Climate change, airborne allergens, and three translational mitigation approaches

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Summary

One of the important adverse impacts of climate change on human health is increases in allergic respiratory diseases such as allergic rhinitis and asthma. This impact is via the effects of increases in atmospheric carbon dioxide concentration and air temperature on sources of airborne allergens such as pollen and fungal spores. This review describes these effects and then explores three translational mitigation approaches that may lead to improved health outcomes, with recent examples and developments highlighted. Impacts have already been observed on the seasonality, production and atmospheric concentration, allergenicity, and geographic distribution of airborne allergens, and these are projected to continue into the future. A technological revolution is underway that has the potential to advance patient management by better avoiding associated increased exposures, including automated real-time airborne allergen monitoring, airborne allergen forecasting and modelling, and smartphone apps for mitigating the health impacts of airborne allergens.

Keywords: **Climate change; Allergen; Pollen; Asthma; Adaptation; Translation**

Introduction

It is unequivocal that human influence has warmed the Earth's atmosphere and that this is occurring at an unprecedented rate.[1] This warming is driven by emissions of greenhouse gases from human activities, with, for example, the global atmospheric carbon dioxide (CO_2) concentration having increased from a pre-industrial level of approximately 280 parts per million to 414.71 parts per million in 2021.[2]

These changes in the Earth's atmosphere and related changes in the broader climate system are having impacts on physical, biological, and human systems, including human health. The Intergovernmental Panel on Climate Change's most recent assessment of the impacts of climate change on health, projects a significant increase in ill health and premature deaths from climate-sensitive diseases and conditions, with, for example, an excess of 250,000 deaths per year by 2050 attributable to climate change.[3]

One of the important impacts of climate change on human health is its impacts on sources of airborne allergens such as pollen and fungal spores, and the resulting impacts on allergic respiratory diseases such as allergic asthma and allergic rhinitis.[4,5] Increasing air temperatures as well as increasing atmospheric CO_2 concentrations can impact airborne allergen seasonality, production and atmospheric concentration, allergenicity, and geographic distribution. These impacts result in changes in allergen exposure, with important consequences for both development of disease and symptoms.[6] Allergic respiratory diseases are already serious public health challenges in many countries and regions. For example, asthma affects more than 350 million people worldwide and is the most common chronic disease in children, affecting at least 30 million children and young adults in Europe,[7] with the estimated indirect costs of such diseases alone in the European Union at € 55–151 billion a year.[8]

This review provides a synthesis of what is known about the impacts of climate change on airborne allergens and allergic respiratory diseases, with a focus on recent developments. It then explores three translational mitigation approaches that may lead to improved health outcomes, these being automated real-time airborne allergen monitoring, airborne allergen forecasting and modelling, and smartphone apps for mitigating the health impacts of airborne allergens. While each of these is a significant advance in its own right, we highlight the power of their integration and resulting revolution in the management of allergic respiratory diseases (Fig. 1). Our exploration also briefly proposes future directions in this field and highlights important questions for future research.

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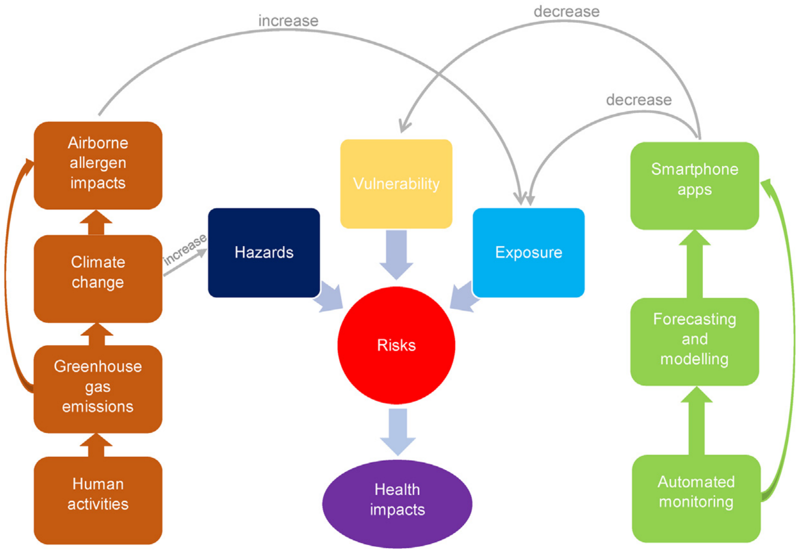

Fig. 1: Diagram summarising the drivers and impacts of climate change on airborne allergens (brown) and the consequent impacts on human health. Central to this is the concept of risk, which is a function of hazards, vulnerability and exposure. Also illustrated are three connected adaptation approaches (green) that can prevent or reduce health impacts by decreasing exposure and vulnerability.

