Anthropogenic climate change and allergen exposure: The role of plant biology

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Accumulation of anthropogenic gases, particularly CO_2, is likely to have 2 fundamental effects on plant biology. The first is an indirect effect through Earth's increasing average surface temperatures, with subsequent effects on other aspects of climate, such as rainfall and extreme weather events. The second is a direct effect caused by CO_2-induced stimulation of photosynthesis and plant growth. Both effects are likely to alter a number of fundamental aspects of plant biology and human health, including aerobiology and allergic diseases, respectively. This review highlights the current and projected effect of increasing CO_2 and climate change in the context of plants and allergen exposure, emphasizing direct effects on plant physiologic parameters (eg, pollen production) and indirect effects (eg, fungal sporulation) related to diverse biotic and abiotic interactions. Overall, the review assumes that future global mitigation efforts will be limited and suggests a number of key research areas that will assist in adapting to the ongoing challenges to public health associated with increased allergen exposure. (J Allergy Clin Immunol 2012;129:27-32.)

Key words: *Climate change, aerobiology, pollen, allergen, allergic rhinitis, asthma, exposure*

That certain gaseous molecules (eg, CO_2, methane, and H_2O) absorb in the infrared portion of the electromagnetic spectrum and contribute to Earth's surface temperatures has been recognized for approximately 200 years.[1] That human activities, principally fossil fuel use and deforestation, continue to add significant amounts of these gases to the atmosphere, with concurrent effects on climate stability, is recognized by the scientific community at large.[2,3] Indeed, as population increases in conjunction with land and energy use, projected concentrations of CO_2 by 2100 are likely to increase to 2× to 4× greater than preindustrial levels of the 18th century.[2]

To date, the most comprehensive review and assessment of the science of climate change rests with the Intergovernmental Panel on Climate Change (IPCC).[3] Beginning in 1990, the IPCC has done a methodical and extensive analysis of current peer-reviewed studies, direct observations, historical records, and the paleoclimatologic evidence. On the basis of these evaluations, the IPCC has devised a systematic, weight-of-evidence approach regarding future climate projections that has resulted in an international scientific consensus as to the confidence of anthropogenic climate change. It is clear that climate change is unequivocal, largely anthropogenic, and, given the lack of effective global mitigation, very likely to continue throughout the 21st century. The goal of the current review is not to restate the IPCC findings but rather to provide a relevant context of those findings to plant biology and subsequent effects on allergen exposure and public health.

Abbreviations used
IPCC: Intergovernmental Panel on Climate Change
PM: Particulate matter

Within the rubric of anthropogenic climate change, there are 2 global factors that are of particular significance with respect to allergens and the aerobiology of plants. The first is related to differential spatial increases in global surface temperatures. Such increases are a function of the relative proportion of the different greenhouse gases.[3] For example, at the equator, where it is warm and humid, water vapor is the dominant greenhouse gas, and increasing CO_2 concentrations has a smaller relative effect than adding CO_2 to regions with less water vapor (eg, poles and deserts); a similar case can be made temporally because winters in northern latitudes are colder (and hence drier) and would be expected to warm faster than summers.[3,4] This differential increase in surface temperatures, a likely driver of extreme weather events, will certainly have global significance to plant lifecycles. A second factor is that almost all aspects of plant biology are likely to be directly affected by increasing CO_2 concentrations because CO_2 is the sole supplier of carbon for photosynthesis and growth. How both factors affect the production, distribution, dispersion, and allergenic potential of pollen and plant species is the focus of the current review.

INCREASING CO_2 CONCENTRATIONS AND TEMPERATURE: POLLEN PRODUCTION, SEASON, AND DISTRIBUTION

Recent estimates suggest that approximately 34 million Americans have been given a diagnosis of asthma.[5] Results from the International Study of Asthma and Allergies in Childhood indicate that the global (and North American) burden of asthma is continuing to increase.[6] A range of possible mechanisms for the increased prevalence of allergic disease have been postulated.

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At present, the role of changes in plant aeroallergen exposure times and concentrations associated with increasing CO_2 concentrations, climate change, or both as a potential contributor to the observed increase in asthma is still being elucidated.[7,8] However, it is recognized that there are 3 distinct plant-based contributions to allergenic pollen likely to be affected by anthropogenic change: trees in the spring, grasses and weeds in the summer, and ragweed (*Ambrosia* species) in the fall (autumn).

