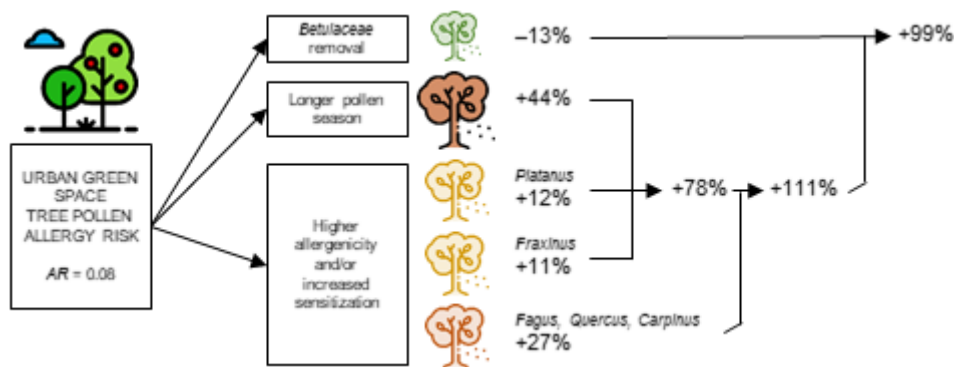


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# **Tree pollen allergy risks and changes across scenarios in urban green spaces in Brussels, Belgium**

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## **Highlights**

- We studied allergy risks (AR) of 18 green spaces in Brussels, Belgium
- We examined present and possible future AR across contrasting scenarios
- Increased tree allergenic potential resulted in 11–27% higher AR
- Increased pollen season duration resulted in 44% higher AR
- AR increased by 99% in combined scenarios despite preventive tree removal

## Abstract

Urban green spaces may improve human health and well-being. However, green spaces may also emit allergenic pollen and these may trigger asthma, allergic disease, and respiratory infections. How allergy risks in green spaces may be modified by environmental change is still not widely understood.

This study analyzed tree inventory data of 18 urban green spaces (5940 trees; 278 taxa; 93 ha) in the Brussels Capital Region, Belgium. We investigated present tree pollen allergy risk (AR) and changes in AR driven by changes in tree species composition, allergenic potential and pollen season duration. AR was estimated by calculating the allergenicity index  $I_{UGZA}$  (range 0–1, 1 worst) for the present situation and 13 scenarios.

The average AR was 0.08 (SD 0.05; range 0.002–0.17). The AR increased by 11–27% in increased allergenic potential scenarios, and by 44% in the increased pollen season duration scenario. Preventive removal of birch, hazel and alder reduced the AR by 13%. The AR increased by 99–111% in combined scenarios with and without preventive removal of the main allergenic taxa.

These findings indicate that tree pollen allergy risks could considerably rise when ongoing environmental changes lead to a combination of longer pollen seasons, increased pollen allergen potency, and increased sensitization for one or more species. The preventive removal of the main allergenic tree species cannot sufficiently counter allergy risks caused by other species and that are amplified by environmental change, highlighting the importance of careful tree species selection in urban green space policy and planning.

## Keywords

Allergy risk scenarios; Allergenic trees; Index of allergenicity; Urban green areas; Urban parks; Climate change

## Glossary

Urban green space tree pollen allergy risk (AR)	Relative risk of an urban green space to provoke allergic symptoms, compared to a green space with the highest possible density of the most allergenic tree species growing in optimal conditions (e.g. homogeneous birch forest)
Tree allergenicity	Contribution of an individual tree to the AR of a green space
Allergenic potential (AP)	A combination of pollen allergen potency and allergen sensitization of the population that determines the allergenicity of tree species
Pollen allergen potency	The amount of allergens measured as mass per pollen grain

# 1. Introduction

Urban green spaces may improve human health and well-being, for example by improving social cohesion, by promoting physical activity, or by reducing noise, heat and other environmental stress (James, Banay, Hart, & Laden, 2015; van den Bosch & Sang, 2017; Collins et al., 2020). Trees in urban green spaces are considered to be among the best nature-based solutions for a number of important challenges in the urban environment: trees ameliorate the urban microclimate and reduce the urban heat island effect, trees intercept precipitation and help to prevent peak water runoff, and trees help to mitigate the effects of the climate crisis by capturing and storing carbon (Roy, Byrne, & Pickering, 2012; Salmond et al., 2016). As a result, trees often emerge as the drivers of the numerous health benefits that are associated with urban green space, including improved mental health (Aerts et al., 2020), lower allergen sensitization rates (Gernes et al., 2019), lower odds of diabetes and hypertension (Astell-Burt & Feng, 2019), improved childhood respiratory health (de Oliveira e Almeida et al., 2020), lower cardiovascular and respiratory mortality risk (Donovan et al., 2013; Blount et al., 2020), and the reduction of preventable premature deaths (Kondo et al., 2020).

However, trees in urban green spaces may also produce and emit allergenic pollen (Thompson & Thompson, 2003; Cariñanos & Casares-Porcel, 2011; Cheng & Berry, 2013; Cariñanos et al., 2017; Kasprzyk, Cwik, Kluska, Wojcik, & Cariñanos, 2019; Lara, Rojo, Fernández-González, & Pérez-Badia, 2019; Cariñanos, Ruiz-Peñuela, Valle, & de la Guardia, 2020). An increasing number of studies has found that allergenic pollen, in combination with air pollution and other agents such as fungal spores, may initiate airway inflammation, trigger allergic respiratory disease, and increase susceptibility to respiratory viral infections (Dadvand et al., 2014; Lambert et al., 2017; Eisenman, Jariwala, & Lovasi, 2019; Lai & Kontokosta, 2019; Gilles et al., 2020; Lambert et al., 2020; Lee et al., 2020). The health risks

associated with tree pollen are therefore important public health aspects of urban green spaces (van Dorn, 2017; Eisenman et al., 2019; Jia, Wang, van Vliet, Skidmore, & van Aalst, 2020; Sousa-Silva, Smargiassi, Paquette, Kaiser, & Kneeshaw, 2020).

The allergy risks posed by trees in urban green spaces are primarily determined by the tree species composition (allergenic vs. non-allergenic tree species) and the abundance of trees (the number of trees). The allergenicity of individual trees depends on their dimensions (in particular crown volume, which depends on tree height, crown diameter and crown shape) and on a number of specific traits of the tree species: the pollen allergen potency (the amount of allergens measured as mass per pollen grain), the pollen dispersal syndrome (higher risks in wind-dispersed species), and the pollen season duration (Cariñanos, Casares-Porcel, & Quesada-Rubio, 2014). The allergenicity of individual tree species may vary across regions as there are regional differences in pollen allergen sensitization (Röseler et al., 2020). For example, planes (*Platanus* spp.), olive (*Olea europaea*), and some maples (*Acer* spp.) may be highly allergenic throughout their native distributional range but only mildly allergenic (at the population level) in their introduced range. Non-indigenous allergenic plants usually have less impact on allergies than indigenous allergenic plants because they are generally found in lower abundance and produce allergens for which the general population is not yet sensitized. However, in some cases, introduced species may become important allergenic plants outside of their natural ranges, especially when these species are cultivated or when they have become naturalized, occur in large quantities and are present in or near densely populated areas (e.g. *Cupressus arizonica* in Spain or *Ambrosia artemisiifolia* in Central Europe) (Rojo, Rapp, Lara, Sabariego, Fernández-González, & Pérez-Badia, 2016; Lake et al., 2017). In urban green spaces in NW Europe, three indigenous taxa, i.e. birch (*Betula* spp.), alder (*Alnus* spp.) and hazel (*Corylus* spp.), are the most important sources of allergenic tree pollen (Damialis, Traidl-Hoffmann, & Treudler, 2019).

