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REVIEW

Impacts of climate change on aeroallergens: past and future

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Summary Human activities are resulting in increases in atmospheric greenhouse gases, such as carbon dioxide, and changes in global climate. These, in turn, are likely to have had, and will continue to have, impacts on human health. While such impacts have received increasing attention in recent years, the impacts of climate change on aeroallergens and related allergic diseases have been somewhat neglected. Despite this, a number of studies have revealed potential impacts of climate change on aeroallergens that may have enormous clinical and public health significance. The purpose of this review is to synthesize this work and to outline a number of research challenges in this area. There is now considerable evidence to suggest that climate change will have, and has already had, impacts on aeroallergens. These include impacts on pollen amount, pollen allergenicity, pollen season, plant and pollen distribution, and other plant attributes. There is also some evidence of impacts on other aeroallergens, such as mould spores. There are many research challenges along the road to a more complete understanding of the impacts of climate change on aeroallergens and allergic diseases such as asthma and hayfever. It is important that public health authorities and allergy practitioners be aware of these changes in the environment, and that research scientists embrace the challenges that face further work in this area.

Keywords allergen, carbon dioxide, climate change, distribution, mould, plant, pollen, season, spore, temperature

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Introduction

Global climate change is likely to have had, and will continue to have, impacts on human health. While such impacts have received increasing attention in recent years, the impacts of climate change on aeroallergens and related allergic diseases have been somewhat neglected. Despite this, a number of studies have revealed potential impacts of climate change on aeroallergens that may have enormous clinical and public health significance.

Human activities have resulted in increases in the concentrations of atmospheric greenhouse gases and changes in global climate. Before the Industrial Era (circa 1750) atmospheric carbon dioxide (CO_2) concentration was 280 ± 10 p.p.m. for several thousand years [1]. It has risen since then, with the mean annual concentration at Mauna Loa (one of the most favourable locations for measuring CO_2) in 2002 at 373.10 p.p.m. [2]. The best estimate of global average surface temperature change is a 0.6 °C increase since the late 19th century, with a 95% confidence interval of 0.4–0.8 °C [3].

The Special Report on Emissions Scenarios (SRES) [4] produced a series of scenarios of CO_2 emissions representing outcomes of distinct narratives of economic development and demographic and technological change [1]. Using six of these scenarios and two fast carbon cycle models, Prentice et al. [1] examined the implications for future CO_2 concentrations. Projected CO_2 concentration by 2100 ranged from 541 to 970 p.p.m. (approximately 1.9 and 3.5 times the pre-industrial concentration), with uncertainties around these values of −14% to +31%. Global average surface temperature is projected to rise over the period 1990–2100 under all SRES scenarios, ranging from 1.4 °C to 5.8 °C [5].

Many natural and human systems are sensitive and vulnerable to climate change. Observational evidence indicates that recent regional changes in climate, particularly temperature increases, have already affected a diverse set of physical and biological systems in many parts of the world [6]. Such impacts of climate change are expected to continue, many of which will be adverse.

A number of reviews of the potential impacts of climate change on human health have been published since about 1990. These reviews have considered the impacts on aeroallergens and related diseases to varying extents. A number of them have neglected this important area of health altogether [7], some have provided brief qualitative expert judgements [8–12], and others have attempted more complete examinations of the topic (e.g. [13–17]). The initial paucity of research in this area is likely to have been a factor in the superficial treatment of this area in early reviews. However, there is now a considerable body of literature that considers a number of aspects of the potential impacts of climate change on aeroallergens. The purpose of this review is to synthesize

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this work and to outline a number of research challenges in this area.

Climate change is likely to have impacts on hayfever (allergic rhinitis) and asthma via its impacts on pollens and other aeroallergens. These other aeroallergens include mould spores, and the house dust mite (HDM) and cockroach allergens. Atmospheric variables that may have impacts on these allergens include CO_2 concentration, temperature, rainfall, humidity, and wind speed and direction. With allergic diseases already being a significant public health issue in many countries, such as the UK, Australia, and New Zealand, the potential for any adverse impact resulting from climate change is of serious concern.

Most work on the impacts of climate change on aeroallergens has been done on plants and pollens using a range of methods, and this work can be divided into a number of distinct areas, including impacts on pollen amount, pollen allergenicity, pollen season, plant and pollen distribution, and other plant attributes. Each of these is discussed in turn in the following sections, followed by an examination of what work there has been done on other aeroallergens and then research challenges in this area.

