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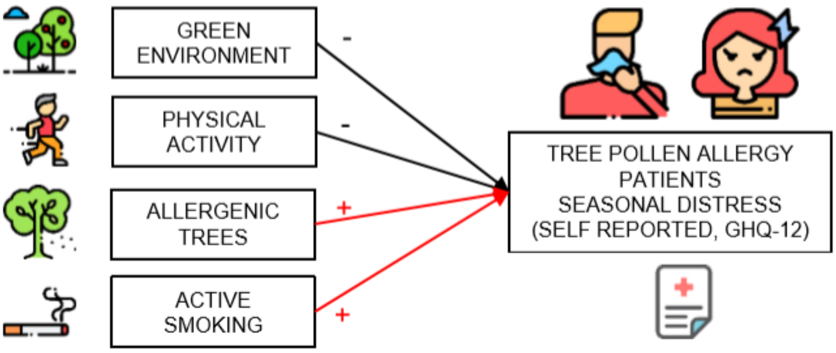


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# Residential green space and seasonal distress in a cohort of tree pollen allergy patients

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ABSTRACT

*Background:* Residential green space may improve human health, for example by promoting physical activity and by reducing stress. Conversely, residential green space may increase stress by emitting aeroallergens and exacerbating allergic disease. Here we examine impacts of exposure to residential green space on distress in the susceptible subpopulation of adults sensitized to tree pollen allergens.

*Methods:* In a panel study of 88 tree pollen allergy patients we analyzed self-reported mental health (GHQ-12), perceived presence of allergenic trees (hazel, alder, birch) near the residence and residential green space area within 1 km distance [high (≥ 3 m) and low (< 3 m) green]. Results were adjusted for patients' background data (gender, age, BMI, smoking status, physical activity, commuting distance, education level, allergy medication use and chronic respiratory problems) and compared with distress in the general population (N = 2,467).

*Results:* Short-term distress [mean GHQ-12 score 2.1 (95% confidence interval 1.5–2.7)] was higher in the study population than in the general population [1.5 (1.4–1.7)]. Residential green space had protective effects against short-term distress [high green, per combined surface area of 10 ha: adjusted odds ratio OR = 0.94 (95% confidence interval 0.90–0.99); low green, per 10 ha: OR = 0.85 (0.78–0.93)]. However, distress was higher in patients who reported perceived presence of allergenic trees near their residence [present vs. absent: OR= 2.04 (1.36–3.07)].

*Conclusions:* Perceived presence of allergenic tree species in the neighbourhood of the residence of tree pollen allergy patients modulates the protective effect of residential green space against distress during the airborne tree pollen season.

**Keywords:** Residential green space; Tree pollen allergy; Respiratory hypersensitivity; Emotional distress; Mental health; GHQ-12

## 1. Introduction

Allergic rhinitis, conjunctivitis and bronchial asthma are common manifestations of allergies (Gilles et al., 2018). These allergic disorders are associated with a relative high burden of disease because of their high prevalence, often life-long morbidity and impacts on mental health and health-related quality of life (Chen et al., 2013; Sanna et al., 2014). Therefore, they are a major public health concern (Lake et al., 2017; Linneberg et al., 2016). The past decades, the allergy prevalence has globally increased (Brożek et al., 2017; D'Amato et al. 2016; Gilles et al. 2018). At present, the total prevalence of allergies to common aeroallergens in Europe is almost 30% of the total population (D'Amato et al., 2007). This prevalence is expected to even further increase in the following decades, as a result of prolonged pollen seasons and amplified aeroallergenic pollen loads driven by climate change, air pollution and various interactions between changes in environment and lifestyle (D'Amato and Cecchi, 2008; Damialis et al., 2019; Gilles et al., 2018; Reinmuth-Selzle et al., 2017; Ziska et al., 2019).

There is increasing evidence that exposure to green space may improve human health and well-being (Aerts et al., 2018; Fong et al., 2018; Hartig et al., 2014). In particular exposure to residential green space, which includes public parks, private gardens and urban green infrastructure such as street trees near the residence, has been associated to beneficial health effects. Exposure to residential green space has, for example, been associated with positive birth outcomes (Cusack et al., 2018), improved respiratory health (Tischer et al., 2017), better subjective general health (Dadvand et al., 2016), lower risk of psychiatric disorders (Engemann et al., 2019; Gascon et al., 2015), improved mental health (Andrusaityte et al., 2019; Gascon et al., 2018), reduced psychosocial stress (Van Aart et al., 2018) and reduced cardiovascular and cerebrovascular morbidity and mortality (Gascon et al., 2016; Orioli et al. 2019; Vienneau et al., 2017; Yeager et al., 2018). Green space may improve human health in various ways, for instance by reducing stress, by promoting physical activity, and by reducing air pollution, heat, noise and other environmental nuisances (Dadvand et al., 2016; Markevych et al., 2017). In urban areas, the presence of green space and access to green space in the neighbourhood of the residence may thus be associated with numerous and important health benefits.

