus,* and *Betula*; they comprise 71% of airborne pollen measured and 93% of estimated pollen production (107 quadrillion pollen grains; however, pollen production was not estimated for all taxa). Previous municipal planting decisions have resulted in the high abundance of *Platanus* × *acerifolia*; it accounts for 34% of total street tree basal area and has an estimated annual pollen production of 27.7 ± 6.4 quadrillion grains. In contrast, *Morus* and *Betula* are generally unplanted, indicating that tree planting decisions will have smaller effects on their future pollen production rates in NYC. *Quercus* trees produced an estimated 68.2 ± 12.3 quadrillion pollen grains and accounted for almost 25% of airborne pollen collected, but were very abundant in parks and were mostly unplanted, suggesting that planting has not and will not have a major effect on city-wide pollen production. Overall, this study demonstrates that tree planting decisions can have important and long-lasting consequences for city-wide pollen production but only for species that are both primarily planted and large producers of allergenic pollen.

1. Introduction

Exposure to pollen results in allergic reactions that substantially reduce quality of life for the approximately 20% Americans that have seasonal allergies (Ng and Boersma, 2023; Zablotsky et al., 2023) and are sensitized to pollen (Meltzer, 2016; Meltzer et al., 2009). Urban trees produce large quantities of pollen (Katz et al., 2020; Maya-Manzano et al., 2017) and tree pollen has been implicated in elevated rates of asthma-related emergency department visits (Anenberg et al., 2017; Darrow et al., 2012; Sun et al., 2016). There have been several calls for selecting plants with low allergenic potential (Cariñanos and Casares-Porcel, 2011; Green et al., 2018; Maya-Manzano et al., 2017; Nowak and Ogren, 2021), but more information is needed to quantitatively link tree planting and demographic rates (i.e., growth and mortality) to contemporary and future pollen production. This understanding could eventually help bridge the gap between management decisions (e.g., species selection during tree planting) and the long-term effects on airborne pollen concentrations, pollen exposures, and the resulting health consequences including allergic rhinitis symptoms and asthma exacerbations.

The allergic consequences of tree planting decisions depend in part on the proportion of trees that are intentionally planted by people compared to those trees that are not intentionally planted (Nowak, 2012; Nowak and Ogren, 2021); these unplanted trees are sometimes

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known as naturally recruited trees or ingrowth. Specifically, tree selection decisions can gradually shift the composition of planted trees but have weaker effects on natural areas, vacant lots, and other minimally managed areas (Nowak, 2012). Street trees, which often account for ~5–10% of total trees in cities in the United States (McPherson et al., 1997; McPherson et al., 2016), are owned by cities and their composition is in part the result of centralized decisions. Thus, from a municipal government perspective, allergenic pollen production from street trees is both a responsibility and a problem that could be addressed with little extra effort when planting new trees.

The lengthy lifespan of trees means that tree planting decisions have long-term consequences; current pollen production is often the result of decisions made several decades ago. The exact timescales of these effects will depend upon tree growth and mortality rates which vary among taxa, regions, and urbanization gradients (McPherson et al., 2016; Rötzer et al., 2020). Certain species may also display non-linear increases in pollen production as a function of tree size (Katz et al., 2020) or may reach sexual maturity at varying ages or sizes. Thus, the time-scales over which planting decisions will affect pollen production is an important consideration, but little work has quantified changes in tree pollen production over time due to tree growth, mortality, and recruitment.

Tree planting campaigns have garnered substantial interest nationally in the United States (Eisenman et al., 2021a; Sousa-Silva et al., 2023) and the Inflation Reduction Act of 2022 is investing an additional $1.5 billion in urban and community forestry. For example, in New York City (NYC), further tree planting campaigns are gaining momentum, as exemplified by the *Million More Trees* proposal (Rubinstein, 2022). A recent publication concluded that tree cover in NYC could reasonably be increased from 22% to 30 – 42% (Treglia et al., 2022) and in 2023 the New York City Council passed resolution 1065, which aims to increase tree canopy coverage to 30%.

Here, we explore how previous tree planting decisions have affected pollen production and how pollen production may change in the future due to tree establishment, growth, and mortality using NYC as a case study. Specifically, we quantify current city-wide pollen production by combining allometric equations of pollen production with data from two complementary tree surveys; pollen production is also compared to airborne pollen measurements. We then assess how previous tree selection decisions have affected current pollen production and simulate how tree growth, mortality, and recruitment could affect future pollen production. Finally, we review and discuss various relevant processes, including the spatial scales of pollen production and dispersion, the role of atmospheric dispersion, botanical sexism (the preferential selection of males of dioecious species to prevent production of fruits), and generalizability to other metropolitan areas.

2. Methods

2.1. Study site description

New York City is home to 8.5 million people; 11% of children there have asthma (New York State Department of Health, 2009). Asthma is closely connected to allergic rhinitis (Giavina-Bianchi et al., 2016; Grossman, 1997), and pollen is one of the major triggers of seasonal allergies (Bousquet et al., 2008). In NYC, airborne pollen concentrations have been linked to asthma-related emergency department visits in the Bronx (Jariwala et al., 2014, 2011) and tree cover has been linked to pollen sensitization (Lovasi et al., 2013).

New York City is currently 22% forested (17,254 ha or 42,635 acres), with approximately half of that in areas managed by the NYC Department of Parks and Recreation, including 28% in parks (approximately one third of which is in landscaped areas) and 25% in rights of way including street trees; about 35% is on privately owned land (Maxwell et al., 2021a). From 2010 to 2017, at least 518 ha of new canopy developed separately from existing tree canopy; this can coarsely be assumed to be the result of new plantings, such as the 136,871 street trees and 17,440 trees planted in landscaped park areas during that period (Maxwell et al., 2021b).