Impacts of climate change on aeroallergens

Pollen amount

A number of studies have found increases in pollen associated with increases in CO_2 concentration and/or temperature. Two experimental studies have examined the impacts of increasing CO_2 concentration alone (Table 1). Ziska and Caulfield [18, 19] found pollen production of common ragweed increased significantly both from pre-industrial to current and current to the future CO_2 concentration. Similarly, Wayne et al. [20] found a significant increase in ragweed pollen production under an approximate doubling of the atmospheric CO_2 concentration, although the increase was smaller than that found previously by Ziska and Caulfield [18, 19], who had examined a smaller increase in CO_2 concentration from current to future.

A few studies, in three distinct regions of the world, have examined trends in pollen amount over time, and related these to trends in temperature over the same periods. Spieksma et al. [26] examined atmospheric birch (*Betula*) pollen data from five European stations (Basel, Vienna, London, Leiden, and Stockholm) spanning the period 1961–1993 with records from 18 to 30 years. They found weakly rising trends of annual sums of daily concentrations at all five stations, with that at three of the stations being statistically significant at the 1% probability level. The authors did not attempt to explain the cause of these trends. More recent European studies, in Denmark [27] and Switzerland [28], also found trends to increasing amounts of pollen over the latter decades of the 1900s, that were related to climate change. Teranishi et al. [29] studied the association between Japanese cedar (*Cryptomeria japonica*) pollen and temperature from 1983–1998 at an urban location in Japan. They found a significant positive correlation between total pollen count in a year and temperature in July the previous year. Although the authors attributed changes in pollen over the study period to climate change over the same period, they failed to account for the potential for urban warming as a cause. In North America, Levetin [30] has found statistically significant increases in the cumulative seasonal total pollen (the summed average daily concentrations) of a number of taxa, including *Juniperus*, *Quercus*, *Carya*, and *Betula*, since 1987, although one taxon, *Ambrosia*, had significantly decreased. There is

Table 1. Summary of studies of impacts of elevated atmospheric CO_2 concentration on allergenic plants

Attributes studied	Plant studied	CO_2 concentration(s) (p.p.m.)	Results	Reference
Pollen amount	Common ragweed (*Ambrosia artemisiifolia* L.)	280 370 600	132% increase from 280 to 370 p.p.m., and 90% increase from 370 to 600 p.p.m.	[18, 19]
Pollen amount	Ragweed (*A. artemisiifolia* L.)	350 700	61% increase from 350 to 700 p.p.m.	[20]
(a) Shoot growth (b) Biomass	Perennial ryegrass (*L. perenne* L. cv. Parcour)	390 690	17% increase in (a) from 390 to 690 p.p.m.; −4% to 107% change in (b) from 390 to 690 p.p.m.	[21]
Root biomass	Perennial ryegrass	350 700	Increase from 350 to 700 p.p.m.	[22]
Foliar chemical composition	Paper birch (*Betula papyrifera*)	560 (target level during daylight hours of the growing season)	C : N ratios, starch concentrations, and condensed tannins increased in enriched CO_2	[23]
Above- and below-ground mass Carbon Nitrogen Hexose sugar Gas exchange properties	*P. lanceolata*	35 Pa partial pressure 71 Pa partial pressure	Water use efficiency increase, and total mass increased by 15% from 35 to 71 Pa partial pressure	[24]
(a) Seed weight (b) Germination percentage and rate (c) Seedling size for the progeny	*P. lanceolata*	350* 675	(a) decreased and (b) and (c) increased from 350 to 675 p.p.m.	[25]

*These two CO_2 concentrations were studied under two temperature conditions (26 °C day/20 °C night and 20 °C day/14 °C night) some evidence that such increases have been associated with increases in average winter temperatures.

The impact of climate change on pollen production of common ragweed (*Ambrosia artemisiifolia*) has also been assessed by Ziska et al. [31], who used an existing CO_2/temperature gradient between rural and urban areas. The higher CO_2 concentration and air temperature of the urban area resulted in ragweed that produced significantly greater pollen than that at the rural areas. The authors suggest that this study method (i.e. rural–urban comparison as an empirical analogue) might provide a low-cost alternative to current experimental methods (such as that used by Wayne et al. [20]).