In the context of allergies, there is growing evidence for a positive association between exposure to residential green space and reduced atopic sensitization (Jackson et al., 2017; Lee et al., 2018; Ruokolainen et al., 2015). Early-life exposure to beneficial microbiota in the environment may lead to improved development of the immune system and lower risks to develop chronic inflammatory diseases and allergies in later life (Hanski et al,. 2012; Rook, 2013). However, residential green spaces also contain trees, shrubs, grasses and other plants that produce and emit pollen in the air (Thompson and Thompson, 2003). Exposure to aeroallergens emitted by green spaces could potentially increase the risks for asthma, reduced lung function and allergic sensitization (Dadvand et al., 2014; Erbas et al., 2013; Fuertes et al., 2016; Lambert et al., 2017; 2018) and exacerbate the burden of seasonal pollen allergies in sensitized individuals (Cariñanos and Casares-Porcel, 2011; Lai and Kontokosta, 2019; Lovasi et al., 2013). Moreover, aeroallergens are also shown to play a role in the development of mental depression (Chen et al., 2013; Sanna et al., 2014).

Exposure to residential green space may be protective against the development of allergies and improve mental health, but green spaces also pose specific challenges in terms of seasonal pollen allergies to persons that are already sensitized to pollen, potentially affecting well-being and mental health. However, to our knowledge, no studies have examined the effects of exposure to residential green space on mental health in the susceptible subpopulation of pollen allergy patients so far. Therefore, in the present observational study, we aim to examine whether residential green space and the perceived presence of allergenic tree species near the residence may impact short-term mental health of allergy patients sensitized to pollen of hazel, alder and/or birch during the airborne pollen season of these tree species, accounting for potential effects of the participants' gender, age, BMI, smoking status, physical activity, commuting distance, education level, allergy medication use and chronic respiratory problems.

We also aim to compare distress in our study population to distress reported in the general population of the study area.

## 2. Methods

### *2.1. Study design and population*

Adults were recruited from the general population in 2016 and 2017 in the framework of the RespirIT study on green space and respiratory health (for more information about the RespirIT study, see https://www.sciensano.be/en/projects/assessing-spatio-temporal-relationships-between-respiratory-health-and-biodiversity-using-individual). The inclusion criteria of the RespirIT study required that participants (1) were aged 20 years or older, (2) resided in Belgium, (3) were healthy at the time of recruitment, (4) were sensitized to pollen of common hazel (*Corylus avellana*), alder (*Alnus* spp.) and/or birch (*Betula* spp.), (5) agreed to use a smartphone application to record whereabouts and daily allergy symptoms and (6) agreed to complete mental health questionnaires and provide detailed background information. The study protocol was approved by the Ethical Commission of the KU Leuven University Hospital in Leuven prior to recruitment (Belgian registration number B322201629692). Informed consent was obtained and documented. A total of 225 persons expressed interest to participate of which 189 persons (84%) met the inclusion criteria and were included in the RespirIT study. The present cross-sectional study used anonymized data from 88 (47%) participants that resided in Flanders (Fig. S1, Fig. S2). The study was limited to participants living in Flanders because we used detailed environmental data that was only available for Flanders at the time of the study (i.e. the data was not available for the other two regions in Belgium, the Walloon Region and the Brussels Capital Region).

## *2.2. Definition of mental health as the outcome variable*

We used the self-administered 12-item General Health Questionnaire (GHQ-12; GL Assessment, https://www.gl-assessment.co.uk/products/general-health-questionnaire-ghq/) which we translated into Dutch and French. The GHQ-12 is a short form of the GHQ, which is a validated multi-item scale to identify non-psychotic and minor psychiatric disorders. Items in the GHQ-12 assess the presence or absence of emotional disorders, non-psychotic psychiatric disorders and/or minor psychiatric disorders at the time of administration (current state) and ask if and how much the current state differs from the usual state. The GHQ-12 measures disorders in three dimensions: social dysfunction (e.g. GHQ-01 "*Have you recently been able to concentrate on what you are doing?"*), anxiety and depression (e.g. GHQ-02 "*Have you recently lost much sleep over worry?"*) and loss of confidence (e.g. GHQ-10 "*Have you recently been losing confidence in yourself?"*). The GHQ-12 is not sensitive to long-standing attributes of respondents. Using the standard bimodal scoring method (0-0-1-1) the GHQ-12 yields a score which can be interpreted as an indicator of short-term emotional distress (scale range 0–12, 0 best). In the Belgian Health Interview Survey (https://his.sciensano.be), a GHQ-12 score ≥ 2 is interpreted as an indicator of psychological distress; a GHQ-12 score ≥ 4 as an indicator of a probable mental disorder. Participants used an online survey to complete the validated questionnaire, which was administered one month after the start of the airborne tree pollen seasons, as determined by the Belgian Aerobiological Surveillance Network (responsible for outdoor aeroallergen monitoring in Belgium, http://www.airallergy.be). An independent study found a good agreement between a web-based self-administered version of the GHQ-12 and the traditional paper-and-pencil questionnaire (Braekman et al., 2018). The mental health data was obtained during the airborne pollen seasons of hazel, alder and birch trees of 2017 and 2018.

*2.3. Definition of potential predictors*

***Sociodemographic characteristics.*** We included the participants' gender and age as well as a number of indicators of socioeconomic status and fitness: body mass index (BMI), smoking status (yes/no), frequency of physical activity (more than 1×/week 20 minutes of activity vs. 1×/week or less), estimated daily commuting distance (km) and education level (higher education vs. no higher education).

***Health status.*** We included medication use (antihistamines and/or corticosteroids: yes/no) and chronic disease (asthma and/or chronic respiratory disease: yes/no) to account for potential effect modification.