2.2. Data sources

One of the primary sources of data on trees across NYC was a stratified random plot-based survey in the summer of 2013 that sampled 296 plots, each of which was one tenth of an acre (Nowak et al., 2018). This survey used the i-Tree Eco sampling approach and data management system (Nowak et al. 2008; https://www.itreetools.org) and counted and identified all woody plants with a diameter at breast height (DBH) > 2.54 cm (1 in.); tree size, land use, and planting status (planted vs unplanted trees; these naturally recruited trees are also sometimes referred to as 'ingrowth') were also recorded. Planting status was determined by trained field crews based on field observations of tree maintenance, the site conditions around each tree, and the location of the tree relative to anthropogenic objects such as buildings, streets, fence lines, and vacant lots (Nowak, 2012). For example, trees in lawns were often classified as planted whereas those in vacant lots or natural areas were often classified as unplanted; ambiguous trees were classified as having an 'unknown' planting status. In total, 1075 trees were measured in this city-wide census. This dataset is statistically representative of trees in NYC but includes relatively few trees; it also has fairly few plots in natural areas based on a random sample of the city area (Pregitzer et al., 2019).

In NYC, the majority of trees that are mapped are street trees, as is true in many cities, (Keller and Konijnendijk, 2012). In 2015 and 2016, a street tree inventory was implemented by NYC Parks staff and volunteers (NYC Parks Department, 2017). In total, 652,088 living street trees were identified and mapped; these data are publicly available at: https://tree-map.nycgovparks.org/. DBH was also recorded for each tree. Street trees are owned and managed municipally and are thus the easiest to affect through centralized tree species selection decisions. While this dataset has a large number of trees, it does not include the far larger number of trees in natural areas (estimated at 6 million trees; Pregitzer et al., 2019), private property, and other non-mapped areas. The street tree dataset is therefore not representative, which is why we complement it with the smaller but more representative city-wide i-Tree Eco dataset; results from these two datasets are presented separately.

Airborne pollen data were collected in Manhattan using a Burkard sampler on the Lincoln Center roof (15 m above street level). Pollen was collected during 2009 – 2012; the first day of collection in most years was March 1 (with the exception of 2009, where it was April 6), and the final day of collection was Oct 31. This period of pollen collection is standard for the region and encompasses peak pollen release of early pollen releasing taxa, such as Cupressaceae (data not shown), although the peak may not have been fully captured in 2009. Pollen was identified to 87 taxonomic groups; these were generally at the genus level, with some exceptions where identification is only feasible at the family level (e.g., Poaceae/Gramineae and Cupressaceae) or where pollen types cannot be readily distinguished (e.g., *Carpinus* and *Ostrya*). Pollen monitoring followed standard protocols for aerobiological sampling (American Academy of Allergy Asthma & Immunology, 2022; Galán et al., 2014; Levetin, 2004). All pollen identification personnel were National Allergy Bureau certified and used a curated collection of reference specimens provided by Aerobiology Instruction and Research, LLC (Trumansburg, NY, USA).

2.3. Data analysis

Pollen production was estimated as a function of tree basal area for several species using the equations developed by Katz et al., 2020a. Briefly, these equations were based on pollen production estimates of urban trees for 13 tree species in Ann Arbor, Michigan; for each species pollen production of at least 10 individuals were measured by quantifying the number of pollen grains per anther, the number of anthers per flower, the number of flowers per inflorescence, the number of inflorescences per flower cluster, and the number of flower clusters per tree (mostly by taking hemispherical photos of trees and estimating the number of flower clusters in those images). These numbers were multiplied together to calculate total pollen production and linear, quadratic, or exponential equations were developed to predict pollen production as a function of tree basal area and canopy area. Variation was assessed with bootstrapping and was included as standard deviations for each parameter (e.g., slope and intercept for linear equations). Among species the average $R^2 = 0.72$ (range of R^2: 0.41 – 0.99). Pollen production equations were available for the following species: *Acer negundo* (L.), *Acer platanoides* (L.), *Acer rubrum* (L.), *Acer saccharinum* (L.), *Betula papyrifera* (Marsh.), *Gleditsia triacanthos* (L.), *Juglans nigra* (L.), *Morus alba* (L.), *Platanus* × *acerifolia* (Aiton Willd.), *Populus deltoides* (W. Bartram ex Marshall), *Quercus palustris* (Munchh), *Quercus rubra* (L.), and *Ulmus americana* (L.). Within *Betula, Morus, Quercus,* and *Ulmus*, we applied the same pollen production equations to other species within those genera, including: *Betula lenta* (L.), *Betula nigra* (L.), *Betula occidentalis* (Hook.), *Betula populifolia* (Marshall), *Quercus alba* (L.), *Quercus bicolor* (Willd.), *Quercus phellos* (L.), *Quercus prinus* (Willd.), *Quercus velutina* (Lam.), *Ulmus parvifolia* (Jacq.), and to *Morus* and *Ulmus* individuals that were only identified to the genus level. For *Ulmus,* we used a linear version of the equation (pollen produced in billion grains/yr = 546.56 ± 89.86 × basal area in m^2 + 23.76 ± 17.06) instead of the exponential version published in Katz et al. 2020 to prevent unrealistic pollen production estimates for very large individuals. Due to the high variation in tree structure, pollen production, and pollination syndrome within *Acer,* pollen production was not extrapolated to other *Acer* species. City-wide pollen production was calculated by summing total pollen production for each tree of the included taxa from the i-Tree data. The equations from Katz et al. (2020) provide variation in the estimates of the pollen production parameters (e.g., standard deviations for slope and intercept in linear models); that variation was carried through to the present estimates of pollen production by sampling 1000 times from the parameter distributions and calculating the standard deviation (SD) of pollen production estimates. Street tree pollen production was estimated by converting the DBH of each tree to basal area. These estimates adjust for tree sex for dioecious *Morus* (male: 57.8%) and for the polygamodioecious *Acer rubrum* (male: 10.6%) based on observed sex ratios presented elsewhere (Katz et al., 2020); sex ratios for the dioecious species *Acer negundo* were based on an estimate from the literature (male: 55.6%; Ramp and Stephenson, 1988). These pollen production equations are being incorporated into the i-Tree Eco software suite and will be available for the northeastern US in a subsequent version of i-Tree Eco. Pollen production estimates are only qualitatively compared to airborne pollen concentrations, as airborne pollen was only measured at a single site and may not be representative for the entire city (as discussed below).