Search strategy and selection criteria

Data for this review were identified by searches of Web of Science, MEDLINE, Current Contents, PubMed, and references from relevant articles using the search terms “climate change”, “allerg*”, “pollen”, “fungal spore”, “mold spore”, “mould spore”, “automat*”, “monitor”, “forecast”, “model”, “app”, and “smartphone”. Abstracts and reports from meetings were excluded. Only articles published in English between 2000 and 2022 were included. Particular emphasis was placed on literature published in the past 5 years (2018–2022).

Climate change and airborne allergens

Impacts on airborne allergen seasonality

The impacts of climate change on airborne allergen seasonality have been the subject of many studies. The first of these studies appeared in the 1990s and early 2000s, analysing pollen records over the latter decades of the 1900s.[9,10] Impacts have been found on the start date, date of maximum pollination (i.e., peak), end date, and duration of the pollen season. Most studies have investigated airborne allergen records over the past few decades in Europe and North America. For example, recent studies from Europe illustrate the complexity and diversity of climate change impacts on pollen seasonality, being both species- and location-specific. Adams-Groom et al.[11] investigated Poaceae (grass), *Betula* (birch) and *Quercus* (oak) pollen seasons in the UK over the 26 years from 1995 to 2020. They found increasing temperatures have been associated with *Quercus* pollen seasons starting earlier, earlier first high Poaceae pollen day in central UK, but no change in the seasonality of *Betula* pollen. Similarly, Velasco-Jiménez et al.[12] investigated pollen season trends in winter flowering trees in South Spain over the 24-year period 1994–2017, finding that pollen season start dates and end dates were delayed for some taxa and locations and advanced for other taxa and locations.

From North America, Manangan et al.[13] investigated trends in the pollen season of 13 allergenic plant taxa in Atlanta, Georgia, over the 27-year period from 1992 to 2018, finding that the start date of the pollen seasons was advancing for multiple species and that this was associated with increasing temperatures. Although much less studied, research is also emerging on the impacts of climate change on fungal spore seasons, with one such study being that by Paudel et al.[14] who found an increase in the duration of fungal spore exposure in San Francisco, California, over the period 2002 to 2019.

The most comprehensive assessment in recent years investigated temperature-related changes in airborne allergenic pollen seasonality of multiple plant taxa from 17 locations across the Northern Hemisphere (Europe, North America, and Asia).[15] It found 11 of the locations showed a significant increase in pollen season duration over time, increasing by 0.9 days per year on average. A number of studies have also investigated projected future pollen seasonality, with recent research showing longer pollen seasons over the continental United States due to increasing temperatures.[16]

Impacts on pollen and fungal spore production and atmospheric concentration

The impacts of climate change on the production of airborne allergens and their atmospheric concentrations have been similarly well studied. In addition to analysis of records of airborne allergens over the past few decades, which has examined multiple taxa and numerous locations, experimental studies under controlled conditions have contributed significantly to understanding of the effects of both increasing temperature and increasing CO_2 concentrations on allergen production. Most studies have found increasing airborne allergens associated with increasing temperature and/or increasing CO_2 concentrations, although results can vary from species to species and location to location, with instances of no change or decline also found.

Recent research has tended to focus on analysis of records of airborne allergens over the past few decades and/or projections of future airborne allergen levels. Single-site studies[13,17] as well as the comprehensive assessment of multiple plant taxa from 17 locations across the Northern Hemisphere by Ziska et al.[15] clearly show pollen concentrations are increasing over time in many taxa and locations (including 12 of those analysed by Ziska et al.). Recent experimental research has investigated the response of pollen production of sawtooth oak trees (*Quercus acutissima*) to elevated levels of ambient CO_2, using three open-top chambers at the National Institute of Forest Science in Suwon, Korea.[18] Compared to current CO_2 concentrations, trees grown at elevated CO_2 concentrations produced substantially more pollen.[18]

Much less studied are impacts of climate change on fungal spore concentrations, making the recent study by Olsen et al.[19] of airborne *Cladosporium* and *Alternaria* spore concentrations over the 26 years from 1990 to 2015 in Copenhagen, Denmark, an important contribution to the field. They found decreasing airborne spore concentrations in both taxa, with this being attributed to concurrent temporal changes in land use, i.e., urbanisation around the greater Copenhagen area and changes in agricultural practices.