Pollen allergenicity

A couple of studies have examined the relationship between environmental factors and the allergenicity of pollen. Ahlholm et al. [32] examined the quantity of the major birch pollen allergen, Bet v 1, produced by mountain birch (*Betula pubescens* ssp. *czerepanovii* [Orl.] Hämet-Ahti) grown at two temperatures. During the growing season the daily mean temperatures were on average 1.0–2.5 °C different, and the length of the growing seasons also differed. The year before the pollen samples were collected, the temperatures differed by 1.1 °C (June–August). Significantly stronger allergenicity was found in the pollen from trees grown at the higher temperatures. In an earlier study, Hjelmroos et al. [33] examined the heterogeneity of antigenic proteins and allergens within individual white birch (*B. pendula*) trees, and found these were greatest in pollen from the south side of the trees. They suggested this was probably partly because of higher temperature on the south sides of trees (in the Northern Hemisphere).

Pollen season

Changes in the start of the pollen season have also been studied. In an early examination of the potential impacts of climate change on pollen seasons of allergenic plants in the European region, Emberlin [34] suggested that many central areas north of the Alps would have longer grass pollen seasons. A number of studies have since identified a trend to earlier pollen seasons in pollen records. Emberlin et al. [35] examined records of the start of the birch (*Betula*) pollen season from the city centres in Cardiff, Derby, and London in the UK, and found a trend to earlier seasons that was related to an increase in cumulative temperatures over 5.5 °C in January, February, and March. In a recent extension of this work, Emberlin et al. [36] studied relationships between changes in the start dates of birch (*Betula*) pollen seasons and changes in spring temperatures at six sites across Europe over approximately the last two decades of the 1900s. Four of the sites showed trends towards earlier start dates, with an advance of about 6 days over the next 10 years if the trend continues. Another two European studies, in Denmark [27] and Switzerland [28], also found trends to earlier pollen seasons over the latter decades of the 1900s, that were related to climate change. Finally, two recently published studies have revealed an earlier start to the pollen season associated with a warming over the period 1981–2000 in Italy [37, 38]. Both studies also reported a prolonging of the pollen season for Urticaceae, a family of particular clinical significance in the region. Yet other similar reports have been presented at a meeting organized by the World Health Organization, European phenology network and International Centre for Integrative Studies [39]. The meeting concluded that 'an earlier start and peak of the pollen season is more pronounced in species that start flowering earlier in the year' and that 'duration of the season is extended in some summer and late flowering species'.

Some work on trends in pollen seasons has also been done outside Europe. In North America, there is some evidence of earlier start dates in the pollen season, especially for taxa such as *Juniperus*, *Ulmus*, and *Morus*. The earlier start time for *Juniperus* pollen was significantly related to increasing winter temperatures [30]. Teranishi et al. [29] also found the first day of the Japanese cedar (*C. japonica*) pollen season in Japan advanced over the period 1983–1998, from mid-March to late February, according to mean temperature in February. Finally, and most recently, Ziska et al. [31] found the higher CO_2 concentration and air temperature of the urban area resulted in ragweed (*A. artemisiifolia*) that flowered earlier than that at the rural areas.

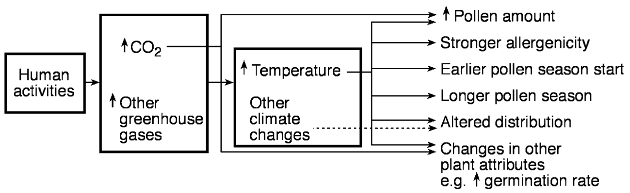

Fig. 1. Schematic summary of the impacts of climate change on allergenic plants and pollens. ↑ represents increase.

Plant and pollen distribution

The potential for changes in the distribution of allergen-producing species has been recognized since the early days of climate change and human health work [9]. Emberlin [34] suggested that the northern limit of *Betula* growth in the Northern Hemisphere would extend by several hundred kilometres, with a corresponding increase in the height of the altitudinal tree line, but there would also be some contraction of the distribution in the south. A similar extension of the northern limit of olive (*Olea europaea*) production could be expected [34]. In addition to a northward migration in the European region, *Parietaria* would likely become more prolific in disjunct locations, such as the UK [34]. Finally, it has been suggested that areas of perennial ragweeds are likely to extend, and northern colonies of annual ragweed, such as that in the UK, will probably become more persistent [34].