There are a number of global environmental challenges which are expected to increase the amount and the allergen potency of airborne allergenic pollen, resulting in higher allergy risks (Damialis et al., 2019; D'Amato, Cecchi, Annesi-Maesano, & D'Amato, 2018). Higher temperatures under the influence of climate change and the urban heat island effect, combined with traffic-related air pollution (ozone [O<sub>3</sub>] and nitrogen dioxide [NO<sub>2</sub>]), elevated carbon dioxide (CO<sub>2</sub>) concentrations and nutrient deposition (e.g. nitrogen), may contribute to increases in length and intensity of pollination seasons (Reed & Gamble, 2009; D'Amato, Vitale, Lanza, Molino, & D'Amato, 2016). Several studies have already reported an earlier onset of the pollen season for birch, oak (*Quercus* spp.), ash (*Fraxinus* spp.) and plane, an increase in daily airborne tree pollen concentrations of alder, hazel, ash and plane, and an increase of the number of days with pollen concentrations exceeding the critical threshold for provoking allergy symptoms in the sensitized population (Zielo et al., 2012; Bruffaerts et al., 2018; Hoebeke et al., 2018; Damialis et al., 2019; Ziska et al., 2019). Increased CO<sub>2</sub> concentrations have been associated with higher plant total biomass and pollen production (Ziska et al., 2003), whereas long-term high O<sub>3</sub> and NO<sub>2</sub> levels in urban environments have been associated with increased allergenicity of pollen of a number of species including birch (Beck et al., 2013; Zhao et al., 2016; Gilles et al., 2018; Plaza, Alcázar, Oteros, & Galán, 2020). As a result of longer exposure to higher amounts of more potent allergenic pollen, sensitization rates for the major tree pollen allergens have increased, as well as the frequency and severity of pollen-induced allergy, asthma, and respiratory disease (Heinzerling et al., 2009; D'Amato & Cecchi, 2008; Damialis et al., 2019).

Previous works on urban green space allergy risks have insufficiently addressed the potential impacts of environmental change. A better understanding of the existing and potential future allergy risks posed by urban green spaces may guide urban planning decisions (van Dorn, 2017), inform urban green space management (Cariñanos & Casares-



Porcel, 2011), and help pollen allergy patients to avoid environmental triggers during the airborne pollen season (D'Amato et al., 2020). The aim of our study was therefore to examine tree pollen allergy risks in urban green spaces in the Brussels Capital Region, Belgium, and changes in allergy risks associated with green space interventions, potential changes in tree allergenic potential and increased pollination duration.

## 2. Methods

### 2.1. Study sites and tree data

We used tree inventory datasets of 18 urban green spaces in the Brussels Capital Region, Belgium (Table S1, Fig. 1). The datasets contained records for all trees present in the 18 green spaces ( $n = 5940$  trees). For each tree, we extracted the following data: X and Y coordinates of the tree, species name, circumference at 1.5 m height (cm), tree height class (2–5 m, 5–10 m, 10–15 m, 15–20 m, 20–25 m, 25–30 m), and crown diameter class (1–5 m, 5–10 m, 10–15 m, 15–20 m, 20–25 m, 25–30 m). The extent of each green space was determined in Google Earth, using the tree location data as reference. Green space surface areas were measured (ha) and these values included, when present, impervious surfaces and water bodies located within the urban green space. The surface areas and numbers of trees recorded in the green spaces included in this study are listed in Table S1.

### 2.2. Tree pollen allergy risk

The present tree pollen allergy risk of urban green spaces was determined using the urban green zone allergenicity index ( $I_{UGZA}$ ) method, which was proposed by Cariñanos, Casares-Porcel, & Quesada-Rubio (2014). It takes into account tree dimensions and the allergenic potential, pollination syndrome, and pollen season duration of different tree species. Here we extended the  $I_{UGZA}$  method to assess changes in tree pollen allergy risk associated with aspects of

environmental change. The formula to calculate  $I_{UGZA}$  was modified in such a way that the index could be calculated using the data from individual trees contained in our tree inventory datasets:

$$I_{UGZA} = \frac{1}{a \times S_T} \sum_{i=1}^n AP_i \times PS_i \times PSD_i \times S_i \times H_i$$

where  $n$  = the number of trees,  $AP_i$  = the allergenic potential of tree  $i$  (0: non-allergenic, 1: low allergenicity, 2: moderate allergenicity, 3: high allergenicity, or 4: main local allergen, in this study  $AP_i = 4$  for *Betula pendula*, *Alnus glutinosa*, *Alnus incana*, and *Corylus avellana*; D'Amato et al., 2007; Damialis et al., 2019),  $PS_i$  = the pollination syndrome of tree  $i$  (0: no pollen dispersal (only female individuals), 1: entomophilous (insect-pollinated), 2: amphiphilous (insect- or wind-pollinated), 3: anemophilous (wind-pollinated)),  $PSD_i$  = the pollen season duration of tree  $i$  (1: 1–3 weeks, 2: 4–6 weeks, 3: more than 6 weeks),  $S_i$  = the vertical crown projection area of tree  $i$  (m<sup>2</sup>) calculated from the crown diameter  $D_i$  as  $S_i = \pi \times (D_i/2)^2$ ,  $H_i$  = the height of tree  $i$  (m),  $S_T$  = the total surface area of the urban green space (m<sup>2</sup>), and  $a$  = a scale variable that sets the range of  $I_{UGZA}$  so that  $I_{UGZA} = 0$  for non-allergenic urban green spaces and  $I_{UGZA} = 1$  for urban green spaces with maximum tree pollen allergy risk. The scale variable depends on the maxima of four variables:  $a = AP_{imax} \times PS_{imax} \times PSD_{imax} \times H_{imax} = 4 \times 3 \times 3 \times 30 = 1080$  [note that we have used a maximum tree height of 30 m, which is larger than the maximum tree height used in Cariñanos, Casares-Porcel, & Quesada-Rubio (2014) (14 m) but which is better adapted to the local growing conditions]. A hypothetical homogeneous, even-aged birch forest with 100% crown cover and canopy height of 30 m maximally fills the hypothetical green space with the most allergenic tree species (in this region) and would obtain  $I_{UGZA} = 1$ .  $I_{UGZA}$  can thus be interpreted as the relative tree pollen allergy risk compared to the reference urban green space with the highest tree pollen allergy risk, i.e. homogeneous birch forest (Fig. S1). The values of the allergenic potential, pollination

syndrome and pollen season duration of the allergenic tree species ( $AP_i > 0$ ) that were used in this study were adapted from Cariñanos, Casares-Porcel, & Quesada-Rubio (2014) based on the airborne pollen observations of the Belgian Aerobiological Surveillance Network and are listed in Table S2.

Because tree height and crown diameter were ordinal (class) data, we used a randomization function to assign random integer values between the lower and upper limits of the classes as estimates for tree height  $H_i$  and crown diameter  $D_i$ . We calculated multiple values of  $I_{UGZA}$  for each urban green space, in which new random integer numbers for  $H_i$  and  $D_i$  were generated for each tree for every calculation of  $I_{UGZA}$  ( $k = 20$  iterations for every green space  $\times$  scenario combination). The standard deviations associated with average  $I_{UGZA}$  values consequently reflect uncertainty in the tree dimension data.

### 2.3. Change scenarios

First, the tree pollen allergy risk of each urban green space was calculated for the present situation (baseline  $I_{UGZA}$ ). Then  $I_{UGZA}$  was calculated repeatedly for 13 scenarios that represented potential changes in tree species composition, allergenic potential, and pollen season duration, respectively by removing trees from the inventory, by adjusting  $AP_i$  values, or by adjusting  $PSD_i$  values (Table 1). Changes in allergenic potential could be due to increased pollen allergen potency, increased sensitization of the population, or increased cross-reactivity between pollen of different tree species (e.g. between birch pollen and pollen of oak, beech [*Fagus sylvatica*], chestnut [*Castanea sativa*] and hornbeam [*Carpinus betulus*]).