***Residential green space.*** Participants reported the presence or absence of hazel, alder and/or birch trees in the vicinity of their residence. Because we did not verify this presence by independent field observations, the presence of allergenic trees near the residence should be interpreted as perceived presence of those species. We included an indicator of non-allergenic tree richness to account for green space tree diversity (non-allergenic tree richness is here defined as generic tree richness, i.e. the number of tree genera present from the genera *Aesculus*, *Carpinus*, *Fagus*, *Fraxinus*, *Juglans*, *Platanus*, *Populus*, *Quercus*, *Salix* and *Tilia*). Tree richness data was extracted and extrapolated from Florabank1, a grid-based database on vascular plant distribution in the northern part of Belgium with >4 Mi georeferenced records. Florabank1 contains data gathered by both professionals during formal surveys and by amateur botanists. In addition, it contains distribution data that were published in botanical journals and data from herbarium specimens. The dataset is continuously updated (Van Landuyt et al., 2012). To objectively quantify residential green space, we used the Groenkaart Vlaanderen 2012 (http://www.geopunt.be/), which is a 1 m² resolution raster geodataset derived from orthorectified aerial imagery and which classifies every pixel in the entire region as 'not green', 'agriculture', 'low green' (vegetation < 3 m tall; among others, non-agricultural grasslands, meadows, shrubs and small trees) and 'high green' (vegetation ≥ 3 m tall, i.e. trees). Evidence from recent systematic reviews demonstrates that greenness in larger buffer sizes (500-2000 m) better predict physical health than smaller ones (250-500 m) (Browning and Lee, 2017; Su et al., 2019). Accordingly, we quantified residential green space as the total surface area of low green and the total surface area of high green within 1 km distance of the residence. These indicators were determined in ArcGIS 10.6.1 (ESRI, Redlands, CA)

### *2.4. Statistical analyses*

We used generalized linear models based on the Poisson probability distribution with log-link function to estimate the effects of residential exposure to green space on mental health (GHQ-12 score). We calculated unadjusted and confounder-adjusted estimates and their 95% Wald confidence intervals. We examined mental health outcomes in study population subgroups. Stratification was based on presence of allergenic tree species near the residence (present vs. absent), amount of low green (< P50 vs. ≥ P50; P50 = 70.0 ha), amount of high green (< P50 vs. ≥ P50; P50 = 54.5 ha) and frequency of physical activity (≤1×20'/week vs. >1×20'/week).

We used Bayesian Poisson inference using an exponential prior distribution with rate parameter $\lambda = 0.5$ (defined as a Gamma distribution with shape parameter $k = 1.0$ and scale parameter $\theta = 2.0$) to estimate posterior average distress (GHQ-12) and 95% credible intervals in subgroups. We included these Bayesian analyses because of their superior performance in estimating credible intervals. We used Welch's unequal variances t-test to compare overall average distress and observed and inferred average distress of subgroups with average distress reported by the general population in Flanders (Health Interview Survey 2013 data, N = 2,467; 1,172 males and 1,295 females aged 15 years and over). The Welch's t tests were performed with GraphPad QuickCalc software (https://www.graphpad.com/quickcalcs/). All other analyses were performed with IBM SPSS Statistics Subscription 11-2018 software. The reporting of this study conforms to the STROBE statement for cross-sectional studies (von Elm et al., 2007).

## 3. Results

### *3.1. Population characteristics*

The characteristics of the study population are presented in Table 1. Our panel of allergy patients comprised 47 women (53%) and 41 men (47%), aged between 21 and 70 years (median age 38, IQR difference 17.5). The majority of the participants had a normal body weight (59% normal BMI; median BMI 23.2 kg $m^{-2}$, IQR difference 5.7), did not smoke (97%), was physically active (at least 20 minutes active > 1×/week: 80%) and had a high education level (86%). The use of allergy medication was prevalent (93%), with 61% of the participants using antihistamines only, 8% corticosteroids only and 24% a combination of antihistamines and corticosteroids. A total of 25% of participants reported to suffer from chronic respiratory problems in addition to seasonal pollen allergy (asthma: 21%; chronic respiratory disease: 1%; both: 3%). On average, participants were exposed to a total of 65.2 ha high green (95% CI 57.5–72.9; P50 = 54.5 ha; 20.8% relative cover) and 70.1 ha low green (95% CI 65.9–74.3; P50 = 70.0 ha; 22.3% relative cover) within a radius of 1 km distance from the residence. The median residential (non-allergenic) tree richness was 9 (IQR difference 2). Hazel, alder and/or birch trees were reported to be present in the immediate vicinity of the residence by 75% of the participants. Physical activity tended to be higher in neighbourhoods with high levels (>P50) of high green [OR (95% CI): 2.38 (0.80–7.04)] and lower in neighbourhoods with high levels (>P50) of low green [0.57 (0.20–1.63)] but these differences were not significant. There was no association between high education and high levels (>P50) of high green [0.68 (0.20–2.33)] or low green [1.00 (0.30–3.38)].

### *3.2. Pollen season severity*

Based on the official aeroallergen concentration data, 2017 could be classified as a weak pollen season with a late start of the hazel pollen season, shorter pollen seasons of hazel and alder and consistently below-average pollen concentrations for hazel, alder and birch (z-scores –0.77, –0.66 and –0.87, respectively; reference period 2012–2018). Conversely, 2018 could be classified as a severe pollen season with early starts of the hazel and alder pollen seasons and a longer alder season with above-average pollen concentrations for hazel and birch (z-scores 1.61 and 1.06) (Table 2). The critical pollen concentrations (above which the sensitized population is expected to experience allergy symptoms; for birch 80 grains/m³) were exceeded in both pollen seasons.