A recent field-based experimental study has attempted to provide a more qualitative and quantitative assessment of such changes. Buckland et al. [40] investigated the impacts of experimental manipulation of climate, soil fertility, and disturbance on the abundance of 36 plant species, including *Plantago lanceolata*, a common allergen producer. While the study found that all but one of the species either became extinct, declined (as in the case of *P. lanceolata*) or remained unchanged in abundance 3 years after terminating the experimental manipulation, it also found that disturbance was a significant factor, with *P. lanceolata* benefiting from disturbance.

There is some evidence that vegetational response to abrupt climate change, such as that expected over the coming decades, may be rapid [41]. Weber [42] has recently suggested that one of the implications of increased pollen production associated with increased CO_2 concentration, could be more efficient wind pollination, and ultimately, greater propagation of the plant species.

Pollen distribution is also influenced by atmospheric conditions, such as wind speed and direction, rainfall, humidity, etc. Emberlin [34] has suggested that an increase in the strength of the Atlantic westerlies over north-west Europe would enhance the long-range transport of pollen from northern and central Europe to Scandinavia.

Other plant attributes

There is also evidence of other allergenic plant attributes responding to increases in CO_2 concentration and/or temperature. A number of studies have simply examined the response to increases in CO_2 concentration (Table 1). Schenk et al. [21] found perennial ryegrass seedlings grown at elevated CO_2 concentration had increased shoot growth and generally increased biomass. In a similar study, Van Ginkel et al. [22] found increases in root biomass of perennial ryegrass grown at elevated CO_2 concentration. Lindroth et al. [23] found C : N ratios, starch concentrations, and condensed tannins of paper birch significantly increased in response to enriched CO_2. In the study by Klus et al. [24], of *P. lanceolata*, many of the physiological variables measured (above- and below-ground mass, carbon, nitrogen, hexose sugar, and gas exchange properties) were significantly effected by CO_2 concentration during growth and at the time of measurement. For example, water use efficiency and total mass increased at elevated CO_2.

In an early examination of the potential impacts of climate change on growing seasons of allergenic plants in the European region, Emberlin [34] suggested that growing seasons of trees such as birch (*Betula*) could start earlier, perhaps by as much as several weeks. Subsequently, Menzel [43] examined trends in phenological phases (such as leaf unfolding, needle flush, and flowering) in species such as *B. pubescens* and *Quercus robur* in Europe between 1959 and 1996. She found that spring events had advanced on average by 6.3 days, whereas autumn events had been delayed on average by 4.5 days, resulting in the annual average growing season lengthening by 10.8 days since the 1960s. She related these trends to increases in air temperature because of the 'anthropogenic greenhouse effect'.

Only a small number of studies have examined the combined effects of changes in CO_2 concentration and temperature. Wulff and Alexander [25] found elevated CO_2 concentration decreased seed weight, increased germination percentage and rate, and increased seedling size for the progeny of *P. lanceolata* (Table 1). Ziska et al. [31] found the higher CO_2 concentration and air temperature of the urban area resulted in ragweed (*A. artemisiifolia*) that grew faster and produced significantly greater above-ground biomass than that at the rural areas. Pollen was not examined in any of these studies except that by Ziska et al. [31].

Other aeroallergens

Fungi Although there are many studies that have demonstrated relationships between climate and weather, and moulds and the atmospheric concentration of their spores [44–46], few studies have examined the potential impacts of climate change on these important aeroallergens. Besides a number of reviews of climate change and human health that have simply noted the likelihood of impacts on mould spores, at least one recent review [15] and one recent study [47] have examined in more detail the potential impacts, although with a focus on fungal infections rather than allergic disease. Similarly, Harvell et al. [48] have recently reviewed disease risks (including fungal infections) of climate warming for terrestrial and marine biota, and cited numerous climate/fungi relationships of importance in particularly plant disease, but also wildlife diseases and marine diseases.

Perhaps the most significant work in this area, however, is that by Corden and Millington [49], who examined long-term trends of *Alternaria* spore concentrations in Derby, UK, from 1970 to 1998. Their study examined both the seasonal (June–October) concentrations and start dates. The seasonal *Alternaria* spore concentrations showed a distinct upward trend over this period, which started gradually from 1970 to 1991 and then increased markedly from 1992 onwards [49]. The start dates for *Alternaria* showed there was a trend for an earlier seasonal start (from late June around the beginning of the record, to early June around the end of the record). Associated with this was a trend for a longer *Alternaria* season. Corden and Millington [49] related the trend to an earlier seasonal start, to an increase in cumulative winter and early spring temperatures in Derby.