The main scenarios were: TR1, removal of all ash trees following ash dieback [an ongoing destructive fungal disease caused by the ascomycete fungus *Hymenoscyphus fraxineus* (syn. *Chalara fraxinea*) and which may temporarily intensify ash pollen emissions (Gassner, Schmid-Grendelmeier, & Clot, 2019)]; TR2, preventive removal of all birch, alder,

and hazel trees to reduce allergy risk; TR3, removal of all horse chestnut trees following horse chestnut dieback (an ongoing disease primarily caused by the bacterium *Pseudomonas syringae* pv. *aesculi*); IP1, increased allergenic potential of birch, alder, and hazel; IP2, increased allergenic potential of plane; IP3, increased allergenic potential of ash; IP4, increased allergenic potential of oak, beech, chestnut and hornbeam; IPD, increased pollination duration; CS1, increased pollination duration + increased allergenic potential of ash and plane (scenarios IP2 + IP3 + IPD); CS2, increased pollination duration + increased allergenic potential of ash, plane, oak, beech, chestnut, and hornbeam (scenarios IP2 + IP3 + IP4 + IPD); and CS3, increased pollination duration + increased allergenic potential of ash, plane, oak, beech, chestnut, hornbeam, birch, alder, and hazel (scenarios IP1 + IP2 + IP3 + IP4 + IPD).

We then combined the preventive tree removal scenario TR2 with two combined scenarios (CS1, CS2) to determine whether preventive removal of the main allergenic tree species could sufficiently counter increases in AR caused by other species (CS4: scenarios IP2 + IP3 + IPD + TR2; CS5: scenarios IP2 + IP3 + IP4 + IPD + TR2). We did not combine CS3 with TR2 as removal of birch, alder, and hazel trees cancels out the effect of increased allergenic potential of these species.

## 2.4. Statistical analysis

Because the magnitude of changes in tree pollen allergy risks depends on the initial risk, urban green spaces were first stratified in two groups: green spaces with ‘low’ vs. ‘high’ initial tree pollen allergy risk (i.e. average baseline  $I_{UGZA}$  below vs. above the overall median). Change scenarios within these two groups were then evaluated using linear mixed models. We used scenario as the fixed effect and green space ID as subject variable. We included a random intercept to account for the multiple estimations of  $I_{UGZA}$  per scenario per

urban green space. We calculated estimated marginal means for all scenarios. We present the mean difference in tree pollen allergy risk between scenario and baseline ( $\Delta I_{UGZA}$ ) and the 95% confidence intervals (CI) of this difference and the associated  $p$  values as the scenario effects. Statistical analyses were performed with IBM SPSS Statistics Subscription 11-2018 software.

### 3. Results

#### 3.1. Green space characteristics

The most abundant tree species were *Acer pseudoplatanus* ( $n = 793$  individual trees; 13% of the trees included in the dataset) and *Taxus baccata* ( $n = 612$ ; 10%), which are considered to play no role in pollinosis in Belgium at the population level. The most abundant allergenic tree species was *Fraxinus excelsior* ( $n = 466$ ; 8%). The most frequent tree species were *Acer platanoides* (present in 17 of 18 green spaces), *F. excelsior* (17) and *Carpinus betulus* (16) (Table 2). The main allergenic tree species, *Corylus avellana*, *Alnus glutinosa* and *Betula pendula*, were present in respectively 6, 8 and 11 green spaces but were much less abundant (only 1.3, 1.3 and 0.2% of all included trees, respectively). Other characteristics of the green spaces are presented in Table S1.

#### 3.2. Baseline allergy risk

The overall average baseline allergy risk across all green spaces was 0.079 (SD 0.047; range 0.002–0.18; 95% CI 0.074–0.084); the median baseline allergy risk was 0.081 (interquartile range IQR = 0.053). In the subset of green spaces with low baseline allergy risk ( $I_{UGZA} <$  median), the average baseline allergy risk was 0.043 (95% CI 0.015–0.071), compared to 0.114 (95% CI 0.089–0.140) in the subset of green spaces with high baseline allergy risk ( $I_{UGZA} >$  median) (Fig. 2; Table S3).

### 3.3. Changes of allergy risk across scenarios

The changes of allergy risks across scenarios are summarized in Fig. 3, Table S3, and Table S4. In the scenarios for increased allergenic potential (IP2, IP3, IP4),  $\Delta I_{UGZA}$  was 0.006 (95% CI 0.003; 0.009) for *Platanus* (+14%,  $p < 0.001$ ), 0.003 (95% CI 0.000; 0.006) for *Fraxinus* (+7%,  $p = 0.042$ ), and 0.013 (95% CI 0.011; 0.016) for the group *Quercus*, *Fagus*, *Castanea*, and *Carpinus* (+30%,  $p < 0.001$ ) in the green spaces with low baseline allergy risk. In the green spaces with high baseline allergy risk,  $\Delta I_{UGZA}$  was 0.014 (95% CI 0.011; 0.018) for *Platanus* (+12%), 0.017 (0.013; 0.020) for *Fraxinus* (+15%) and 0.030 (0.026; 0.033) for the group *Quercus*, *Fagus*, *Castanea*, and *Carpinus* (+26%) (all  $p < 0.001$ ). The scenario for increased allergenic potential of birch, hazel and alder (IP1) had no significant effect on tree pollen allergy risk ( $\Delta I_{UGZA} = 0.001$ , 95% CI  $-0.002$ ; 0.004,  $p = 0.657$  and  $\Delta I_{UGZA} = 0.000$ , 95% CI  $-0.003$ ; 0.004,  $p = 0.917$  for green spaces with low and high baseline allergy risk, respectively) because the allergenic potential was already maximal ( $AP_i = 4$ ) for the main allergenic species.

In the scenario for increased pollination duration (IPD),  $\Delta I_{UGZA}$  was 0.019 (0.016; 0.022) in the green spaces with low baseline allergy risk (+44%) and 0.052 (0.048; 0.055) in the green spaces with high baseline allergy risk (+46%) (all  $p < 0.001$ ).

In the scenarios of combined increased allergenic potential and increased pollination duration (CS1, CS2, CS3),  $\Delta I_{UGZA}$  was 0.033 (0.030; 0.036), 0.048 (0.045; 0.051), and 0.049 (0.046; 0.052) in the green spaces with low baseline allergy risk (+76%, +112%, and +114%) and 0.097 (0.096; 0.101) for CS1 and 0.134 (0.130; 0.137) for CS2 and CS3 in the green spaces with high baseline allergy risk (+85% and +118%) (all  $p < 0.001$ ).

In the scenarios that simulated dieback of *Fraxinus* (TR1), preventive removal of *Betulaceae* (TR2), and dieback of *Aesculus* (TR3),  $\Delta I_{UGZA}$  was  $-0.006$  ( $-0.009$ ;  $-0.003$ ) for TR1 and TR2 (both  $p < 0.001$ ) and  $-0.005$  ( $-0.008$ ;  $-0.002$ ) for TR3 ( $p = 0.002$ ) in the green

spaces with low baseline allergy risk (−14% and −12%) and −0.032 (−0.036; −0.028), −0.015 (−0.019; −0.011), and −0.009 (−0.012; −0.005) in the green spaces with high baseline allergy risk (−28%, −13%, and −8%) (all  $p < 0.001$ ).

In the scenarios that combined the preventive tree removal scenario with the two combined scenarios (CS4, CS5),  $\Delta I_{UGZA}$  was 0.026 (0.023; 0.029) and 0.042 (0.039; 0.045) in the green spaces with low baseline allergy risk (+61%, +98%) and 0.079 (0.075; 0.083) and 0.117 (0.113; 0.121) in the green spaces with high baseline allergy risk (+69%, +103%) (all  $p < 0.001$ ).

## 4. Discussion

### 4.1. Main findings

We investigated tree pollen allergy risks in urban green spaces in the Brussels Capital Region in Belgium. The allergy risk due to exposure to locally emitted pollen is at present low, in part because of the limited presence of the main allergenic tree genera *Corylus*, *Alnus* and *Betula*. However, several tree species with low to moderate allergenicity, in particular *Fraxinus excelsior*, occur in a large proportion of the studied green spaces and in relatively high quantities. Therefore, tree pollen allergy risks could considerably rise when ongoing environmental changes lead to a combination of longer pollen seasons, increased pollen allergen potency, and increased sensitization for one or more species. In our estimates for such combined scenarios, the allergy risk doubles in all green spaces, irrespective of low or high baseline allergy risk. The preventive removal of the main allergenic tree species cannot sufficiently counter increases in allergy risks caused by other species.