### *3.3. Mental health*

The median GHQ-12 score, representing short-term emotional distress, was 1 (range 0–11, IQR difference 3). The overall mean GHQ-12 score was 2.1 [standard deviation (SD) 2.7] and was higher than the mean GHQ-12 score in the general population [1.5 (SD 3.8)] (Welch's t-test $P$ = 0.047) and higher than the threshold for psychological distress (GHQ ≥ 2), indicating above-average distress in the studied population. The GHQ-12 score was higher in the weak pollen season [2017: average GHQ-12 score (SD): 2.36 (3.8)] than in the severe pollen season [2018: 1.80 (3.7)], but this difference was not significant.

### *3.4. Predictors of mental health*

***Unadjusted estimates.*** The unadjusted associations between potential predictors and short-term emotional distress (GHQ-12 score) are presented in Table 3 and Figure S3. Short-term emotional distress was higher in females [unadjusted odds ratio (95% CI), male vs. female: OR = 0.73 (0.54–0.98)] and smokers [smokers vs. non-smokers: OR = 1.81 (0.99–3.33)]. Age [OR = 0.98 per year increase (0.96–0.99)], physical activity [>1×20'/week activity vs. less: OR = 0.60 (0.44–0.82)], medication use [OR = 0.63 (0.39–1.02]), residential exposure to low green [< 3m tall, per combined increase in surface area of 10 ha: OR = 0.87 (0.81–0.93)] and residential exposure to high green [≥ 3m tall, per increase of 10 ha: OR = 0.94 (0.89–0.98)] were protective factors against the development of short-term emotional distress.

***Adjusted estimates.*** Figure 1 and Table 3 show the results from the multivariable analyses. Short-term emotional distress (GHQ-12 score) increased with BMI [adjusted odds ratio (95% CI): OR = 1.06 per 1 unit increase (1.02–1.10)], was higher in smokers [OR = 2.10 (1.02– 4.38]) and in patients who reported perceived presence of allergenic trees near their residence [OR = 2.04 present vs. absent (1.36–3.07)]. Physical activity [> 1×/week 20 minutes of activity vs. less: OR = 0.59 (0.42–0.85)], age [OR = 0.97 per year increase (0.96–0.99)] and exposure to residential green space [≥ 3m tall, per combined increase in surface area of 10 ha: OR = 0.94 (0.90–0.99); < 3m tall, per increase of 10 ha: OR = 0.85 (0.78–0.93)] had protective effects against short-term distress. There were no effects of commuting distance or tree richness. Higher education [higher education vs. no higher education: OR = 0.90 (0.56–1.43)], medication use [use vs. no use: OR = 0.78 (0.45–1.36)] and chronic disease [disease vs. no additional disease: OR = 0.69 (0.45–1.04)] were associated with lower short-term emotional distress but these associations were not statistically significant.

***Comparison with the general population.*** Allergy patients that perceived to be living in proximity of allergenic tree species (Fig. 2a), that were not physically active (Fig. 2d), and that were exposed to less than median high green (Fig. 2b) or less than median low green (Fig. 2c) reported higher short-term distress during the airborne pollen season than the general population. Observed and inferred average stress were higher in allergy patients deprived of high (Fig. 2b) or low residential green (Fig. 2c) [residential green area < P50; less than 54.5 ha high green (17.3% cover) or less than 70.0 ha low green (22.3% cover)] than in the general population (observed vs. inferred means: Table S1). Conversely, the point estimates for distress reported by tree pollen allergy patients living in neighbourhoods with high levels of low green or high green (>P50) were similar to distress in the general population (Figure 2; Table S1). In Belgium, a GHQ score ≥ 2 indicates psychological distress. Physically inactive allergy patients

(Fig. 2d) [observed GHQ-12 (95% CI): 3.06 (1.45–4.66)] had the poorest mental health outcomes (GHQ-12 score > 2), followed by pollen allergy patients deprived of low green [GHQ-12 = 2.66 (1.69–3.62)] or high green [GHQ-12 = 2.55 (1.69–3.40)] (Table S1)

## 4. Discussion

### *4.1. Main findings*

Our key findings in a panel of 88 tree pollen allergy patients (in Flanders, Belgium), followed during two tree pollen seasons (2017 and 2018), were i) that short-term emotional distress during these airborne tree pollen seasons was higher than in the general population, ii) that residential green space had a protective effect against the development of short-term emotional distress and iii) that the perceived proximity to allergenic tree species was associated with higher distress.

### *4.2. Comparison with other studies*

***Green space, activity and mental health.*** We found additive protective effects of the quantity of residential green space (~20% cover high/low green or more) and physical activity on short-term mental health in tree pollen allergy patients. A study that used data from 3,000 people in the UK, aged 18–70 years, demonstrated that people living in urban areas and who were exposed to low amounts of nature or green space tended to have worse health outcomes, including poor self-reported mental and physical health (Cox et al., 2018). In a similar study based on survey data of 263 respondents living in the UK, higher levels of vegetation cover around the residence (20–30% cover or more) were associated with better mental health outcomes (Cox et al., 2017). A study in a sample of 720 students in Bulgaria demonstrated that the association between residential green space and mental health (assessed by use of the GHQ-12) was mediated by indirect pathways that included green space perceptions, restorative quality and physical activity (Dzambov et al., 2018). A study in New Zealand using data from 8,157 respondents to the New Zealand Health Survey 2006/07 found that the greenest neighbourhoods had the lowest risk of poor mental health (OR = 0.81; 95% CI 0.66–1.00); improved physical activity only partially explained the positive impact of neighbourhood green space on mental health (Richardson et al., 2013). A study using data from 8,793 respondents to the Catalunya Health Survey in Spain found an association between green spaces and better mental health while there was no association between green spaces and physical activity (Triguero-Mas et al., 2015). Our results therefore support the idea that residential green space and physical activity may have protective effects on mental health, but to our knowledge, the present study is the first that analyzed this effect in a susceptible study population that is sensitized to tree pollen allergens.