Two recent studies have focussed on projected future airborne pollen loads. Rojo et al.[20] studied the effects of future climate change on birch abundance and their pollen load in Germany. They found birch tree abundance will decrease at lower altitudes but increase at higher altitudes, with airborne birch pollen loads similarly decreasing and increasing in these areas respectively. Zhang & Steiner's study[16] of the impacts of climate change on pollen emission over the continental United States by the end of the century found temperature and precipitation alter daily pollen emission maxima by −35 to 40% and increase the annual total pollen emission by 16–40% due to changes in phenology and temperature-driven pollen production. They also noted that increasing atmospheric CO_2 may increase pollen production, and that doubling production in conjunction with climate increases end-of-century emissions up to 200%.[16]

Jochner-Oette et al.[21] have recently suggested that linear models, which are usually used to analyse long-term changes in pollen concentrations, may not be fully suitable for describing these changes in recent decades. They analysed several pollen taxa from six locations in Switzerland using both Bayesian statistics that describe discontinuities (i.e., change points) and linear models, finding that trends of linear regressions differed considerably in magnitude or even differed in sign compared to the Bayesian results.[21] Similarly, Glick et al.[22] analysed changes in pollen season in Switzerland between 1990 and 2020 using both linear regression and locally estimated scatterplot smoothing (LOESS), with the latter indicating that these multi-decade pollen changes are typically nonlinear. They also demonstrated that different pollen season definitions impact the magnitude, direction, and significance of trends in the start date, duration and intensity of the pollen season.[22]

Impacts on airborne allergen allergenicity

Research on a number of plant and fungal species has demonstrated impacts of elevated atmospheric CO_2 concentrations and increasing temperatures on the respective pollen and fungal spore allergenicity. A significant recent advance in this field is the study by Rauer et al.[23] who demonstrated that pollen from ragweed plants grown experimentally under elevated CO_2 elicits a stronger allergic response *in vivo* and *in vitro*. Also recently, Gentili et al.[24] examined experimentally the response of ragweed to increasing temperature. They found that pollen allergenicity was a temperature-responsive trait, with pollen allergenicity increasing with temperature.[24]

Two other noteworthy studies are those by Albertine et al.,[25] who examined the impact of elevated CO_2 and ozone (O_3) on timothy grass pollen and allergen production, and El Kelish et al.,[26] who examined the impact of elevated atmospheric CO_2 concentration and drought stress (which will also occur under climate change in some parts of the world) on ragweed pollen allergenicity. These experimental studies were particularly significant because of their more-realistic bivariate nature, compared to earlier studies that had only varied CO_2. The former study showed that elevated O_3 reduced the allergen content of the pollen, but the elevated CO_2 increased the amount of grass pollen produced to such an extent (by about 50% per flower) that the net effect of elevated levels of both gases would likely be increased allergen exposure.[25] The latter study showed that ragweed pollen would likely become more allergenic under conditions of elevated CO_2, drought stress, and elevated CO_2 plus drought stress.[26]

Impacts on airborne allergen distribution

Allergen-producing organisms (such as plants) live within required and optimal temperatures, and these influence the geographic ranges of species. The

Intergovernmental Panel on Climate Change's (IPCC) most recent assessment is that approximately half of the >4000 species globally that have been studied in the context of climate change have shifted their ranges to higher latitudes or elevations due to climate change.[27] While relatively few studies have been focussed on the impacts of climate change on allergenic species ranges, those that have, have found changes consistent with the shifts found for many other species. Xie et al.[28] studied the species composition of Australian grasslands from 2003 to 2017 and found that the ratio of warm season grasses to cool season grasses had increased over this period, although this was related to changes in seasonal rainfall rather than changes in temperature. Important research has also been conducted on projected future allergenic plant range shifts. Key examples include the studies by Chapman et al.[29] and Storkey et al.,[30] both of which modelled ragweed, finding a northward expansion of the available climatic niche for populations to establish and persist in both North America and Europe.