## 4.2. Comparison with other studies

The allergenicity index  $I_{UGZA}$  was used earlier to assess the allergy risks of urban green spaces, with the majority of studies carried out in Mediterranean cities. In the original study that described the allergenicity index, one green space located in Granada (Spain) had a  $I_{UGZA} = 0.14$  (Cariñanos, Casares-Porcel, & Quesada-Rubio, 2014). In a study of the 8 most important urban green areas in the city of Córdoba (Spain), the  $I_{UGZA}$  ranged between 0.04 and 0.60, with an average of 0.25 (95% CI 0.06–0.43) (Velasco-Jiménez, Alcázar, Cariñanos, & Galán, 2020). In a study of 26 urban green spaces in 24 Spanish cities, the  $I_{UGZA}$  ranged between 0.07 and 0.87, with an average of 0.34 (95% CI 0.25–0.43) (Cariñanos et al., 2017). In a broader study of 34 urban green spaces located in 23 cities in six Mediterranean countries (France, Italy, Morocco, Portugal, Spain, and Slovenia), the  $I_{UGZA}$  ranged between 0.03 and 1.00, with an average of 0.27 (95% CI 0.18–0.37) (Cariñanos et al., 2019). One study of three green spaces in Rzeszów (South-Eastern Poland) reported an average  $I_{UGZA}$  of 0.26 (SD 0.06) (Kasprzyk, Cwik, Kluska, Wojcik, & Cariñanos, 2019) and another study of one green space located in Eichstätt (Germany) reported an  $I_{UGZA} = 0.17$  (Jochner-Oette, Stitz, Jetschni, & Cariñanos, 2018).

The  $I_{UGZA}$  values recorded in the urban green spaces of the Brussels Capital Region were on average much lower than those recorded in the Mediterranean cities and elsewhere, and could in most cases be considered to be low (Fig. 2, Table S3). Compared to the Mediterranean green spaces, *Platanus* was much less frequent and abundant in Brussels, leading to lower  $I_{UGZA}$  values. In the Mediterranean cities more taxa contributed to the allergenicity index. Some taxa with high allergenicity in the Mediterranean green spaces such as Australian pine (*Casuarina equisetifolia*) and Tuscan cypress (*Cupressus sempervirens*) were not present in our sample. Two other species, paper mulberry (*Broussonetia papyrifera*) and mulberry (*Morus* spp.), were present in the studied green



spaces in Brussels but there were only a few individuals. Both species are not considered to play a role in pollinosis in the region (yet) ( $AP = 0$ ), although they have pollen that has been linked to allergic reactions elsewhere (Zanforlin & Incorvaia, 2004; Wu, Su, Lung, Chen, & Lin, 2019; Qazi, Iqbal, & Khan, 2019; Papia, Incorvaia, Genovese, Gangemi, & Minciullo, 2020). Also, we focused on allergy risks associated with tree pollen and have not included grasses or herbaceous vegetation in our assessment. Including grass in our calculation of allergy risks could considerably increase the values of  $I_{UGZA}$ .

### 4.3. Implication for management

The allergy risks increased by 11–27% in increased allergenic potential scenarios, and by 44% in the increased pollen season duration scenario. Preventive removal of birch, hazel and alder reduced the AR by 13%. The AR increased by 99–111% in combined scenarios with and without preventive removal of the main allergenic taxa. The increased pollen season duration was therefore the main driver of increased allergy risks. The length of the pollen season nor the allergenic potential of tree species can be influenced by green space management. Therefore, removing allergenic tree species and replacement by non-allergenic taxa seems to be the only method to efficiently counter increasing tree pollen allergy risks. Indeed, Mrdan, Ljubojevic, Orlovic, Cukanovic, & Dulic (2017) suggested to remove birch and other allergenic tree species from school yards to reduce childhood allergy risks. Maya-Manzano et al. (2017) proposed to reduce the number of trees with wind-dispersed pollen and to eliminate male (pollen-producing) trees to decrease the amount of allergenic pollen in the air. However, the removal of the main allergenic genera *Corylus*, *Alnus* and *Betula* (TR2) resulted only in a limited reduction of the allergy risks because these taxa are present but not numerous in the studied green spaces. Therefore, the marginal reduction of the allergy risk probably does not justify the potential biodiversity losses that would be caused by removing

these tree species. Similarly, increased sensitization to *Platanus* pollen amplified green space allergenic potential, but only by 12%. Because the ecosystem services of *Platanus*, in particular providing shade and mitigating urban heat, may outweigh the potential increases in pollen allergy burden, and because the removal of large old trees is usually not appreciated by the public, removing *Platanus* trees is – at present – not recommended either. We propose that management options that aim to mitigate the impact of allergens on the health of the population and that include tree removal, should always be screened for their effectiveness by calculating allergy risk changes across different scenarios. For the design of new green spaces, allergenicity of tree species should be taken into account (Vogt et al., 2017; Lara et al., 2020).

#### 4.4. Limitations

Our research may have a number of limitations. First, the allergenicity index does not take into account the inter-annual variability of pollen season intensities and can therefore not be used to compare the allergy risks between low seed years and mast seeding years. Second, the allergenicity index does not take into account variability in the pollen production capacity. At very local and even individual tree scale, tree phenology can be influenced by many environmental factors including intra-urban temperature variation (Katz, Dzul, Kendel, & Batterman, 2019). Therefore, green spaces with exactly the same allergenicity index might present different AR because of locally modified pollen production intensity and duration. Third, the allergenicity index as used in this study focusses on tree pollen, and therefore does not take into account allergy risks associated with grass pollen and allergenic herbs such as mugwort (*Artemisia vulgaris*) and novel pollen allergens such as the invasive alien ragweed (*Ambrosia artemisiifolia*) and Bermuda grass (*Cynodon dactylon*) (Röseler et al., 2020). Grass pollen is the leading aeroallergen in world (García-Mozo, 2017) and ragweed may become a

major source of allergens throughout Europe (Lake et al., 2017). However, lawns probably contribute little to the overall allergy risk of urban green spaces as frequent mowing limits flowering and hence pollen emissions. Fourth, the allergenicity index does not take into account pollen released by vegetation in the surrounding landscape, such as street trees, gardens, road verges or other urban green spaces, nor does it account for long range transport of allergenic pollen. Finally, it is difficult to translate tree pollen allergy risk of urban green spaces to risks at the level of the individual, as exposure to a single allergenic tree in full bloom may provoke strong allergic reactions in sensitized individuals even if the green space has an overall low allergy risk.

## 5. Conclusion

In conclusion, we estimated that the tree pollen allergy burden of urban green spaces could considerably increase under the influence of global environmental changes that lead to longer pollen season duration, increased pollen allergen potency, and higher sensitization of the population. Allergenic tree diseases and preventive removal of the main allergenic trees may only partially mitigate allergy risks that are amplified by environmental change. While it may be worth to invest in the establishment of new hypoallergenic green spaces in and near cities, the removal of allergenic tree taxa such as *Betula* and *Platanus* from existing green spaces is not recommended in the light of the conservation of biodiversity and important ecosystem services. These results highlight the importance of careful tree species selection in future urban green space policy and planning.