***Actual and perceived green space quality.*** The present study showed that exposure to residential green space had protective effects against short-term distress, and that this effect was stronger for low vegetation than for high vegetation and not modified by the expected (non-allergenic) tree diversity. This result is in line with earlier studies that showed that effects of green space on human health and well-being may be influenced by green space structural composition but not *per se* by the number of species in those green spaces (Aerts et al., 2018). Structural green space characteristics have impacts on wellbeing and stress through cascading effects on perceived green space safety, walkability and physical activity (Ali et al., 2017; Weimann et al., 2017). High green and low green may also differ in their allergenic potential. A study in Ohio and Kentucky investigated the effect of tree and grass cover in urban green spaces on outdoor tree and grass aeroallergen sensitization in 478 children. Tree cover (high green) was consistently associated with lower sensitization rates and grass cover (low green) to higher sensitization rates (Gernes et al., 2019). We found that perceptions about residential green space quality – i.e. the presence or perceived presence of allergenic trees near the home – had an impact on mental health. These results are in line with a study of 3,897 postpartum mothers in Australia, where perceived residential green space quality rather than actual quantity determined psychological distress (Feng and Astell-Burt, 2018). Effects of residential green space on allergy and mental health may therefore also be modified by botanical knowledge. A nocebo effect occurs when negative expectations of a patient amplify the negative effects of a real or perceived exposure (see e.g. Jaén and Dalton, 2014; Szemerszky et al., 2010; Verrender et al., 2018). Patients that are familiar with allergenic species recognize the risk and this may provoke allergy symptoms, even in the absence of allergens [in an exemplary study by Metzger (1947), a patient developed severe allergy symptoms after being exposed to paper replicas of *Solidago* flowers]. Similarly, patients that are less familiar with allergenic species may believe they are at risk in a green environment, which may be sufficient to trigger psychosomatic allergy symptoms and distress.

***Allergy and stress.*** Allergy and psychological stress are related (Dave et al., 2011). Combined data from two household surveys in the USA (n = 10,334) suggests that lifetime seasonal allergies are associated with mood disorders (OR = 1.45; 95% CI 1.26–1.67) and anxiety disorders (OR = 1.60; 95% CI 1.42–1.78) (Oh et al., 2018). A study of 1,673 adolescents in Taiwan showed that adolescents with allergic rhinitis had increased hazard ratios for major depression (HR 1.59; 95% CI 1.02–2.50) (Chen et al., 2013). In a cross-sectional study of 2,027 males and females, atopic disorders (asthma, seasonal pollen allergy and eczema) were associated with an increased likelihood of depression (OR = 1.50; 95% CI 1.20–1.97) (Sanna et al., 2014). Psychological stress can affect immunoregulatory functions and trigger allergic sensitization or exacerbate existing allergic disease (Dave et al., 2011; Sansone and Sansone, 2011). Conversely, exposure to allergens or allergen sources that cannot be avoided, such as airborne pollen or allergenic tree species near the residence, may lead to psychological stress in sensitized individuals, as demonstrated in this study. Furthermore, allergies may disrupt sleep and affect cognitive functioning and thus exacerbate anxiety, depression and psychiatric disturbance (Sansone and Sansone, 2011; Trikojat et al., 2017). The combined associations between perceived exposure, stress and allergy suggest that pollen allergy patients may be sensitive to positive feedback loops between manifestations of pollen allergy and affective states. Perceived and actual exposure to allergenic tree species may trigger emotional distress and elicit allergy symptoms; these allergy symptoms amplify stress and stress worsens the allergy symptoms.

### *4.3. Strengths and limitations*

The challenges posed by green spaces in terms of increasing risks for human allergies are acknowledged (Cariñanos and Casares-Porcel, 2011; Cheng and Berry, 2013; Damialis et al., 2019) but hardly accounted for in studies on green space and health. Large cohort studies have adjusted estimates of green space effects on health for a wide range of environmental (e.g. air pollution, noise) and socioeconomic (e.g. occupation, education, socio-economic status) variables (e.g. Vienneau et al., 2017) but not for sensitization to pollen allergens. Here we show that effects of green space on human health may differ substantially between the general population and the specific susceptible subgroup of people sensitized to tree pollen allergens.