Impacts on human health

While research on the impacts of climate change on airborne allergens has been conducted since the 1990s and is now well-established, original research on the impacts on allergic respiratory diseases has only started to appear in the last few years. In a landmark study, the first to quantify the impacts of climate change on pollen allergy, Lake et al.[31] projected sensitisation to ragweed will more than double in Europe, from 33 to 77 million people, by 2041–2060. More recently, several studies have emerged from the United States that have quantified the present and projected future impacts of changes in pollen seasonality on both asthma and allergic rhinitis (hay fever). Neumann et al.[32] projected increases in emergency department visits for asthma due to increases in pollen season length of between 8 and 14% by the year 2090, with increases in the grass pollen season being a major contributor to this. Sapkota et al.[33] analysed asthma hospitalisations in Maryland from 2001 to 2012 and found an increased risk associated with very early onset of spring. In another study by Sapkota et al.,[34] it was found that adults living in US counties with a very early (and very late) onset of spring had a 14% (18%) higher odds of hay fever compared to those living in counties where onset of spring was within the normal range.

There are important interactions between aeroallergens and air pollutants such as ozone, nitrogen oxides, and combustion- or traffic-related airborne particulate matter, and climate change impacts not only aeroallergens but also air pollutants.[35] For example, air pollutants can act as adjuvants and alter the immunogenicity of allergenic proteins.[36] As such, the impacts of climate change on allergic respiratory diseases are complex and in some cases will be augmented by synergistic effects. Similarly, other global changes such as desertification, urbanisation, and biodiversity loss will also have impacts on airborne allergens, and the relative importance of these in combination with climate change will likely vary from place to place and over time.[37–39]

Finally, as understanding of the impacts of climate change on allergic respiratory diseases builds as new studies are conducted, it will be important for such studies to investigate not only the impacts of increases in temperature and CO_2 on allergens and diseases but also the impacts of climate change on the weather and climate extremes that also influence these diseases, such as thunderstorms through thunderstorm asthma and flooding through increases in indoor mould and spore production.[40–42]

In summary, there is substantial evidence of both present and projected future impacts of climate change on airborne allergens, and growing evidence of associated adverse impacts on allergic respiratory diseases. There are two fundamental responses to reduce and/or avoid these impacts: one is to reduce emissions or enhance the sinks of greenhouse gases and thereby reduce the atmospheric concentration of greenhouse gases and the magnitude of climate change, and the other is the process of adjustment to actual or expected climate and its effects.[43] In the global climate change community, these are termed mitigation and adaptation, respectively. While both responses are required, the following sections explore three examples of the latter—translational approaches that may reduce and/or avoid the adverse impacts of climate change on allergic respiratory diseases and lead to improved health outcomes.

Automated monitoring

Airborne pollen and fungal spore monitoring networks have developed at the initiative of allergists in the second part of the 20th Century, as pollen concentrations are essential data to prevent, diagnose and treat pollen allergy. To date, all over the world, aeroallergen data are still produced manually by counting particles under the microscope, and expressed in daily average concentrations, which are usually available after a delay of several days.[44]

Recent technological developments have brought to the market automatic, stand-alone instruments delivering aeroallergen concentrations at high temporal resolution (hourly or less), i.e., of duration close to the meteorological phenomena that influence the dispersion of particles,[45,46] and in real-time, i.e., data are available a few seconds or minutes after the measurement. This revolution enables the timely information of all users, in particular a significant improvement of aeroallergen forecast accuracy (see also next section).[47]

Thanks to a higher amount of particles sampled and a measurement free from variations due to manual counting, the automatic data are also more robust: such quality data are of particular importance to detect signals of changes in the environment and evaluate future trends. Parallel measurement campaigns ensure that manual and automatic data are comparable for long-term studies.[48]

All systems include two main steps: the instrument pumps air and collects information about the particles it contains, by using, for example, microscope imaging, holography, and/or fluorescence spectroscopy.[49] Huffman et al.[50] have provided an in-depth description and review of these and several other real-time techniques for automated monitoring. Then an artificial intelligence algorithm identifies these particles by comparison with reference datasets. There are however huge differences (e.g., technology, price, maturity, type of information, robustness) between systems from different manufacturers and the results they produce are not always comparable.[51,52] Most systems have, to date, focused on the main pollen types present in Central Europe. However, many research groups are actively working to extend the current capabilities to fungal pathogens[53,54] and other types of particles (e.g., Šikoparija et al.[55]), in convergence with aerosol and air quality observations.