To calculate future potential pollen production, we used the forecast module within i-Tree Eco, which has been widely used to simulate future urban forest composition and size structure (Amini Parsa et al., 2019; Nyelele et al., 2019; Steenberg et al., 2017). This model estimates annual changes from initial urban forest condition based on tree growth, mortality, and establishment. Growth rates depend on initial conditions measured in i-Tree Eco plots, such as crown light exposure, tree location (open-grown and street trees, park trees, and forest trees), crown condition (amount of canopy dieback), and local growing season length; they also vary among species (divided into three categories: slow growing, moderate growing, or fast growing); limitations of this approach are discussed later. Growth rates also saturate as trees approach their maximum sizes. Here, mortality rates are set at the default rate of 3%, which is based on empirical measurements from several studies (Nowak et al., 2016, 2013, 2004). We set the annual recruitment rate at 200,000 new individuals per year, approximately the annual mortality rate; the composition of new trees matches city-wide tree composition. New trees establish at an initial DBH of 5.08 cm (2.0 in.). City-wide pollen production per species per year was estimated as a function of individual tree basal area as described above. This simple simulation does not account for the many potential drivers of urban forest change (e.g., invasive pests and pathogens, extreme weather events, land use change, etc.,) or pollen production (e.g., changes in CO_2 or temperature); however, it does provide a baseline expectation of how we expect pollen production to change over time due to somewhat predictable shifts in the size distribution and abundance of the taxa. These same pollen production equations are being incorporated into the i-Tree Eco Forecast module, which will allow others to use similar methods to easily explore how pollen production might change in their own cities over time and how that could vary as a function of easily adjusted parameters (e.g., taxon-specific mortality and establishment rates).

Data were analyzed in R 4.1.2 (R Core Team, 2018,) using several packages within the Tidyverse (Wickham et al., 2019). Code is available at: https://github.com/dankatz/nyc_tree_planting.git.

3. Results

Several tree genera of allergenic concern are both prevalent and achieve high airborne pollen concentrations in NYC, including *Quercus, Platanus, Betula,* and *Morus* (Table 1; a version of this table that includes all taxa is available in SI Table 1). Together, these taxa account for 71% of the airborne pollen monitored at the Lincoln Center pollen monitoring station. Of particular note is the strong disjunct between relative basal area and share of airborne pollen for certain taxa; for example, *Betula* is estimated to include 1.7% of total basal area in NYC but accounts for 12% of measured airborne pollen (annual pollen integral: 5600 ± 7800 pollen × day/m^3; the ± SD is among years). Similarly, *Morus* accounts for 0.7% of total basal area but 23% of airborne pollen (annual pollen integral: 10,300 ± 5400 pollen × day/m^3). In contrast, *Quercus* accounts for 27% of total basal area and 24% of airborne pollen (annual pollen integral: 11,000 ± 2200 pollen × day/m^3). With a basal area of 8% and accounting for 12% of airborne pollen (annual pollen integral: 5500 ± 1900 pollen × day/m^3), *Platanus* is an important producer of allergenic pollen and it is especially well represented among street trees, accounting for 34% of all street tree basal area. Table SI 2 summarizes the street tree database by species and Table SI 3 summarizes the i-Tree data by species.

Based on i-Tree plot estimates of city-wide tree abundance and size and pollen production equations, the genera with the highest estimated pollen production were *Quercus, Platanus, Morus, Ulmus,* and *Betula* (Fig. 1). The single species with the highest estimated pollen production was *Platanus* × *acerifolia*, with a total annual pollen production of 25.7 ± 6.0 quadrillion pollen grains in NYC. Pollen production equations were not available for species in the Cupressaceae and Pinaceae families, so pollen production estimates for those taxa are not included here; nor are equations for other species of *Acer*. For street trees, the genera with the highest estimated pollen production were *Platanus, Quercus, Gleditsia,* and *Ulmus* (Fig. 1). *Platanus* were the largest street trees; their average DBH was 54.7 cm, substantially greater than any other species and there were relatively few small *Platanus* trees.

Genera with the highest proportion of planted trees were *Gleditsia* and *Platanus* (Fig. 2); for example, of the 24 *Platanus* trees recorded in the i-Tree plots, 17 were classified as planted. Genera with the lowest proportion of planted trees were *Morus, Betula*, and *Quercus.* Note, however, that sample sizes for certain taxa were small (e.g., *Morus* was based on nine individuals). There were also differences in species composition and pollen production among land uses (SI 4). For example, *Quercus* trees were especially common in parks and *Platanus* was especially common in residential land uses.

Large changes in pollen production are expected over the coming decades, including increases for *Ulmus* and decreases for *Platanus* (Fig. 3). For other taxa such as *Acer* and *Quercus*, decreases in the pollen

Table 1
Allergenic pollen producing trees in New York City based on citywide i-Tree plots, street tree database, and airborne pollen collection from 2009 – 2012. Any taxon with > 1% relative basal area (in either the i-Tree plots or the street tree database) or with > 1% of total airborne pollen collected is included here. *Pollen concentrations provided for *Thuja* also include other members of the Cupressaceae family, including *Juniperus, Cryptomeria*, and *Taxodium*. For wind pollination, + = at least partially wind pollinated, - = wind pollination is rare. For allergic concern + = of allergic concern, - = not of allergic concern, and ~ = of unknown or minor allergic concern. The allergenic importance for these genera were assigned based on an informal assessment of several sources described elsewhere (Sousa-Silva et al., 2021).