However, this study has a number of limitations: the limited sample size and the self-reported nature of pollen allergy. The limited sample size is related to the fact that we could only use participants that resided in Flanders because the detailed environmental data used in this study (in particular the amounts of high green and low green around the residence) was only available for this region. In addition, relatively few participants (189) were successfully recruited in the original cohort study (Fig. S1), because the original study protocol required participants to continuously wear a mobile health system with a GPS tracker application or use an application on their own smartphone – tasks that limited the initial recruitment success. Small sample sizes may inflate variability. This was the main reason for including Bayesian inference in our analysis. Bayesian inference makes use of prior knowledge of the distribution of the outcome variable (here, prior knowledge that the distribution of responses to the GHQ-

12 would be skewed, with a high number of zeros and a dominance of low values). This method improved estimates of means and yielded credible intervals that were less wide than the confidence intervals that were based on the data alone. Finally, this study was designed and approved as a non-invasive study and therefore we had to rely on self-reported allergy status. In an invasive study, the allergy status could have been confirmed by positive skin-prick tests and/or serum specific IgE antibodies to Betulaceae pollen antigen mix (hazel, alder and birch).

## 5. Key findings and implications

This study found that residential green space had diverging associations with short-term emotional distress during the airborne tree pollen season in adults sensitized to tree pollen allergens. High levels of residential green space may protect against the development of short-term emotional distress. However, perceptions of nearby green space quality may modulate the effects of green space on mental health. We found an association between the perceived presence of allergenic tree species in the immediate vicinity of the residence and distress. Negative expectations of tree pollen allergy patients regarding exposure to allergenic tree species in their living environment may therefore affect mental health through self-amplifying effects on allergic symptoms and distress. Our results support the notion that green space interventions, such as the greening of vacant lots and the improvement of urban green infrastructure, may improve environmental and public health (Hunter et al. 2019), but exposure to allergenic pollen should be minimized through careful design and management of green space.

**Author contributions**

MH, ND, AVN, JMA, JVO, TSN and BS conceived and designed the study and acquired funding. RA secured ethical clearance. RA and MS collected data with assistance of NB, LH,

SD and NDS. RA analyzed the data. RA and NV interpreted the data and wrote the original draft. All authors reviewed and edited the manuscript and approved the final version.

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**Table 1.** Characteristics of the study population of tree pollen allergy patients, potential predictors and indicator of mental health (*n* = 88).

| Characteristic | *n* (%), or mean (SD) and median (25th–75th percentiles) |
|---|---|
| Gender | |
| female | 47 (53.4%) |
| male | 41 (46.7%) |
| Age in years | 39.9 (10.9) |
| | 38.0 (31.0–48.5) |
| BMI | 24.3 (4.5) |
| | 23.2 (21.0–26.7) |
| BMI classes | |
| underweight (<18.5) | 3 (3.4%) |
| normal (18.5–24.9) | 52 (59.1%) |
| overweight (25.0–29.9) | 23 (26.1%) |
| obesity (≥30.0) | 10 (11.4%) |
| Smoking status | |
| non-smoker | 85 (96.6%) |
| smoker | 3 (3.4%) |
| Physical activity (20 minutes or more) | |
| ≤ 1×20’/week | 18 (20.5%) |
| > 1×20’/week | 70 (79.5%) |
| Commuting distance in km | 25.6 (29.6) |
| | 15.0 (5.5–34.5) |

| | |
|---|---|
| Education level | |
| lower education | 12 (13.6%) |
| higher education | 76 (86.4%) |
| Allergy medication use | 82 (93.2%) |
| antihistamines | 54 (61.4%) |
| corticosteroids | 7 (8.0%) |
| both | 21 (23.9%) |
| none | 6 (6.8%) |
| Chronic respiratory problems | 22 (25.0%) |
| asthma | 18 (20.5%) |
| chronic respiratory disease | 1 (1.1%) |
| both | 3 (3.4%) |
| none | 66 (75.0%) |
| Proximity to allergenic tree species | |
| *Betula*, *Corylus* and/or *Alnus* present near residence | 66 (75.0%) |
| not present near residence | 22 (25.0%) |
| Green space quantity within 1 km distance from residence | |
| high green (≥ 3m) (ha) | 65.2 (36.5) |
| | 54.5 (39.7–85.8) |
| low green (< 3m) (ha) | 70.1 (20.0) |
| | 70.0 (58.6–87.3) |
| Modelled non-allergenic tree richness (genera) | 8.6 (1.7) |
| | 9 (8–10) |

| | |
|---|---|
| Patients per cohort year | |
| 2017 (weak Betulaceae pollen season) | 44 (50.0%) |
| 2018 (strong Betulaceae pollen season) | 44 (50.0%) |
| Mental health endpoint | |
| short-term emotional distress (GHQ-12) | 2.1 (2.7) |
| | 1.0 (0.0–3.0) |

**Table 2.** Tree pollen season severity in Belgium in 2017 and 2018 compared to the reference period 2012–2018.

| Year | Species | Season start[a] | Season length[b] | SPI[c] (SD) | *z*-score |
|---|---|---|---|---|---|
| 2012–2018 (ref.) | *Corylus* | 27 | 58 | 910 (534) | |
| | *Alnus* | 47 | 36 | 3,479 (1,455) | |
| | *Betula* | 96 | 20 | 11,411 (8,211) | |
| 2017 | *Corylus* | 42 (late) | 39 (short) | 499 (89) | –0.77 |
| | *Alnus* | 45 | 28 (short) | 2,518 (2,737) | –0.66 |
| | *Betula* | 87 (early) | 22 | 4,238 (3,038) | –0.87 |
| 2018 | *Corylus* | 13 (early) | 62 | 1,769 (302) | 1.61 |
| | *Alnus* | 33 (early) | 48 (long) | 3,467 (1,597) | –0.01 |
| | *Betula* | 98 | 13 (short) | 20,086 (4,871) | 1.06 |

[a]Season start (day of year).