At a very early stage of development of these new technologies, the EUMETNET AutoPollen programme was set up to favour collaboration, as well as to validate the methods and recommend standards[48,49,56] in close collaboration with the metrology community (e.g., Lieberherr et al.[57]). In Europe, the Adopt COST Action[58] contributes to the development of such methods. A few networks (e.g., in Bavaria, Oteros et al.[59]; Serbia-Croatia, Tešendić et al.[60]; and Switzerland) and about a hundred sites are operational around the world, but the interest is huge and new sites are multiplying.

Thanks to these new developments, the study of aeroallergens has entered a new era. The technology has the potential to revolutionise the understanding of aerobiological processes and to make available high-quality information for the benefits of specialists as well as the population in major very topical problems such as air quality, health, crop protection, and climate change impact.[47]

However, this potential now needs to be harnessed, research and standardisation further carried out, monitoring networks built, data freely exchanged at international level, and end-users specific information channels put in place. This ongoing process would be greatly supported by the development of appropriate regulation at local, national and international levels.

Forecasting and modelling

Modelling of aeroallergens is developing along three directions with different goals and approaches, as well as the spatial and temporal scales covered.[61] Historically, first were statistical models constructed for individual stations or small regions or countries. They can describe local/regional season for pollen and, rarely, fungal spores.[62–66] Such models, if properly constructed, can have quite high descriptive and predictive skills in the region they are made for.[67] Progress in machine learning gave an additional boost to these models, potentially increasing their value for both research and application tasks.[68] However, their applicability outside the regions of development and for distant times is strongly doubtful.

Trajectory models of atmospheric dispersion are frequently used for regional analysis of individual episodes at local-to-regional scales.[69,70] Such simulations are useful for a rough assessment of the regions affecting the specific observational site or a city, possible dispersion directions of observed pollen clouds, etc. However, obtained estimates are neither detailed nor accurate and can lead to erroneous conclusions in complicated cases.[71]

During the last two decades, several atmospheric composition models have undertaken a major step towards (semi-)mechanistic simulations of the whole pollen lifecycle including pollen maturation, presentation, release to the air, and atmospheric transport, transformation, and removal.[72–75] Being the most-complicated and difficult to construct and apply, these models are also the most-comprehensive tools available to-date for analysis and forecasting of pollen concentrations at regional-to-continental scales. Extension to fungal spores is yet to achieve maturity. Successful applications of these models have prompted the Europe-wide ensemble pollen forecasting within Copernicus Atmospheric Monitoring Service,[76,77] allowed for detailed complex-terrain predictions,[78] allowed for analysis of regional features of pollen potency (allergen release per pollen grain),[79] opened the possibility of data fusion[77] and assimilation,[80] and gave the foundation to the first multi-decadal hindcast of pollen dispersion at European scale.[81]

Arguably the most-pressing challenge to all bio-aerosol models in connection to climate change is to maintain their skills with changing environment. Statistical models are in the worst position: they quickly get obsolete. By-construction, they reflect apparent correlations valid only for the period and place they were made for, and have no adaptive capacity to new climate, changing vegetation, and land use. Trajectory models are driven by actual meteorological information and do not include any vegetation-related modules, and hence are not affected. The situation with comprehensive pollen models is equivocal. Their transport component, similar to trajectory models, is driven by actual meteorological data and thus climate-change resilient. However, phenological modules might experience problems. In particular, a phenological model of Fu et al.[82] has shown a significant trend of error of phenological season predictions in Germany over recent decades. The authors concluded that several main European plants have already started their adaptation to changing climate. However, this result has not been confirmed in experiments with a phenological model by Sofiev et al.[73] This model, albeit based on similar principles, showed no trend in skills over 1980–2015. This topic deserves a thorough investigation, which can provide a robust conclusion on whether the European vegetation has started adaptation to the changing climate.

The other new frontier in model development is connected to the on-going transition from classical Hirst-trap based pollen observations to new real-time monitoring technology.[49,56] High capital investments in such devices will limit the number of installations compared to Hirst-equipped stations (over 300 in Europe alone), thus increasing the role of models as the primary source of aerobiological information for users.