taxon	i-Tree relative basal area (%)	i-Tree relative number of stems (%)	Street tree relative basal area (%)	Street tree relative number of stems (%)	Pollen (% of total grains collected in air sampling)	Maximum daily pollen concentration (grains/m^3)	Wind pollinated	Of allergenic concern
Quercus	26.52	10.52	18.21	12.71	23.9	2158.8	+	+
Acer	19.68	11.78	15.57	13.61	1.0	119.3	+	+
Platanus	8.29	2.38	34.47	13.34	11.9	2727.6	+	+
Liquidambar	3.49	1.58	1.38	1.63	0.5	87.2	+	~
Tilia	3.22	0.96	5.05	7.86	< 0.1	11.0	-	~
Robinia	3.16	4.08	0.30	0.27	< 0.1	4.0	-	-
Ulmus	2.15	1.19	1.95	2.29	1.1	176.8	+	+
Crataegus	2.11	1.25	0.05	0.51	0.0	0.0	-	-
Fagus	2.04	0.26	0.02	0.06	0.1	27.0	+	-
Fraxinus	1.78	0.57	3.12	3.06	2.0	437.5	+	+
Picea	1.75	1.09	0.05	0.10	< 0.1	8.9	+	-
Betula	1.66	4.87	0.05	0.21	12.3	2396.8	+	+
Pyrus	1.59	2.49	4.39	9.04	0.0	0.0	-	-
Tsuga	1.58	0.82	0.00	0.01	0.1	33.1	+	-
Gleditsia	1.52	0.92	6.11	9.85	0.3	130.4	~	~
Celtis	1.50	2.18	0.10	0.37	< 0.1	2.2	+	+
Unknown	1.42	3.40	0.00	0.00	3.1	189.5	NA	NA
Sophora	1.41	0.46	0.00	0.00	0.0	0.0	-	-
Thuja	1.10	6.32	0.01	0.05	6.4 *	1076.1 *	+	+
Ailanthus	1.02	5.54	0.13	0.12	NA	NA	-	~
Prunus	0.93	3.35	1.37	6.39	< 0.1	43.7	-	-
Zelkova	0.71	0.72	1.91	4.49	0.2	295.63	+	+
Morus	0.69	0.82	0.29	0.18	22.6	4342.6	+	+
Ginkgo	0.57	0.53	1.61	3.22	0.7	311.1	+	~
Pinus	0.26	0.43	0.08	0.11	4.2	365.1	+	-
Styphnolobium	0.00	0.00	1.64	2.97	0.0	0.0	-	-
Populus	0.00	0.00	0.11	0.07	1.0	156.8	+	+

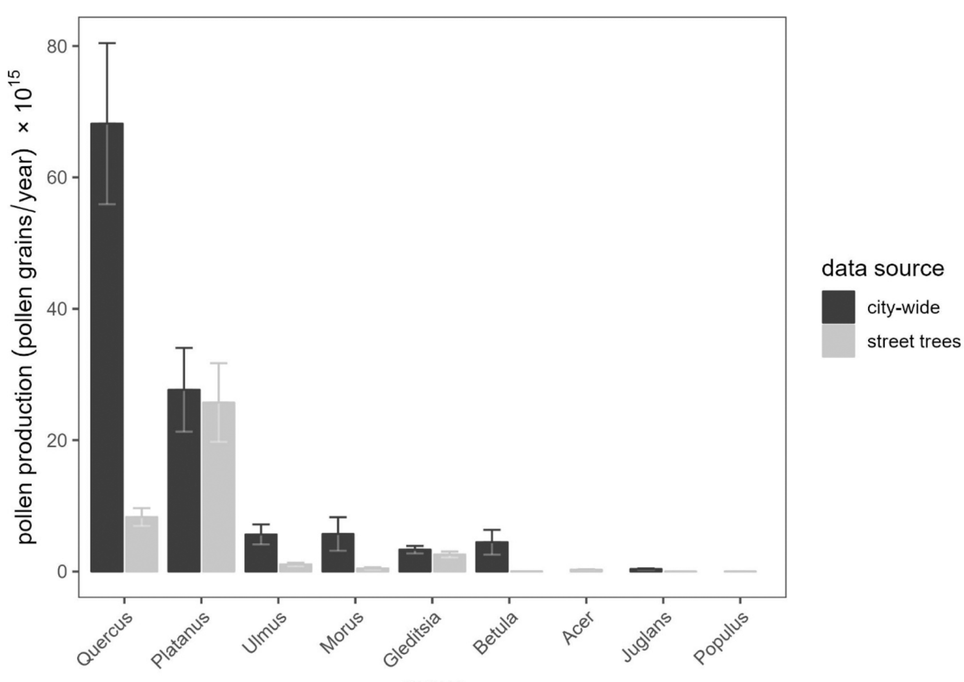

Fig. 1. Estimated total pollen production in quadrillions of pollen grains produced per year for tree genera based on approximately representative city-wide i-Tree Eco dataset and the street tree dataset. Pollen production is based on abundance in each size class for taxa for which allometric equations are available.

produced by current trees (due to mortality) are expected to be approximately offset by the recruitment of new trees. The current size structure of trees (SI 5) varies among taxa as do future changes. For example, *Platanus* trees are currently skewed towards larger sizes, so even with proportional recruitment, pollen production is expected to drop over the coming decades due to diminished growth rates and