Other allergen sources Very little work has been conducted on the potential impacts of climate change on aeroallergens other than pollens and mould spores. It has been suggested that in temperate regions, higher temperatures associated with climate change might encourage cockroaches (*Blattidae*) to venture from the domestic environment and into sewers [11]. Of greater importance to allergic disease, higher temperatures would also facilitate passage of cockroaches between dwellings, making control of infestations more difficult [50].

Research challenges

The research done to date is of concern for at least two reasons. First, it suggests that the future aeroallergen characteristics of our environment may change considerably as a result of climate change, with the potential for more pollen (and mould spores), more allergenic pollen, an earlier start to the pollen (and mould spore) season, and changes in pollen distribution. Second, it demonstrates climate change has probably already had impacts on aeroallergens. However, further work is required. Study of the impacts of climate change on aeroallergens and related diseases presents many challenges. Some of these challenges, along with suggestions for further work, are outlined in this section.

There is a great need for research to examine aeroallergens other than pollens. The presence of a number of important aeroallergens indoors, where the climate will differ from that modelled for the outdoor environment, presents difficulties in projecting future levels of such aeroallergens. While it has been noted elsewhere that it is likely that climate change will have impacts on HDMs [51] and therefore levels of its allergen indoors, this is an area in great need of further investigation.

The complexity of allergic diseases and mechanisms is another challenge. For example, there is evidence of interaction between air pollutants and aeroallergens both in the atmosphere and within the human airways, leading to, for example, increased allergen release from pollen [52–57]. Such interactions may be of such importance that Patz and Kovats [58] have recently included them in the first of six 'hotspots' of climate change and health. Integrated assessments of the potential impacts of climate change on diseases such as asthma will need to examine multiple triggers (such as aeroallergens and air pollutants), their interactions, and their impacts on disease.

It has been stated recently that the climate change health impacts because of the changes in aeroallergens are currently not quantifiable [12]. There is a great need for research to relate projected changes to health outcomes.

Research on the impacts of increased CO_2 concentration and climate changes on other pollens is required. At present, impacts on pollen amount have only been studied in a few major allergenic plant species, including *Ambrosia*, *Betula*, *Cryptomeria*, *Juniperus*, *Quercus*, and *Carya*. Similar studies on other plant species will reveal the extent to which pollen amounts may change in the future. Similarly, there is a need for more work on the potential impacts of climate change on pollen allergenicity and plant and pollen distribution.

More studies examining the combined effects of CO_2 and temperature, as well as interactions between these and other important variables such as water availability, disturbance, nutrients, etc. are required. Competition (both inter- and intraspecific) may be one of these other important factors in determining how some plants respond to climate change. Schenk et al. [21] studied the effects of CO_2 enrichment and intraspecific competition on a range of plant attributes in perennial ryegrass by growing seedlings at five different plant densities and two CO_2 concentrations. Although some attributes changed in response to CO_2 enrichment regardless of plant density, for others there was interaction with plant density. For example, root biomass only increased significantly under enhanced CO_2 in pots with medium to high density. Partanen et al. [59] examined the combined effects of photoperiod and temperature on the timing of bud burst in Norway spruce (*Picea abies*), and found that photoperiod may prevent the premature onset of growth that has been projected by models that only consider temperature regulation.

A number of studies have identified within-species genetic variation [24, 25, 32] in response to changing carbon availability and temperature. As such, a better understanding of this among allergenic plant species is required.

Land-use changes will be a significant factor in determining future aeroallergen, particularly pollen, characteristics. For example, Emberlin [34] has suggested that decreases in grassland and cereals in Europe would lead to decreases in grass pollen, and that the projected increase in oil crops such as oil seed rape (*Brassica* species) may lead to a greater aeroallergen load.

For the purposes of attributing past and monitoring future impacts of climate change on pollen, there is a need for researchers to control for urban warming and/or examine pollen records from non-urban settings, in which the impacts of global climate change and CO_2 concentration increases can more easily be separated from the impacts of local changes in these factors associated with urbanization (such as the urban heat island).

Although further work is required in this area, with the evidence to date, it would seem prudent to consider alternative adaptive strategies. One adaptive strategy would be tighter management of a number of the allergenic plant species discussed in this article. For example, government authorities could consider more carefully which plant species are used in populated areas. The use of such strategies to fight ragweed expansion in Europe has been discussed by Rybníček and Jäger [60]. It is important that public health authorities and allergy practitioners be aware of these changes in the environment, and that research scientists embrace the challenges that face further work in this area.

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