Smartphone apps for mitigating the health impacts of airborne allergens

Airborne allergens have a profound impact on the daily lives of people living with allergic rhinitis and asthma, both of which are common conditions with high personal and social impacts.[83,84] However, the influences of multiple changing and interacting environmental risk factors pose challenges for identifying and managing the contribution of specific allergic triggers to daily symptoms.[85] Further, the escalating environmental impacts associated with climate change, as discussed above, are increasing the health burden associated with allergic respiratory conditions and adding to the difficulty of disentangling different environmental impacts on individuals to support clinical care.[85]

For allergic respiratory conditions and other health conditions that require day to day self-management, mobile health apps are well-accepted tools for supporting health education, symptom tracking and promoting adherence to treatment for improved patient outcomes.[84,86,87] Recent technological advances in pollen detection and forecasting, discussed above, are facilitating a step-change in how mobile apps can support individuals, clinicians and health agencies manage and mitigate the health impacts of environmental triggers of allergic respiratory diseases. A new generation of app-based services that combine educational, clinical and both real-time and forecast environmental information, are emerging.[85,88] These offer promise of considerable improvement in the diagnosis of specific sensitivities in individuals and personalised management options,[84,85,89,90] and considerably improved potential for supporting behaviour change by providing information on personal antecedent risk factors and health outcomes in relation to different environmental conditions and management responses.[88,90]

The ability to generate and share far more accurate short-term forecasts of pollen and allergy risk at both individual and population levels is another major advance that can be supported by mobile app data. For example, inclusion of crowd-sourced symptom data can improve population symptom forecasts, pollen predictions, and forecasts of symptoms in individuals.[83,91,92] As preventive action is central to the management of allergic conditions, through allergen avoidance or preventive medication, validated personalised allergy health risk forecasts are of high value to affected individuals.

Pioneering examples of such approaches in mobile app management tools for pollen allergies have included: the expansion of the European MASK-air app for management of allergic rhinitis, to include information about local pollen and pollution levels and create risk indices for individuals (MASK-POLLAR),[92,93] the Husteblume app (Germany), which enables symptom and medication tracking, and displays forecasts on pollen expected at user's location and provides feedback on how these interact[88]; the AllergyMonitor app (Italy), an eDiary for allergic rhinitis and allergen immunotherapy[87]; and the AirRater app (Australia), that tracks air pollution and a wide range of pollen types, sends real-time, location-specific notifications of elevations in pollen or air pollution and, through individualised statistical models linking these data, provides feedback to support diagnosis and personalised notifications of risk periods.[89]

Mobile app-supported health care for environmental allergies and sensitivities has the potential to reduce the social burden of illness and improve quality of life for individuals.[89,90] This requires ongoing development, evaluation and refinement of the fundamental enablers of high quality personalised information to users, including accurate and timely detection of airborne allergens, accurate geographic forecasts of impacts, and personalised data on sensitivities, impacts and options for self-management. The days of unvalidated warnings based on season and meteorological data alone should be well behind us.

Conclusion

Climate change, and in particular increases in atmospheric CO_2 concentration and air temperature, is having an impact on airborne allergens such as pollen and fungal spores. Impacts have already been observed on the seasonality, production and atmospheric concentration, allergenicity, and geographic distribution of airborne allergens, and these are projected to continue into the future. While impacts vary by species, and in some cases, by location, it is often found that the pollen season is advancing and/or getting longer, pollen production, atmospheric concentration and allergenicity are increasing, and plants are shifting their ranges poleward, and in mountainous regions, upward. All of these impacts have important consequences for allergic respiratory diseases.

While further research is required on the impacts of climate change on airborne allergens, and in particular on the consequences of these impacts for allergic respiratory diseases, it is vital that the management of these diseases be adjusted and enhanced to avoid or at least reduce harmful exposures and improve health outcomes. A technological revolution is underway that has the potential to achieve this, including automated real-time airborne allergen monitoring, airborne allergen forecasting and modelling, and smartphone apps for mitigating the health impacts of airborne allergens.

Outstanding questions

Despite the exciting advances that have been made in understanding of the impacts of climate change on airborne allergens, there remain many important questions for future research. Most of the observational research is of the Northern Hemisphere, with very little research and knowledge of impacts in the Southern Hemisphere. Experimental research is currently limited to just a few key species, so there is an urgent need for such research of other important allergenic species, including experiments that vary two or more variables. Finally, research on the impacts of climate change on allergic respiratory diseases themselves is extremely limited, with just a few studies having emerged in the past few years. Detecting change in such diseases and evaluating the relative contribution of climate change to this is perhaps the greatest challenge facing this field.

Contributors

PJB conceived and designed the work and all authors made substantial contributions to the acquisition, analysis, or interpretation of data for the work. All authors made substantial contributions to drafting the work and revising it critically for important intellectual content. All authors read and gave final approval of the version to be published. All authors gave agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Declaration of interests

The authors declare no conflicts of interest.

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