[b]Season length (days) defined as the time window between the days of the 5$^{th}$ and 95$^{th}$ percentile cumulative concentration of the seasonal pollen index.

[c]Seasonal Pollen Index (grain×days m$^{-3}$). Overall and annual means (and SD) from three pollen monitoring stations (Brussels, Genk and Marche-en-Famenne) of the Belgian Aerobiological Surveillance Network.

**Table 3.** Unadjusted and adjusted associations between potential predictors and short-term emotional distress (GHQ-12) in a cross-sectional sample of 88 pollen allergy patients in Flanders (Belgium), during the airborne tree pollen seasons of 2017 and 2018.

| | Unadjusted | | Adjusted[1] | |
|---|---|---|---|---|
| Predictor | OR (95% CI) | *p* | OR (95% CI) | *p* |
| Gender | | | | |
| female | 1.00 (reference) | | 1.00 (reference) | |
| male | 0.73 (0.54–0.98) | 0.035 | 0.90 (0.64–1.26) | 0.522 |
| Age in years | 0.98 (0.96–0.99) | 0.001 | 0.97 (0.96–0.99) | 0.002 |
| BMI | 1.02 (0.99–1.05) | 0.310 | 1.06 (1.02–1.10) | 0.003 |
| Smoking status | | | | |
| non-smoker | 1.00 (reference) | | 1.00 (reference) | |
| smoker | 1.81 (0.99–3.33) | 0.056 | 2.10 (1.02–4.38) | 0.044 |
| Physical activity (20 minutes or more) | | | | |
| ≤ 1×20'/week | 1.00 (reference) | | 1.00 (reference) | |
| > 1×20'/week | 0.60 (0.44–0.82) | 0.001 | 0.59 (0.42–0.85) | 0.004 |
| Commuting distance in km | 1.00 (1.00–1.01) | 0.399 | 1.00 (0.99–1.01) | 0.602 |
| Education level | | | | |
| lower education | 1.00 (reference) | | 1.00 (reference) | |
| higher education | 0.87 (0.58–1.31) | 0.512 | 0.90 (0.56–1.43) | 0.643 |
| Allergy medication use | | | | |
| no | 1.00 (reference) | | 1.00 (reference) | |
| yes | 0.63 (0.39–1.02) | 0.058 | 0.78 (0.45–1.36) | 0.385 |

| | | | | |
|---|---|---|---|---|
| Chronic respiratory problems | | | | |
| no | 1.00 (reference) | | 1.00 (reference) | |
| yes | 0.95 (0.68–1.33) | 0.765 | 0.69 (0.45–1.04) | 0.075 |
| Proximity to allergenic tree species | | | | |
| not present | 1.00 (reference) | | 1.00 (reference) | |
| present | 1.15 (0.82–1.63) | 0.418 | 2.04 (1.36–3.07) | 0.001 |
| Green space quantity | | | | |
| high green (10ha) | 0.94 (0.89–0.98) | 0.006 | 0.94 (0.90–0.99) | 0.013 |
| low green (10ha) | 0.87 (0.81–0.93) | <0.001 | 0.85 (0.78–0.93) | <0.001 |
| Modelled non-allergenic tree richness (genera) | 1.08 (0.98–1.19) | 0.147 | 0.99 (0.88–1.09) | 0.684 |
| Cohort year | | | | |
| 2017 (weak) | 1.00 (reference) | | 1.00 (reference) | |
| 2018 (severe) | 0.76 (0.57–1.02) | 0.065 | 0.82 (0.60–1.13) | 0.222 |

[1]The fully-adjusted model included all predictor variables in one single model.