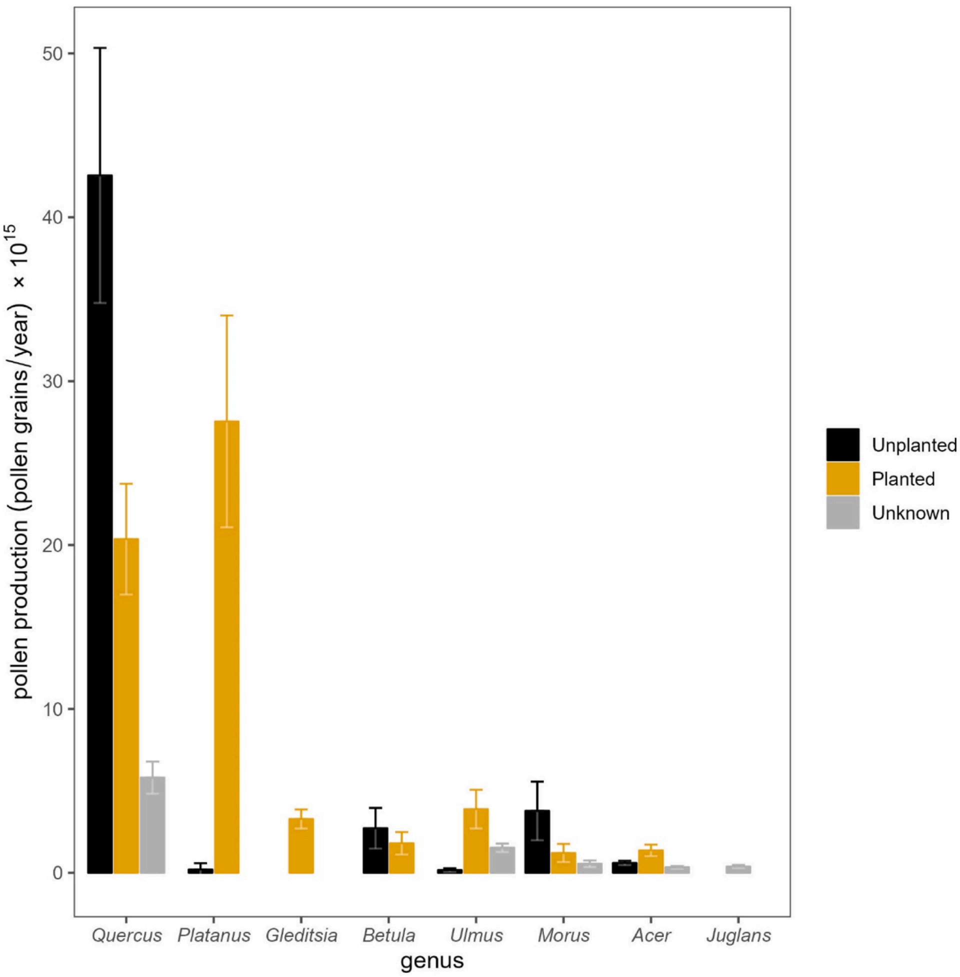

Fig. 2. Pollen production as a function of whether a tree was planted or unplanted or whether the planting status could not be determined ('unknown') according to the city-wide 2013 i-Tree Eco census. Total pollen production for all trees in the focal taxa is summarized at the genus level in quadrillion grains produced per year. The 2013 i-Tree Eco census included measurements from the following number of individual trees in the focal genera: *Acer* (113)*, Betula* (51)*, Gleditsia* (10)*, Juglans* (1)*, Morus* (9)*, Platanus* (24)*, Quercus* (121)*,* and *Ulmus* (12).

deaths of large individuals. In contrast, *Gleditsia* and *Ulmus* trees are skewed towards smaller sizes, so pollen production for these genera are likely to increase over the coming decades regardless of recruitment. The rates of pollen production per individual tree over time also vary substantially among taxa (SI 6).

Airborne pollen was collected on a total of 901 days throughout the primary pollen season in 2009 – 2012. The taxa with the highest relative pollen abundance were *Quercus* (24%), *Morus* (23%), *Betula* (12%), *Platanus* (12%), and Cupressaceae (6%); herbaceous taxa including Poaceae, *Ambrosia,* and *Artemisia,* were of far lower importance (Fig. 4). The taxa with the maximum recorded pollen concentrations (Table 1) were *Morus* (4343 grains/m^3), *Platanus* (2728 grains/m^3)*, Betula* (2397 grains/m^3)*,* and *Quercus* (2159 grains/m^3). Limitations of the airborne pollen concentration data are discussed later.

4. Discussion

4.1. Current pollen production and historical tree selection decisions

Airborne pollen concentrations in NYC are dominated by four tree genera, including *Quercus, Morus, Betula,* and *Platanus.* Of these, only *Platanus* trees were mostly planted, so the historical selection of *Platanus* × *acerifolia* (London planetree; also known as *Platanus* × *hybrida*) for street trees have increased pollen production and subsequent pollen exposure. *Platanus* has also been planted widely in urban areas around the world and is considered of substantial allergenic concern (Cariñanos et al., 2020; Nowak et al., 2012; Varela et al., 1994). However, there are relatively few *Platanus* × *acerifolia* trees in smaller size classes; as existing large trees die over the coming decades, *Platanus* pollen concentrations are expected to decline. The other taxa of substantial allergenic concern are either mostly unplanted (*Morus* and *Betula*) or are already so common in other areas (e.g., parks) that the effects of tree planting on city-wide pollen production have not been major (*Quercus*). While *Gleditsia* was both a moderate producer of pollen and widely planted, its airborne pollen concentrations are generally low; it has also been characterized as entomophilous (Schnabel and Hamrick, 1995). Even so, *Gleditsia* pollen concentrations as high as several hundred grains per cubic meter have been recorded at breathing height elsewhere (Katz and Batterman, 2020).

4.2. Future pollen production and the role of contemporary tree selection decisions

Over the next few decades, we anticipate changes in pollen production due to the growth and mortality of existing trees. For example, based on the i-Tree Eco Forecast simulation, the many small *Gleditsia* trees are expected to continue growing as will their pollen production; this demographically-driven change will not be substantially affected by new plantings but is expected to substantially increase pollen production.