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**Table 1.** Methods to calculate tree pollen allergy risks in urban green spaces for scenarios for changes in tree species composition, allergenic potential and pollen season duration

Scenario	Description	Method
baseline	Present-day allergy risk (Fig. S2)	Calculate $I_{UGZA}$ using baseline values for $AP$ , $PS$ and $PSD$ (Table S2)
TR1	Removal of all ash trees following ash dieback	Set $AP = 0$ for all <i>Fraxinus</i> trees
TR2	Preventive removal of birch, alder and hazel trees to reduce allergy risk	Set $AP = 0$ for all <i>Betula</i> , <i>Alnus</i> and <i>Corylus</i> trees
TR3	Removal of all horse chestnut trees following horse chestnut dieback	Set $AP = 0$ for all <i>Aesculus</i> trees
IP1	Increased allergenic potential of birch, alder, and hazel	Set $AP = 4$ for all <i>Betula</i> , <i>Alnus</i> and <i>Corylus</i> trees
IP2	Increased allergenic potential of plane	Set $AP = 3$ for all <i>Platanus</i> trees
IP3	Increased allergenic potential of ash	Set $AP = 3$ for all <i>Fraxinus</i> trees
IP4	Increased allergenic potential of oak, beech, chestnut and hornbeam	Set $AP = 3$ for all <i>Quercus</i> , <i>Fagus</i> , <i>Castanea</i> , and <i>Carpinus</i> trees
IPD	Increased pollination duration (earlier onset and/or longer duration)	For all trees with $PSD = 1$ or $PSD = 2$ set $PSD = PSD + 1$
CS1	Increased pollination duration + increased allergenic potential of ash and plane	Methods IP2 + IP3 + IPD
CS2	Increased pollination duration + increased allergenic potential of ash, plane, oak, beech, chestnut, and hornbeam	Methods IP2 + IP3 + IP4 + IPD
CS3	Increased pollination duration + increased allergenic potential of ash, plane, oak, beech, chestnut, hornbeam, birch, alder, and hazel	Methods IP1 + IP2 + IP3 + IP4 + IPD
CS4	Increased pollination duration + increased allergenic potential of ash	Methods IP2 + IP3 + IPD + TR2

and plane + Preventive removal of birch, alder and hazel trees to reduce allergy risk

CS5 Increased pollination duration + Methods IP2 + IP3 + IP4 + IPD + TR2 increased allergenic potential of ash, plane, oak, beech, chestnut, and hornbeam + Preventive removal of birch, alder and hazel trees to reduce allergy risk

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**Table 2.** Most frequent and most abundant tree species in 18 urban green spaces in the Brussels Capital Region, Belgium

Rank	Species	RF <sup>a</sup> (%)	Rank	Species	RA <sup>b</sup> (%)
1	<i>Acer platanoides</i>	94	1	<i>Acer pseudoplatanus</i>	13.4
1	* <i>Fraxinus excelsior</i>	94	2	<i>Taxus baccata</i>	10.3
3	* <i>Carpinus betulus</i>	89	3	* <i>Fraxinus excelsior</i>	7.8
4	<i>Acer pseudoplatanus</i>	83	4	<i>Robinia pseudoacacia</i>	5.3
5	* <i>Aesculus hippocastanum</i>	78	5	<i>Acer platanoides</i>	4.6
5	<i>Taxus baccata</i>	78	6	<i>Pinus nigra</i>	4.2
7	* <i>Fagus sylvatica</i>	72	7	* <i>Aesculus hippocastanum</i>	3.7
7	* <i>Platanus × acerifolia</i>	72	8	* <i>Salix alba</i>	3.5
9	* <i>Tilia platyphyllos</i>	67	9	* <i>Populus canadensis</i>	2.6
10	* <i>Betula pendula</i>	61	10	* <i>Carpinus betulus</i>	2.5
10	* <i>Quercus robur</i>	61	11	* <i>Fagus sylvatica</i>	2.3
10	* <i>Quercus rubra</i>	61	12	<i>Ilex aquifolium</i>	2.1
10	<i>Robinia pseudoacacia</i>	61	13	* <i>Quercus robur</i>	2.0
14	<i>Ilex aquifolium</i>	56	14	* <i>Tilia platyphyllos</i>	1.7
14	<i>Pinus nigra</i>	56	15	* <i>Tilia tomentosa</i>	1.4

<sup>a</sup>Relative frequency (proportion of green spaces in which the species is present). The total number of green spaces included in this study = 18

<sup>b</sup>Relative abundance (proportion of trees across all green spaces). The total number of trees included in this study = 5940

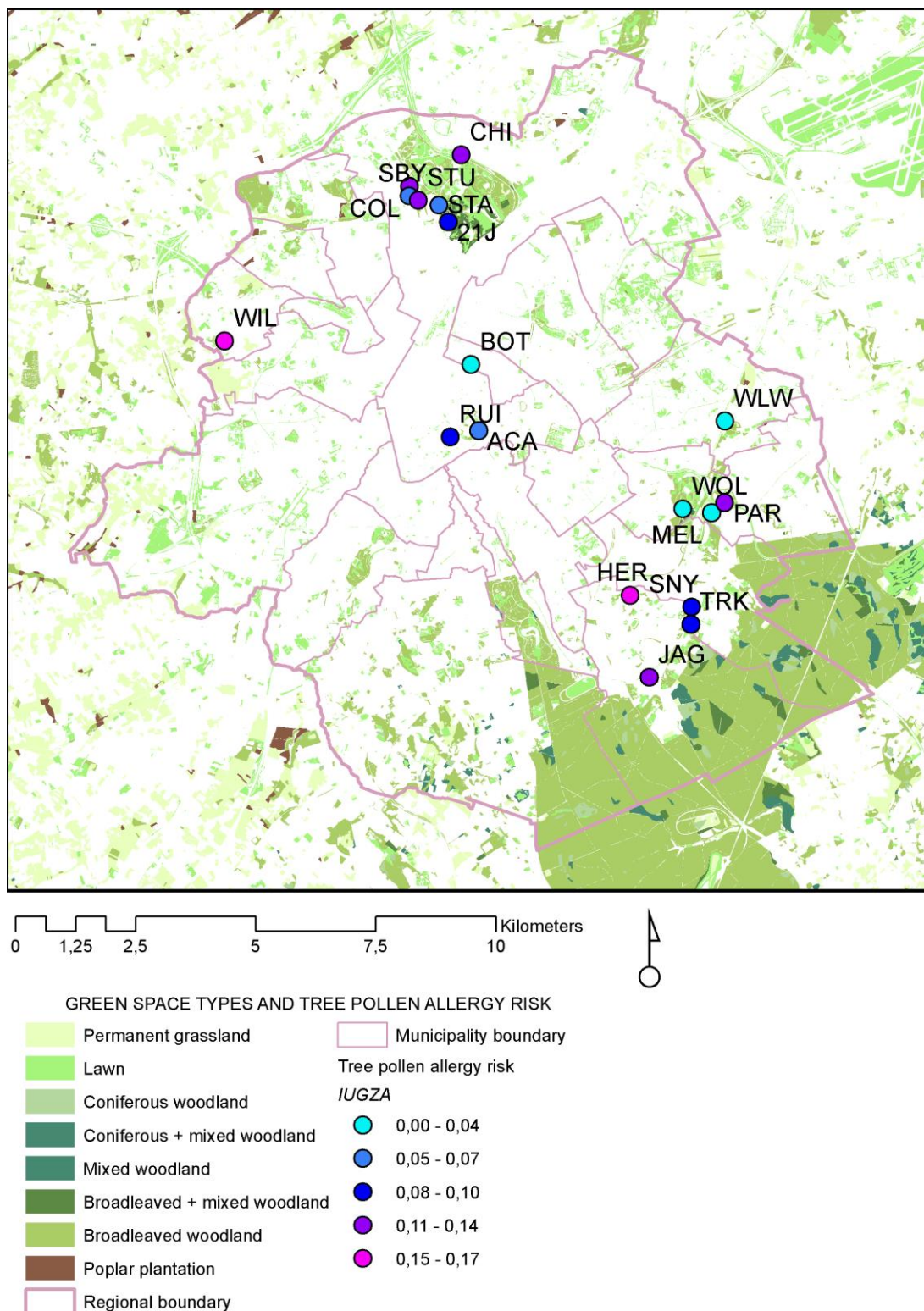
\*Allergenic species. For allergenic properties, see Table S2

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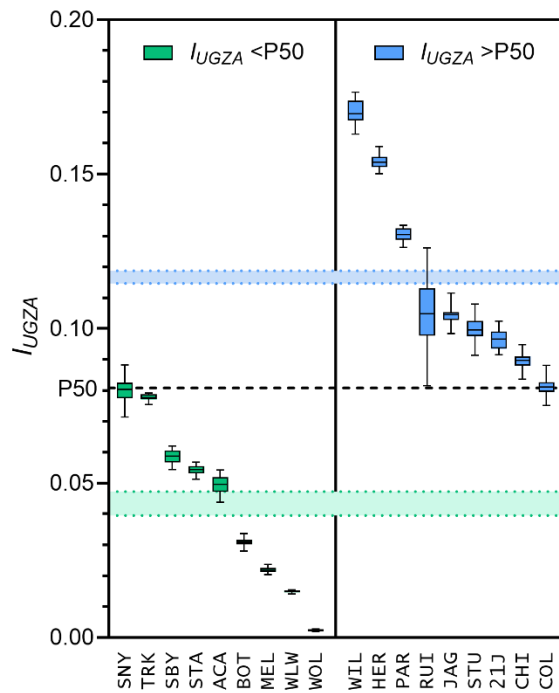
**Fig. 1.** Green space typology in Brussels Capital Region, Belgium, and location of the 18 urban green spaces that were included in the study, with an indication of their average baseline tree pollen allergy risk ( $I_{UGZA}$ ).