Trees

A number of peer-reviewed studies indicate a clear association between anthropogenic climate change and significant advances in spring flowering times with subsequent shifts in plant phenology and anthesis.[9,10] Long-term records have indicated earlier initiation of flowering for oak (*Quercus* species)[11] and birch (*Betula* species)[12] consistent with earlier and warmer spring temperatures. In addition, European pollen data have shown increases in hazel and birch counts in Switzerland and Denmark.[13-16] Studies have also projected an advance of pollen initiation of 1 to 3 weeks for olive *(Olea europaea)*[17] and up to 4 weeks for *Quercus* species (and up to 50% more pollen) with projected warming.[11] Research on loblolly pine *(Pinus taeda)* at the Duke University Free-Air CO_2 Enrichment site showed that increased CO_2 concentrations *per se* could also induce earlier and greater seasonal pollen production.[18]

However, the interactive role of warming temperatures and increasing CO_2 concentrations on pollen production in tree species is complex. Often, tree species, unlike other aeroallergen plants (eg, weeds), require temporal exposures to minimum winter temperatures to break dormancy (ie, vernalization), followed by warmer spring temperatures to speed anthesis. Consequently, projecting pollen release from some tree species, such as birch, is complicated by differential responses among *Betula* species to low winter temperatures,[19] as well as the difficulty of distinguishing pollen among different species of birch. Overall, although trees do release aeroallergens in the spring, warmer winters might result in earlier flowering or flowering delays or even decreased floral numbers, depending on the tree species' specific needs for vernalization. Hence there can be both earlier and later allergen exposures from trees, depending on species and location. Overall, changes in pollen season length, allergenicity, and amounts have not been well quantified, particularly for hardwood trees with respect to increasing CO_2 concentrations or CO_2 concentrations and temperature.

Changes in tree spatial distribution have been both observed and are projected to continue. There are now observations of northward shifts in plant hardiness zones in the United States.[20] Therefore, as minimal winter temperatures increase, allergenic species are also likely to migrate poleward, with subsequent effects on their distribution (eg, *Betula* species).[21,22] Levetin and Van de Water[23] have also recently discussed the expansion of *Juniperus* species in the United States over the past several decades, including potential links with both climate change and increasing CO_2 concentrations.

Weeds and grasses

A number of weed and grass species are known allergenic pollen producers during the summer. In general, an earlier start of the pollen season associated with warmer temperatures has been shown for mugwort (*Artemisia* species),[24] nettle,[25] and some grasses.[26,27] Similarly, the total airborne pollen load has progressively increased for some important weed species, such as *Parietaria* species, over recent decades in association with increasing temperatures.[28] As with trees, however, quantification of combined temperature and CO_2 concentration effects on pollen seasonality, allergenicity, and pollen load has not been determined.

There is now considerable evidence that weed distribution might also be affected by anthropogenic climate change.[29-31] At present, it is unclear whether such expansion will shift the species distribution northward *in toto* or increase the entire range, and further study is needed to determine the potential consequences of altered distribution in regard to aerobiology. However, we would emphasize that, in general, many of the anticipated anthropogenic climatic changes, such as increasing CO_2 concentrations or greater occurrence of abiotic extremes, are associated with environmental conditions that are likely to favor physiologic characteristics associated with weed biology and fecundity.[31] Weeds are, in fact, inherently adapted to disturbance and transition and benefit irrespective of whether such a disturbance is anthropogenic or natural in origin.

Ragweed

Among allergenic species, perhaps the most studied has been ragweed (*Ambrosia* species), the principle fall allergen (Table I).[32-40] This might reflect the pernicious and ubiquitous nature of ragweed pollen. For example, results from the US National Health and Nutrition Examination Survey show that 26.2% of the US population has a positive skin test response to ragweed.[41] The current National Health and Nutrition Examination Survey 2005-2006 survey shows that among those who reported any allergy-related symptoms in the past 12 months, ragweed allergen–specific IgE sensitization rates ranged from 23.0% to 32.8%.[42] The American Academy of Allergy, Asthma & Immunology estimates that about 36 million persons in the United States have seasonal ragweed allergies.[43]

In a prairie experiment, simulation of warming *per se* (1°C-2°C) significantly increased western ragweed pollen production and pollen diameter.[32] Projected increases in atmospheric CO_2 concentrations also stimulated the growth and pollen production of common ragweed by 60% to 90% in indoor studies.[33,34] Manipulation of both temperature and CO_2 concentration in a glasshouse study to simulate the effects of climate change resulted in earlier flowering, greater floral numbers, and greater pollen production in common ragweed.[35]

Because the relevance of experimental results produced in indoor studies to larger regional areas is uncertain, attempts have been made to determine the response of common ragweed to increasing CO_2 concentrations and temperatures at greater spatial and temporal scales. Microclimatic affects of urbanization, most notably a CO_2 concentration and temperature increase, were used as an analog for near-term climate change projections to quantify the growth and pollen production of common ragweed over an urban-rural gradient in Baltimore, Maryland.[36] These data indicated that ragweed plants grew faster, flowered earlier, and produced significantly greater aboveground biomass and pollen at urban relative to rural locations.[37] Microclimatic effects of urbanization have also been linked to longer pollen season and earlier floral initiation for Polish cities.[44]