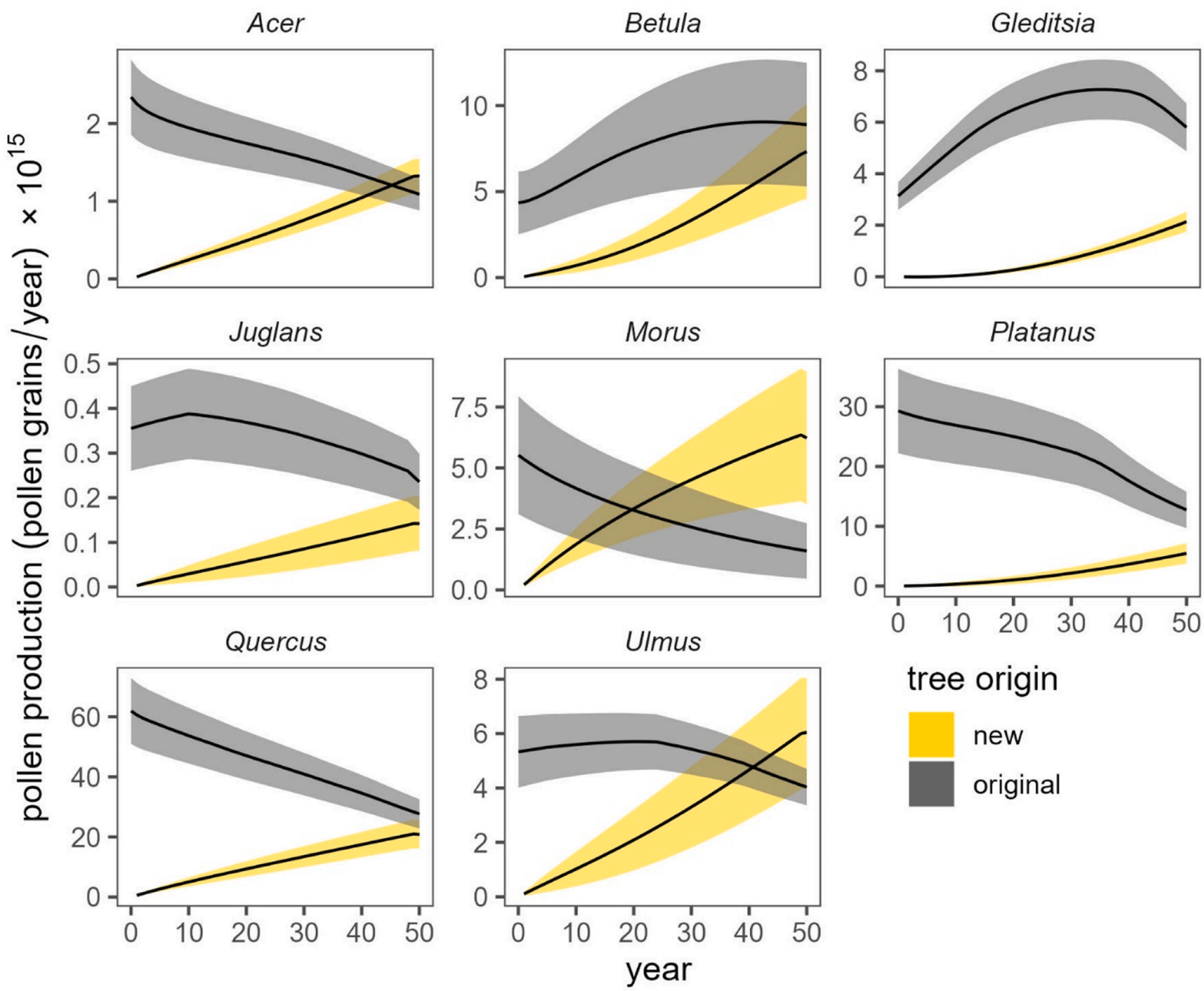

Fig. 3. Simulated pollen production over the coming decades as a function of recruitment, tree growth, and tree mortality. This scenario assumes approximate replacement rates of existing trees (200,000 new trees per year). Estimated pollen production over time (in quadrillion pollen grains per year) is based on equations for tree size as a function of age and equations of pollen production as a function of size. The y-intercept is the 2013 i-Tree Eco city-wide estimate of pollen production for each taxon. Pollen production from existing trees is in gray and pollen production from new trees is in yellow.

Tree planting is the only time when species selection decisions can be easily made (although the effects of tree removal on pollen production has also been explored; Aerts et al., 2021); people have the most potential to influence future pollen production from new individuals (i.e., the yellow bands in Fig. 3). Of tree selection decisions, the most centrally controlled are municipal planting activities, including greening campaigns. Based on current street tree composition in smaller size classes, the NYC Department of Parks and Recreation has been planting relatively few high-pollen tree species recently. Indeed, in the 2015 street tree census there were only 1156 *Morus* street trees (0.18% of total street trees) and 1400 *Betula* trees (0.21% of total street trees). While *Quercus* trees are high pollen producers and are regularly planted as street trees, a relatively low proportion of all *Quercus* trees in NYC are street trees. Thus, if future tree planting decisions by the NYC Department of Parks and Recreation follow trends from recent years, they are unlikely to make a major contribution to city-wide pollen production.

The decisions made by homeowners about what trees to plant – in combination with which species are available from nurseries – have strong influences on tree composition (Avolio et al., 2018); approximately 18% of trees in NYC are on properties of one or two family homes (Maxwell et al., 2021a). Tracking and understanding tree selection decisions by individuals is an area worthy of additional study and might help explain the abundance of certain taxa and perhaps offer a path towards solutions for somewhat reducing the number of highly allergenic trees (e.g., *Betula* and *Morus*). When ranking the importance of various ecosystem services and disservices provided by trees, "spreading pollen" was the 4th lowest item out of 15 (Avolio et al., 2018) and was not raised as a substantial concern by residents in the MillionTreesNYC tree planting campaign (Rae et al., 2011), implying that greater visibility of this issue could help shift tree selection decisions for individuals or perhaps for the nurseries that supply trees to the public.

4.3. Generalizability

Tree cover and composition varies substantially among and within cities and countries due to a range of historical and contemporary circumstances (Roman et al., 2018) as do these trees allergenic potential (Nowak and Ogren, 2021). The results presented here are specific to NYC but may be somewhat similar to other cities in eastern North America (Sousa-Silva et al., 2021), as similar urban processes act to homogenize urban plant composition (Groffman et al., 2014). However, the potential effect of tree planting campaigns on pollen production will likely vary in large part due to the proportion of planted to unplanted trees, which varies dramatically within North America (Nowak, 2012).