**Fig. 2.** Tree pollen allergy risk ( $I_{UGZA}$ ) in 18 urban green spaces in the Brussels Capital Region, Belgium. Urban green spaces were stratified in two groups: green spaces with average baseline  $I_{UGZA}$  below vs. above the overall median (P50  $I_{UGZA}$  = 0.081). Shaded intervals indicate the 95% CIs for  $I_{UGZA}$  subgroup means.

**Fig. 3.** Changes in tree pollen allergy risk ( $\Delta I_{UGZA}$ ) in urban green spaces in Brussels Capital Region, Belgium, across green space intervention, allergic sensitization and pollination duration change scenarios. Urban green spaces were stratified in two groups: green spaces with average baseline  $I_{UGZA}$  below vs. above the overall median (P50  $I_{UGZA}$  = 0.081).  $\Delta I_{UGZA}$  (average and 95% CI) is calculated as the estimated difference between the marginal mean  $I_{UGZA}$  of the scenario and the subgroup mean baseline  $I_{UGZA}$ .



**Fig. 1.** Green space typology in Brussels Capital Region, Belgium, and location of the 18 urban green spaces that were included in the study, with an indication of their average baseline tree pollen allergy risk (*IUGZA*)



**Fig. 2.** Tree pollen allergy risk ( $I_{UGZA}$ ) in 18 urban green spaces in the Brussels Capital Region, Belgium. Urban green spaces were stratified in two groups: green spaces with average baseline  $I_{UGZA}$  below vs. above the overall median ( $P50 I_{UGZA} = 0.081$ ). Shaded intervals indicate the 95% CIs for  $I_{UGZA}$  subgroup means.



## **List of appendices**

Appendix A. Conceptual model of the urban green zone allergenicity index (*IUGZA*) method

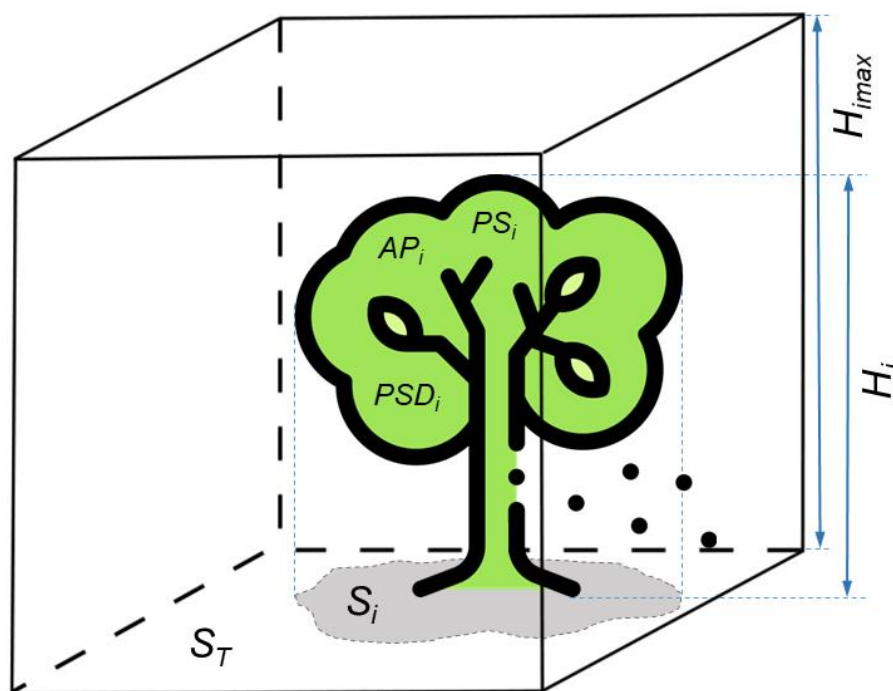
Appendix B. Characteristics of urban green spaces

Appendix C. Allergenic potential, pollination syndrome and pollen season duration of allergenic tree species

Appendix D. Tree pollen allergy risk in 18 urban green spaces in Brussels

Appendix E. Relative change (%) in tree pollen allergy risk in 18 urban green spaces

## Appendix A. Conceptual model of the urban green zone allergenicity index ( $I_{UGZA}$ ) method



**Fig. S1.** Assessment of urban green space tree pollen allergy risk with the urban green zone allergenicity index ( $I_{UGZA}$ ) method. The maximum volume that can be occupied by allergenic trees is defined by the surface area of the green space  $S_T$  and the maximum tree height  $H_{max}$  (in this study  $H_{max} = 30$  m).  $I_{UGZA}$  is determined by the allergenic potential  $AP_i$ , pollination syndrome  $PS_i$ , pollen season duration  $PSD_i$ , tree height  $H_i$  and vertical crown projection area  $S_i$  of all trees in the green space.  $I_{UGZA}$  can be interpreted as the proportion of the volume that is occupied by trees that emit allergenic pollen, or as the relative tree pollen allergy risk compared to a homogeneous birch forest with 100% crown cover and a canopy height of 30 m.

## Appendix B. Characteristics of urban green spaces

**Table S1.** Characteristics of 18 urban green spaces in the Brussels Capital Region, Belgium, that were included in the study

ID	Name	Area (ha)	$N_{trees}$	$N_{taxa}$	Tree density (trees/ha)	Medians and IQR			Dominant taxa (proportion of trees)
						$CBH_{150}$ (cm)	$H$ (m)	$D_{crown}$ (m)	
21J	<u>Square du 21 juillet</u> 21 juli-square	1.39	132	19	95	170 (107)	15 (16)	10 (8)	<i>Taxus baccata</i> (0.42), <i>Aesculus hippocastanum</i> (0.21)
ACA	Palais des Académies Academieën paleis	0.54	75	27	139	75 (157)	8 (10)	5 (9)	<i>Taxus baccata</i> (0.27), <i>Aesculus hippocastanum</i> (0.17)
BOT	<u>Jardin Botanique</u> Kruidtuin	3.99	826	212	207	53 (74)	5 (6)	4 (4)	<i>Tilia tomentosa</i> (0.07), <i>Ilex aquifolium</i> (0.06), <i>Taxus baccata</i> (0.05), <i>Magnolia grandiflora</i> (0.04)
CHI	<u>Jardin du Pavillon chinois</u> Tuin van het Chinees Paviljoen	3.11	307	51	99	146 (84)	20 (10)	10 (6)	<i>Pinus nigra</i> (0.16), <i>Taxus baccata</i> (0.08), <i>Acer pseudoplatanus</i> (0.08)
COL	<u>Jardin Colonial de Laeken</u> Koloniale Tuin	2.21	481	31	218	129 (80)	16 (10)	8 (4)	<i>Taxus baccata</i> (0.46), <i>Pinus nigra</i> (0.16), <i>Fraxinus excelsior</i> (0.09)
HER*	<u>Parc de la Héronnière</u> Reigerbospark	4.48	657	35	147	129 (50)	20 (7)	13 (6)	<i>Acer pseudoplatanus</i> (0.44), <i>Salix alba</i> (0.21), <i>Fraxinus excelsior</i> (0.10)
JAG*	<u>Parc du Jagersveld</u> Jagersveldpark	2.58	273	43	106	160 (107)	19 (11)	10 (8)	<i>Taxus baccata</i> (0.38), <i>Pinus nigra</i> (0.06), <i>Carpinus betulus</i>