TABLE I. Projected changes in the biology of ragweed and the consequences for aeroallergen production, distribution, and exposure from spatial and temporal studies

Methodology	Variables examined	Outcome	Implications	References
Glasshouses, growth chambers, single plants	Projected future CO_2 concentrations, earlier springs	Bigger plants, more flowering, pollen production increases, more allergenic pollen	Pollen production and allergenicity might increase with climate change scenarios	33-35
Prairie grassland, plant mixture	1°C-2°C increase, clipping to simulate herbivory	Significant increases in pollen production and diameter with warming	Warming and herbivory might stimulate pollen size and production	32
Disturbed soil in urban-rural transect, plant succession	Urban microclimate of warmer temperatures, more CO_2, longer growing season	Larger plants, earlier flowering, reduced allergenicity	Microclimate changes similar to near-term IPCC projections might already be stimulating pollen production and increased exposure in urban areas	36-39
National Allergy Bureau and Aerobiology Canada, pollen counts	Start and end of pollen season since 1990s from Texas to Canada	Duration of pollen season increasing as a function of latitude in North America	Warming might have already altered pollen exposure in North America	40

However, microclimatic differences associated with urbanization might only provide part of the story. For example, in the Baltimore study long-term persistence of ragweed and annual weed populations at the urban site did not occur, in part because of climate-induced shifts to woody perennial species that occurred if the soil remained undisturbed.[38] These data suggested that soil disturbance, in addition to any CO_2/climate shift, played an essential role in maintaining ragweed populations in urban and suburban environments.[39]

Recently, pollen data from the National Allergy Bureau in the United States and the Aerobiology Research Laboratories in Canada were analyzed to determine whether recent warming had resulted in a change in the duration of the ragweed pollen season in North America.[40] These data demonstrated that the duration of the ragweed pollen season has been increasing but only as a function of increasing latitude, which is consistent with differential global warming projected by the IPCC (Fig 1).[40] If such warming trends continue, ragweed is likely to migrate poleward with a subsequent increase in its distribution. Additionally, introduction of ragweed (presumably by trade) has resulted in its spread as an invasive pest in parts of Europe, Asia, and Australia,[45,46] suggesting that the empiric affects of CO_2 concentrations and climate change on ragweed aeroallergens described here for North America could be global in scope.

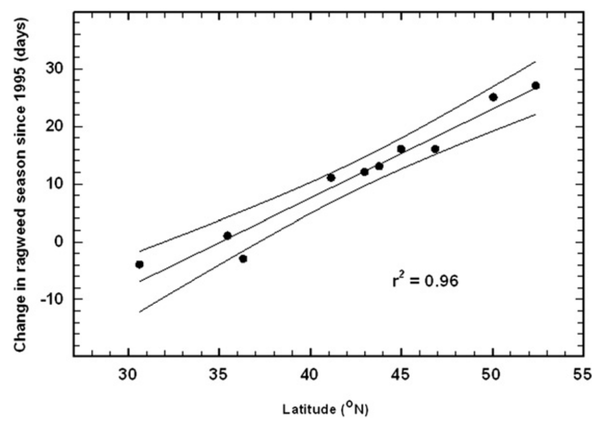

FIG 1. Change in length (in days) of the ragweed pollen season since 1995 as a function of latitude for National Allergy Bureau and Aerobiology Research Laboratories sites in the central United States and Canada, respectively. The *line* represents least-squares first-order regression plus confidence interval. Data are from Ziska et al.[40]

PLANTS, FUNGI, AND AEROALLERGENS

Although the function of climate in the induction and spread of molds is well recognized,[47] it is important to also emphasize the role of plants in fungal biology. Of particular interest in this regard is *Alternaria alternata*, a well-known plant pathogen with more than 350 plant hosts that is also recognized as a significant aeroallergen associated with a number of respiratory problems, such as rhinitis, asthma, allergic sinusitis, and allergic dermatitis. Because changing CO_2 concentrations and temperature will alter host biology, how will this, in turn, alter sporulation of *A alternata*?