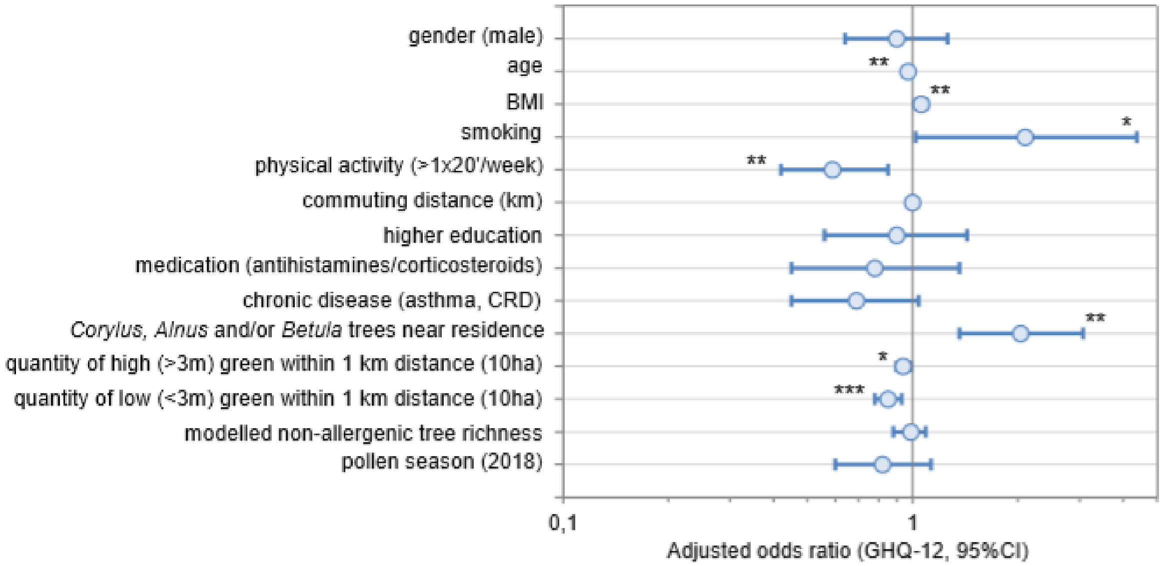


**Figure 1.** Adjusted associations (odds ratios with 95% Wald confidence limits) between potential predictors and short-term distress (GHQ-12 score) in a cross-sectional sample of 88 pollen allergy patients in Flanders (Belgium) during the airborne tree pollen seasons of 2017 and 2018 from multivariable generalized linear models based on the Poisson probability distribution and a log-link function (* P<0.05; ** P<0.01; *** P<0.001). The fully-adjusted model included all predictor variables in one single model.

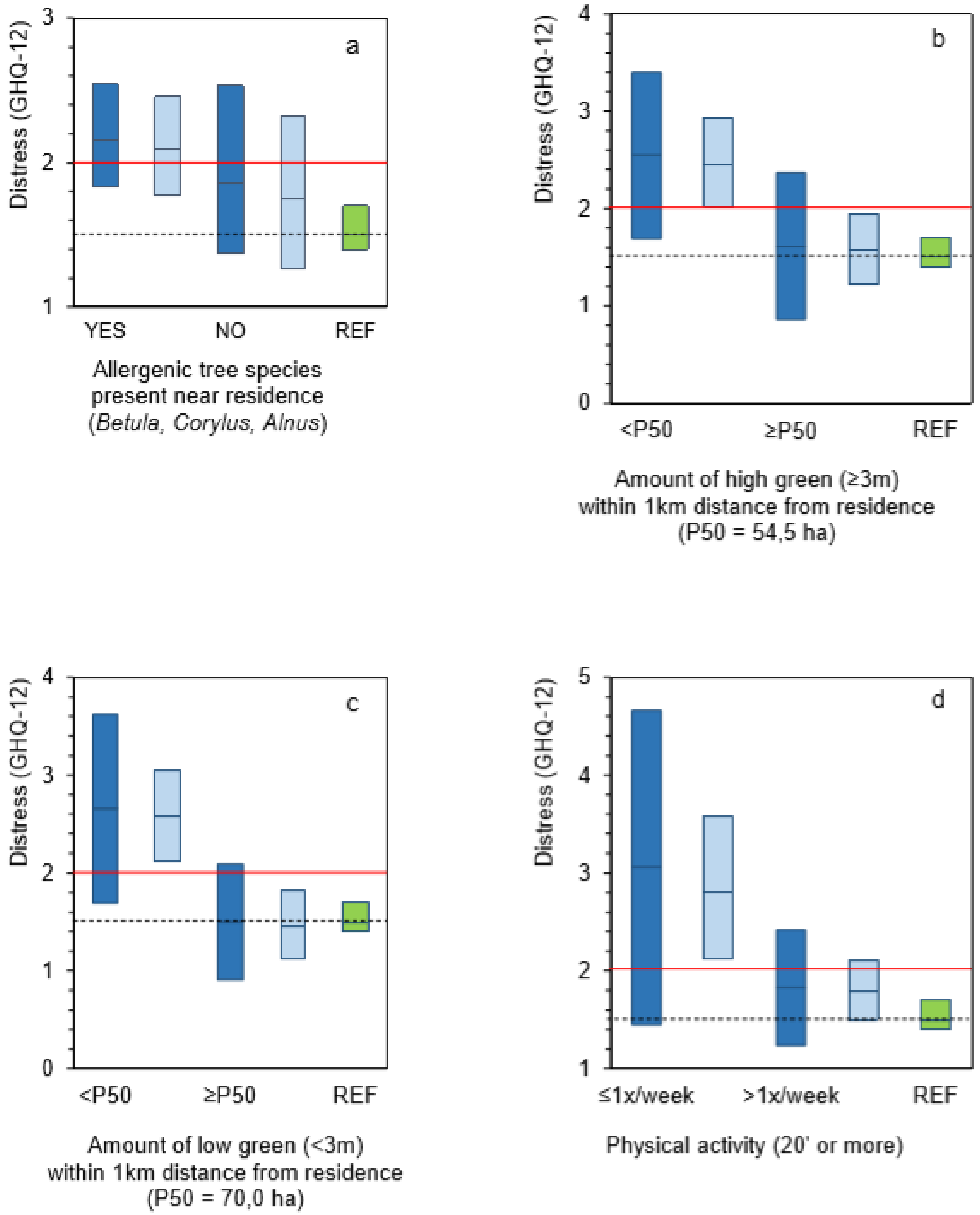


**Figure 2**. Observed (dark bars) and inferred (light bars) average distress (GHQ-12; 95% CI) in 88 allergy patients residing in Flanders (Belgium) during the airborne pollen seasons of 2017 and 2018 stratified by residential green space properties (a: presence of allergenic tree species near residence; b: amount of high green near residence; c: amount of low green near residence) and physical activity level (d) and compared to average distress in the general population in Flanders (REF; 2013, N = 2,467). Posterior (inferred) distress was based on an exponential prior distribution and Bayesian Poisson inference. The full red reference line indicates the threshold for psychological distress (GHQ-12 score ≥ 2).