MEL	<u>Etangs Mellaerts</u> Mellaertsvijvers	6.55	218	35	33	150 (128)	15 (9)	9 (5)	(0.05), <i>Tilia</i> × <i>euchlora</i> (0.05) <i>Fraxinus</i> <i>excelsior</i> (0.12), <i>Populus</i> × <i>canadensis</i> (0.11), <i>Pinus nigra</i> (0.10), <i>Thuja</i> <i>occidentalis</i> (0.07)
PAR*	<u>Parc Parmentier</u> Parmentierpark	37.73	627	37	17	123 (82)	20 (7)	8 (7)	<i>Acer</i> <i>pseudoplatanus</i> (0.22), <i>Acer</i> <i>platanoides</i> (0.10), <i>Robinia</i> <i>pseudoacacia</i> (0.10), <i>Aesculus</i> <i>hippocastanum</i> (0.08), <i>Alnus</i> <i>glutinosa</i> (0.08)
RUI*	<u>Jardin des</u> <u>Sculptures</u> Beeldentuin	0.06	38	8	633	54 (82)	8 (8)	6 (6)	<i>Carpinus betulus</i> (0.45), <i>Acer</i> <i>pseudoplatanus</i> (0.13), <i>Tilia</i> <i>platyphyllos</i> (0.13), <i>Ilex</i> <i>aquifolium</i> (0.13)
SBY	<u>Parc Sobieski</u> Sobieski Park	2.65	211	31	80	136 (89)	18 (8)	9 (6)	<i>Taxus baccata</i> (0.19), <i>Fraxinus</i> <i>excelsior</i> (0.15), <i>Pinus nigra</i> (0.10)
SNY	<u>Parc Seny</u> Senypark	1.98	166	60	84	130 (87)	17 (10)	9 (6)	<i>Pinus nigra</i> (0.15), <i>Taxus</i> <i>baccata</i> (0.07), <i>Salix alba</i> (0.05)
STA	<u>Parc de la Drève</u> <u>Sainte-Anne</u> Sint- Annadreefspark	2.44	511	28	209	132 (85)	18 (8)	8 (5)	<i>Robinia</i> <i>pseudoacacia</i> (0.24), <i>Acer</i> <i>platanoides</i> (0.17), <i>Acer</i> <i>pseudoplatanus</i>

									(0.15), <i>Tilia platyphyllos</i> (0.10), <i>Ulmus minor</i> (0.10)
STU*	<u>Jardins du fleuriste de Stuyvenberg</u> Tuinen van de bloemist van Stuyvenberg	1.15	295	18	257	125 (89)	18 (7)	7 (5)	<i>Acer pseudoplatanus</i> (0.27), <i>Robinia pseudoacacia</i> (0.19), <i>Taxus baccata</i> (0.11), <i>Ilex aquifolium</i> (0.10)
TRK	<u>Parc de l'Etang Ten Reuken</u> Tenreuken park	6.10	373	57	61	150 (104)	23 (10)	12 (6)	<i>Tilia × euchlora</i> (0.08), <i>Acer pseudoplatanus</i> (0.08), <i>Taxus baccata</i> (0.07), <i>Acer platanoides</i> (0.07)
WIL*	<u>Bois de Wilder</u> Wilderbos	6.25	645	29	103	133 (77)	20 (9)	10 (7)	<i>Fraxinus excelsior</i> (0.27), <i>Acer pseudoplatanus</i> (0.14), <i>Populus × canadensis</i> (0.09), <i>Salix alba</i> (0.08)
WLW	<u>Parc Malou</u> Maloupark	14.99	63	8	4	249 (124)	26 (9)	15 (8)	<i>Populus × canadensis</i> (0.75), <i>Fraxinus excelsior</i> (0.10)
WOL	<u>Parc de Woluwe</u> Woluwepark	29.09	42*	15	1	155 (76)	23 (6)	8 (7)	<i>Acer platanoides</i> (0.19), <i>Betula pendula</i> (0.14)

IQR: interquartile range;  $N_{trees}$  : number of trees ;  $N_{taxa}$ : number of taxa (species, subspecies, cultivars and trees identified at genus level);  $CBH_{150}$ : stem circumference at 150 cm above ground;  $H$ : tree height;  $D_{crown}$ : crown diameter; \*The allergy risk is considered moderate in a number of change scenarios (CS2–5).

## Appendix C. Allergenic potential, pollination syndrome and pollen season duration of allergenic tree species

**Table S2.** Allergenic potential, pollination syndrome and pollen season duration of allergenic tree species recorded in 18 urban green spaces in the Brussels Capital Region, Belgium

Species	Vernacular name	Family	Allergenic potential (AP)	Pollination syndrome (PS)	Pollen season duration (PSD)
<i>Aesculus hippocastanum</i>	horse-chestnut	Sapindaceae	1	2	2
other <i>Aesculus spp.</i>	horse-chestnut	Sapindaceae	1	2	2
<i>Alnus glutinosa</i>	black alder	Betulaceae	4	3	2
<i>Alnus incana</i>	grey alder	Betulaceae	4	3	2
other <i>Alnus spp.</i>	alder	Betulaceae	3	3	2
<i>Betula pendula</i>	silver birch	Betulaceae	4	3	3
other <i>Betula spp.</i>	birch	Betulaceae	3	3	2
<i>Carpinus betulus</i>	common hornbeam	Betulaceae	2	3	1
other <i>Carpinus spp.</i>	hornbeam	Betulaceae	2	3	1
<i>Castanea sativa</i>	chestnut	Fagaceae	1	3	2
<i>Corylus avellana</i>	common hazel	Betulaceae	4	3	3
<i>Corylus colurna</i>	Turkish hazel	Betulaceae	3	3	3
<i>Fagus sylvatica</i>	common beech	Fagaceae	1	2	3
<i>Fraxinus excelsior</i>	common ash	Oleaceae	2	3	2
other <i>Fraxinus spp.</i>	ash	Oleaceae	2	3	2
<i>Larix decidua</i>	European larch	Pinaceae	1	3	1
<i>Ligustrum spp.</i>	privet	Oleaceae	1	2	2

<i>Olea europaea</i>	olive	Oleaceae	1	3	2
<i>Platanus spp.</i>	plane	Platanaceae	1	3	2
<i>Populus spp.</i>	poplar	Salicaceae	1	3	2
<i>Quercus petraea</i>	sessile oak	Fagaceae	2	3	2
<i>Quercus robur</i>	common oak	Fagaceae	2	3	2
other <i>Quercus spp.</i>	oak	Fagaceae	2	3	2
<i>Salix spp.</i>	willow	Salicaceae	1	2	2
<i>Tilia cordata</i>	small-leaved lime	Malvaceae	1	2	2
<i>Tilia platyphyllos</i>	large-leaved lime	Malvaceae	1	2	2
<i>Tilia tomentosa</i>	silver lime	Malvaceae	1	2	2
<i>Tilia × euchlora</i>	Crimean lime	Malvaceae	1	2	2
other <i>Tilia spp.</i>	lime	Malvaceae	1	2	2
<i>Ulmus minor</i>	field elm	Ulmaceae	1	3	1
other <i>Ulmus spp.</i>	elm	Ulmaceae	1	3	1
Other species (not allergenic)			0	NA	NA

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Allergenic potential (AP): 0, non-allergenic; 1, low allergenicity; 2, moderate allergenicity; 3, high allergenicity; 4, main local allergen

Pollination syndrome (PS): 2, amphiphilous (insect- or wind-pollinated); 3, anemophilous (wind-pollinated)

Pollen season duration (PSD): 1, 1–3 weeks; 2, 4–6 weeks; 3, more than 6 weeks

## Appendix D. Tree pollen allergy risk in 18 urban green spaces in Brussels

**Table S3.** Tree pollen allergy risk in 18 urban green spaces ( $I_{UGZA}$ ) in the Brussels Capital Region, Belgium, across green space intervention, allergenic potential and pollination duration change scenarios.