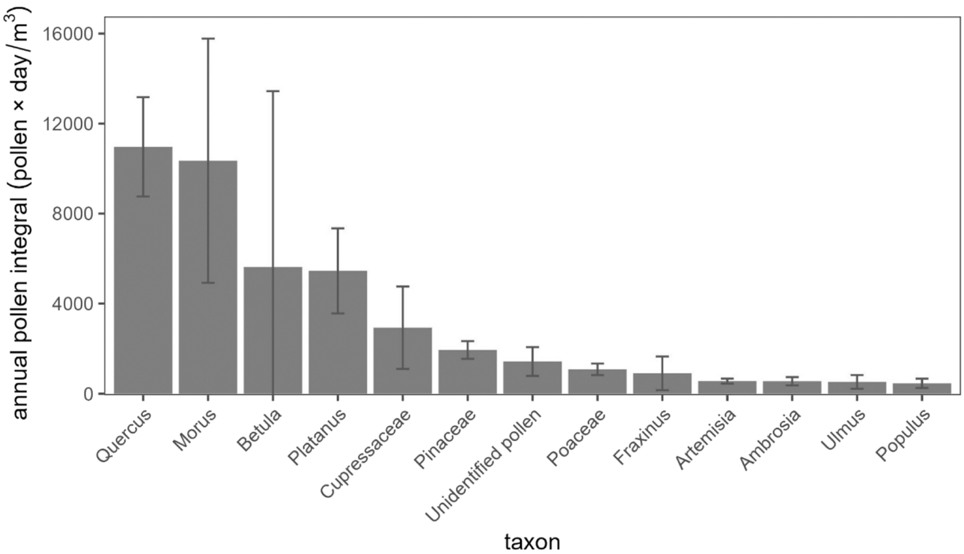

Fig. 4. Annual pollen integral (i.e., cumulative annual pollen concentration) collected for each taxonomic group for taxa that contributed > 5% of total measured pollen. Pollen collection occurred over four years (2009 – 2012) using a Burkard sampler located in Manhattan; error bars are the standard deviation of pollen integrals among years.

4.4. Sex bias ('botanical sexism') in tree planting

There has been considerable discussion of the disproportionate planting of male trees for dioecious species in popular science (Ogren, 2015). However, based on the data from this study, sex bias or 'botanical sexism' is unlikely to play a major role in pollen exposure in NYC. Of the top pollen producing taxa for which we could estimate pollen production, the most important dioecious species belong to the *Morus* genus. Anecdotally, *Morus alba* trees are common as unplanted naturally-regenerating individuals, and are especially frequent along fence lines, vacant lots, and other less-managed areas, suggesting a minimal role for planting let alone botanical sexism in their establishment. In NYC, of the 9 *Morus* trees measured in the i-Tree census, only 2 were marked as planted (Figure SI 4). In Baltimore, 0% of *Morus alba* trees were classified as planted, in Chicago, 25% of *Morus* trees were planted and in Hartford, CT 8% of *Morus rubra* trees were planted (Nowak, 2012). Overall, the low number of planted *Morus* trees leaves relatively few individuals for bias to act upon; in Ann Arbor, MI 57.8% of *Morus alba* trees were male (Katz et al., 2020). The other species with varying sex ratios that we could estimate pollen production for (*Acer negundo, Acer rubrum,* and *Populus deltoides*) do not appear to be substantial producers of allergenic pollen across NYC; moreover, *Acer negundo* and *Populus deltoides* are early successional species and rarely planted intentionally. In contrast, only males of the dioecious species *Ginkgo biloba* are planted because the female fruit-like structures contain butyric acid. While *G. biloba* can cause allergic responses in high risk and exposure populations (Yun et al., 2000), it comprised less than 1% of airborne pollen (but see discussion on the limitations of the airborne pollen data below). Additionally, Cupressaceae does contain many dioecious taxa, including several *Juniperus* species and was a moderate portion of airborne pollen (6% of airborne pollen). We can not conclude that there is no effect of botanical sexism on pollen exposure in NYC, just that it can, at most, determine a few percent of total allergenic pollen exposure. Still, disproportionate planting of male trees of allergic concern could certainly be an issue in regions of the world where there are more dioecious species of allergenic concern (Cariñanos and Casares-Porcel, 2011). Moreover, for dioecious species that are important sources of allergenic pollen, preferentially planting female individuals would reduce local pollen production which could have some effect on nearby airborne pollen concentrations and exposures.

4.5. Spatial variation and pollen dispersion

There is a growing body of literature demonstrating intra-municipal variation in airborne pollen concentrations (Katz et al., 2023, 2019; Katz and Batterman, 2019; Weinberger et al., 2018, 2015; Zapata-Marin et al., 2021), due in part to spatial variation in plant abundance. There is evidence that airborne pollen concentrations are most affected by plants within the same neighborhood i.e., airborne pollen concentrations measured at breathing height are most strongly correlated with source plant abundance within hundreds of meters to a few kilometers for both trees (Katz et al., 2023, 2019) and herbaceous plants (Hjort et al., 2016; Katz and Carey, 2014). This is relevant to the current study in part because the local nature of pollen dispersion cautions against using measurements from Lincoln Center as representative of the entire city. This could help to explain some of the mismatches between predicted pollen production and airborne pollen concentrations (even so, four of the five top genera for city-wide pollen production and airborne pollen measurements overlapped and both estimated pollen production and airborne pollen concentrations were highest for *Quercus*). Indeed the effects of local trees on airborne pollen concentration measurements were observed anecdotally; in the mid-2010 s several large *Platanus* and *Morus* trees near the Lincoln Center pollen monitoring site were removed during construction; lower pollen concentrations were subsequently recorded for those genera (G. Robinson, *personal observation*). This leads to a critical point for tree planting decisions: even though certain taxa may not be especially important producers of pollen on an municipal scale, they could still be of substantial local concern. Thus, a better understanding of which trees occur where and how their pollen disperses is required for fully-informed tree planting decisions.