Green space ID	Scenario $I_{UGZA}$ <sup>a</sup>													
	Baseline	TR1	TR2	TR3	IP1	IP2	IP3	IP4	IPD	CS1	CS2	CS3	CS4	CS5
2IJ	0.096	0.078	0.096	0.051	0.097	0.095	0.106	0.116	0.144	0.156	0.181	0.180	0.157	0.185
ACA	0.050	0.050	0.051	0.032	0.051	0.059	0.049	0.094	0.065	0.078	0.121	0.121	0.080	0.120
BOT	0.031	0.025	0.027	0.028	0.031	0.038	0.033	0.039	0.046	0.061	0.072	0.073	0.056	0.069
CHI	0.089	0.061	0.076	0.085	0.091	0.096	0.103	0.127	0.128	0.155	0.199	0.202	0.144	0.184
COL	0.081	0.037	0.081	0.071	0.081	0.082	0.104	0.116	0.115	0.149	0.185	0.185	0.149	0.185
HER	0.154	0.103	0.115	0.148	0.153	0.157	0.181	0.173	0.219	0.259	0.283	0.285	0.216	0.238
JAG	0.104	0.086	0.097	0.102	0.103	0.149	0.112	0.148	0.152	0.232	0.288	0.281	0.222	0.279
MEL	0.022	0.018	0.019	0.019	0.021	0.024	0.023	0.026	0.031	0.038	0.042	0.043	0.035	0.040
PAR	0.130	0.108	0.106	0.120	0.131	0.149	0.142	0.175	0.190	0.237	0.296	0.298	0.204	0.262
RUI	0.105	0.105	0.101	0.104	0.104	0.160	0.104	0.117	0.164	0.251	0.269	0.272	0.240	0.269
SBY	0.059	0.027	0.049	0.056	0.059	0.059	0.074	0.065	0.086	0.110	0.119	0.122	0.098	0.109
SNY	0.080	0.076	0.050	0.078	0.083	0.101	0.082	0.095	0.109	0.144	0.161	0.165	0.111	0.131
STA	0.054	0.046	0.055	0.039	0.054	0.057	0.059	0.055	0.084	0.095	0.096	0.096	0.094	0.097
STU	0.100	0.045	0.100	0.098	0.100	0.101	0.129	0.130	0.150	0.193	0.229	0.232	0.188	0.229
TRK	0.078	0.076	0.073	0.078	0.079	0.088	0.079	0.118	0.115	0.132	0.182	0.181	0.123	0.173
WIL	0.170	0.119	0.122	0.171	0.170	0.172	0.199	0.196	0.232	0.273	0.304	0.302	0.220	0.253
WLW	0.015	0.014	0.015	0.015	0.015	0.015	0.015	0.015	0.022	0.023	0.024	0.023	0.023	0.023
WOL	0.002	0.002	0.001	0.002	0.002	0.002	0.002	0.003	0.003	0.003	0.003	0.004	0.002	0.002

<sup>a</sup>Scenarios:

Tree removal scenarios: TR1, Ash dieback and removal; TR2, Preventive birch, alder and hazel removal; TR3, Horse-chestnut dieback and removal

Increased sensitization scenarios: IP1, Increased allergenic potential of birch, alder, and hazel; IP2, Increased allergenic potential of plane; IP3, Increased allergenic potential of ash; IP4, Increased allergenic potential of oak, beech, chestnut, and hornbeam

IPD, Increased pollination duration

Combined scenarios: CS1: IP2+IP3+IPD; CS2: IP2+IP3+IP4+IPD; CS3: IP1+IP2+IP3+IP4+IPD; CS4: IP2+IP3+IPD+TR2; CS5: IP2+IP3+IP4+IPD+TR2

et al.,

## Appendix F. Relative change (%) in tree pollen allergy risk in 18 urban green spaces

**Table S4.** Relative change (%) in tree pollen allergy risk in 18 urban green spaces ( $I_{UGZA}$ ) in the Brussels Capital Region, Belgium, across green space intervention, allergenic potential and pollination duration change scenarios.

Green space ID	Baseline $I_{UGZA}$	Relative change per scenario (%) <sup>a</sup>												
		TR1	TR2	TR3	IP1	IP2	IP3	IP4	IPD	CS1	CS2	CS3	CS4	CS5
2IJ	0.096	-18.7	-0.6	-46.7	+1.0	-1.3	+10.3	+20.4	+49.0	+61.7	+88.2	+87.4	+62.9	+91.8
ACA	0.050	+0.8	+3.1	-34.9	+2.4	+18.5	-0.3	+89.9	+30.9	+56.7	+144.5	+144.2	+61.1	+142.9
BOT	0.031	-18.5	-12.9	-8.6	+0.6	+23.4	+6.9	+27.8	+48.3	+97.7	+134.8	+138.1	+83.6	+125.3
CHI	0.089	-31.3	-14.6	-4.4	+1.8	+7.2	+15.7	+41.7	+43.1	+72.8	+122.5	+126.2	+61.0	+105.7
COL	0.081	-54.6	-0.3	-12.0	+0.6	+0.9	+28.0	+43.7	+42.3	+83.3	+128.6	+128.1	+83.6	+128.4
HER	0.154	-32.9	-25.3	-3.7	-0.5	+1.6	+17.5	+12.5	+42.4	+68.2	+83.5	+84.9	+40.2	+54.5
JAG	0.104	-17.7	-7.2	-2.5	-1.0	+43.3	+7.8	+42.3	+45.7	+122.0	+176.4	+169.6	+112.6	+168.0
MEL	0.022	-16.7	-14.0	-10.6	-2.0	+12.2	+5.9	+19.9	+42.4	+75.1	+94.9	+96.8	+59.1	+81.5
PAR	0.130	-17.0	-18.3	-8.3	+0.6	+13.9	+8.6	+34.1	+46.0	+81.6	+127.3	+128.3	+56.3	+101.3
RUI	0.105	+0.2	-4.2	-1.0	-0.8	+52.7	-1.1	+11.2	+56.2	+139.1	+156.1	+159.6	+128.4	+156.5
SBY	0.059	-53.5	-15.7	-4.7	+1.3	+0.9	+26.8	+11.4	+47.0	+88.3	+102.1	+108.0	+67.8	+85.2
SNY	0.080	-5.0	-37.2	-2.6	+3.7	+26.3	+2.9	+18.7	+36.0	+79.4	+100.7	+106.2	+38.1	+63.2
STA	0.054	-14.6	+1.0	-28.7	+0.0	+5.5	+8.1	+2.2	+54.4	+74.3	+77.7	+76.3	+73.1	+78.2
STU	0.100	-54.9	+0.7	-1.8	+0.8	+0.9	+29.2	+30.3	+50.3	+93.6	+129.5	+132.5	+88.7	+130.2
TRK	0.078	-2.3	-6.7	+0.6	+1.4	+12.9	+1.5	+52.1	+47.7	+69.3	+133.9	+133.1	+58.1	+122.9
WIL	0.170	-30.0	-28.4	+0.8	-0.1	+0.9	+16.7	+14.9	+36.6	+60.3	+78.9	+77.8	+29.1	+48.8
WLW	0.015	-3.4	-0.3	-0.1	+0.9	+2.2	+1.8	+1.8	+49.8	+56.9	+59.4	+58.0	+56.3	+58.1
WOL	0.002	-3.6	-55.0	+3.8	+3.1	+0.3	+3.1	+10.8	+24.4	+26.5	+51.6	+54.6	-28.6	-4.7

<sup>a</sup>Scenarios:

Tree removal scenarios: TR1, Ash dieback and removal; TR2, Preventive birch, alder and hazel removal; TR3, Horse-chestnut dieback and removal

Increased sensitization scenarios: IP1, Increased allergenic potential of birch, alder, and hazel; IP2, Increased allergenic potential of plane; IP3, Increased allergenic potential of ash; IP4, Increased allergenic potential of oak, beech, chestnut, and hornbeam

IPD, Increased pollination duration

Combined scenarios: CS1: IP2+IP3+IPD; CS2: IP2+IP3+IP4+IPD; CS3: IP1+IP2+IP3+IP4+IPD; CS4: IP2+IP3+IPD+TR2; CS5: IP2+IP3+IP4+IPD+TR2



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## **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.

## **Ethical clearance**

The protocol for this study did not require ethics approval.

## **CRedit author statement**

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