4.6. Tree pollen allergenicity

Several sources describe the allergic potential of trees (Cariñanos et al., 2016; Ogren, 2015; Pollen.com, 2023), however the information in these metrics are sometimes contradictory between sources or based on expert opinion rather than observed epidemiological effects (Sousa-Silva et al., 2021). Thus, the connection between pollen exposure and health effects remains surprisingly poorly described. This may be due in part to the substantial measurement error of allergenic pollen concentrations in epidemiological analyses (Katz et al., 2019), which makes it challenging to effectively link pollen concentrations with health outcomes. This uncertainty, as well as the complicated nature of allergic sensitization, priming, and both intra- and inter-individual variability in dose-response relationships complicate efforts to connect pollen production to health outcomes. The shape of dose-response curves are directly relevant to tree management decisions such as tree planting. For example, if the effects of pollen on allergic responses are saturating, then attempts to reduce pollen may be wasted effort when there are already many nearby pollen sources. Importantly, allergenicity varies among taxa so the same concentrations of pollen could lead to substantially different health effects.

4.7. Study limitations

The conclusions here are based upon data collected from 2009 – 2016; there were changes in tree composition both within that period and since then (Maxwell et al., 2021b). For example, *Fraxinus* trees have been decimated by the emerald ash borer (*Agrilus planipennis*); it is likely that *Fraxinus* pollen concentrations have dropped since the start of the airborne pollen collection period. However, large changes between the i-Tree survey in 2013 and the street tree survey in 2015 and 2016 are unlikely. A more important source of variation is expected to be the relatively low sample size of the i-Tree survey; only a handful of individuals were recorded for certain taxa of allergic concern, which could contribute substantial stochasticity to estimated city-wide pollen production. In the future, additional tree data from the Urban Forest Inventory and Analysis will be available both in NYC and many other cities nationally (Edgar et al., 2021; US Forest Service, 2016), which could help to address this concern.

Pollen production for several potentially important tree taxa remains unknown; here, this includes Cupressaceae (6% of airborne pollen measured; although this may be a slight underestimate due to the later start of pollen monitoring in 2009) and *Fraxinus* (2% of airborne pollen measured). The approach used here (i.e., applying equations for one or two species to all congenerics within *Quercus, Populus, Morus,* and *Ulmus*) is coarse and adds additional uncertainty to estimated total pollen production. These pollen production equations were also developed with street trees, so may not be as well suited for trees growing in closed canopy forests, which generally experience higher competition. Thus, the results presented here likely overestimate total pollen production for species that are common in natural areas in NYC, including *Quercus.* These pollen production equations were also developed in a different location (although one with a similar climate and likely similar tree maintenance regime) and only include data from two years (Katz et al., 2020); there can be substantial differences in reproductive effort among years (Fernández-Martínez et al., 2012; Ranta et al., 2008) or in general biomass allometry between populations growing in different conditions (Fortier et al., 2017; Hulshof et al., 2015). These are an additional source of uncertainty in the present study and reinforce the need for additional replication of tree pollen production studies. This study also neglects the steps between pollen production and exposure; in addition to differential pollen production, different rates of entrainment and dispersion, such as the explosive release of pollen by *Morus* (Taylor et al., 2006), may also help to explain discrepancies in pollen production compared to airborne pollen measurements.

The i-Tree Eco Forecast simulations also have several limitations, and do not take many potentially important variables into account, such as changes in pollen production due to increases in temperature and carbon dioxide or the effects of invasive pests and pathogens on tree mortality. Here, we used the default mortality rate of 3% and default growth rates, which vary slightly from those of open grown street trees reported elsewhere (McPherson et al., 2016) and do not account for differences in management (e.g., irrigation, pruning, etc.,). The recruitment rate is also dependent upon many considerations, including the implementation of proposed future greening campaigns. Despite these sources of uncertainty, the general premise is sound: somewhat predictable demographic processes like growth and mortality will have direct consequences for pollen production, resulting in decreases in pollen production for taxa that are heavily skewed towards large individuals (e.g., *Platanus*) and the opposite for taxa that have many smaller individuals (e.g., *Gleditsia*).

5. Conclusion

There is substantial interest in tree planting campaigns (Eisenman et al., 2021b; Sousa-Silva et al., 2023) as cities turn towards green infrastructure to increase cooling and other ecosystem services provided by trees (Doroski et al., 2020; Rahman et al., 2020). However, to optimize the benefits of tree planting campaigns, ecosystem disservices such as allergenic pollen must also be taken into account (Eisenman et al., 2019). Urban foresters balance multiple suitability concerns including tree diversity and stock availability when selecting trees for planting; thus, considerations besides allergenicity generally should determine tree selection decisions. However, the results presented here show how planting large numbers of *Platanus* × *acerifolia* trees has had long-term consequences for pollen production and exposure; this example provides strong incentive to include allergenic potential in tree selection decisions. However, other species of allergenic concern were not predominantly planted, and recent municipal planting practices do not seem to have substantially exacerbated citywide allergenic pollen production in NYC. Nonetheless, the increasing evidence of intra-municipal variation in airborne pollen concentrations suggests that planting allergenic pollen producing trees will have notable local and neighborhood level effects over time spans of decades, implying that the worst offending trees should not be planted in or near residential areas. From an allergy perspective, potential substitutes include the many taxa of trees that are insect-pollinated, have non-allergenic pollen, or are females of dioecious species (Cariñanos and Casares-Porcel, 2011; Green et al., 2018).

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CRediT authorship contribution statement

Robinson Guy: Data curation, Writing – review & editing. **Katz Daniel Sylvan Walker:** Conceptualization, Data curation, Formal analysis, Writing – original draft, Writing – review & editing. **Ellis Alexis:** Software. **Nowak David:** Software, Writing – review & editing.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Daniel Katz reports financial support was provided by Bayer Health. There are no additional interests to declare.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ufug.2024.128208.

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