Indirectly, climate change could alter the timing of agricultural harvests with subsequent effects on *Alternaria* species exposure times.[48] For example, differences between 2 towns in the United Kingdom, Derby and Cardiff, in *Alternaria* species spore counts were associated with increased cereal production and changes in climate since the 1970s.[48,49] For quaking aspen *(Populus tremuloides)*, a significant increase in fungal propagules (including a doubling of *A alternata*) was observed in leaf litter under twice-ambient CO_2 concentrations.[50] Wolf et al[51] suggested a mechanistic basis for the observed CO_2/sporulation link by showing that recent and projected increases in CO_2 concentrations could increase the carbon to nitrogen ratio in leaves of timothy grass *(Phleum pratense)*, with subsequent increases in the onset of sporulation of *A alternata*.

PLANT ALLERGENICITY

Increasing temperatures and CO_2 concentrations will almost certainly alter the production, distribution, and dispersion of plant-based allergens from trees, grasses, and weeds; however, the role of these climatic factors in altering the allergenicity of plant allergens remains largely unexplored. Yet allergenicity, in addition to temporal and spatial allergen exposure, is widely recognized as a major determinant of the health effects for sensitized patients.[52]

Quantification of ragweed pollen to increasing atmospheric CO_2 concentrations in indoor studies[33] provided ample pollen to begin qualitative assays. These assays indicated a CO_2-induced increase in the concentration of at least 1 major allergen (Amb a 1) in addition to any stimulation in pollen production.[53] However, the urban-rural transect studies[37] suggested that rural climates (with lower temperatures and CO_2 concentrations compared with urban climates) had greater pollen allergenicity. These contrasting results might be related to the quantity of pollen captured (ie, isolated grains on rotorods for the transect vs bagging of whole catkins in the indoor study), but additional clarification of the ubiquity of the CO_2 response for increased allergenicity is needed for ragweed. For mountain birch (*Betula pubescens* subspecies *czerepanovii*), higher daily mean temperature was associated with an increase in the major birch pollen allergen Bet v 1.[54] This is supported by more recent research on the temperature-dependent expression of the Bet v 1a gene encoding the major birch pollen allergen.[55] However, other studies with birch show greater intraspecific and regional variation in Bet v 1, making any climate-induced allergenic change difficult to detect.[56]

In addition to pollen, there are other plant-based allergens of importance. Contact dermatitis in response to surface allergens might also be affected by increasing CO_2 concentrations. Mohan et al,[57] for example, demonstrated changes in the ratio of unsaturated to saturated urushiol (the surface antigen) as a result of increased CO_2 concentrations over a 6-year period. However, additional details as to other aspects of plant biology likely to be influenced by changing CO_2 concentration/climate are lacking. Similarly, almost nothing is known regarding CO_2 concentration changes, temperature changes, or both in the allergenicity of food allergens, such as peanut.[58] Overall, the role of increasing CO_2 concentrations, temperature, or both on altering plant-based allergens deserves additional study with respect to aerobiology and contact dermatitis.

CHANGES IN CLIMATE EXTREMES

Because the frequency of extreme weather events is likely to increase with climate change,[3] potential modifications in the timing and magnitude of aeroallergen distributions can also occur. For example, extreme weather can increase pollen dissemination of allergens through winds, humidity, flooding, or warmer temperatures. "Thunderstorm asthma," which is potentially associated with the dispersion of more respirable allergenic particles caused by osmotic rupture of the exine, is an additional cause for concern with greater climate extremes.[59-61]

INTERACTIONS WITH AIR POLLUTANTS

A consideration of air pollutants is also vital because of the many and varied interactions between air pollutants and aeroallergens[62] and because climate change will influence some air pollutants. For example, climate change will increase summertime surface ozone levels in polluted regions, with the largest effects in urban areas during pollution episodes; in addition, climate change–enhanced wildfires could become an increasingly important particulate matter (PM) source.[63,64]

Although a number of plant species have shown a negative growth response to tropospheric ozone, common ragweed is not among them.[65] However, some plants might respond to pollutant stressors by altering protein synthesis of specific allergens. For example, *Cupressus arizonica* pollen shows a higher Cup a 3 content in polluted relative to less polluted cities, with a subsequent increase in the allergenicity of cypress pollen in urban areas.[66] Similarly, timothy grass *(P pratense)* releases more allergens when exposed to supra-ambient concentrations of nitrogen dioxide and ozone.[67]

Components of air pollution, including PM, can also act as platforms for transfer of plant-based allergens into respiratory airways.[68-70] Consequently, combustion PM, such as diesel exhaust particles, might allow greater exposure to aeroallergens.[71,72] Lastly, it is worth noting that air pollution might exacerbate the symptoms of subjects with allergic rhinitis, sinusitis, or both, inducing mucosal damage and impaired mucociliary clearance that can facilitate access of inhaled allergens to cells of the immune system.[70]

UNKNOWNS AND CHALLENGES

Human-induced increases in atmospheric CO_2 concentrations and subsequent effects on temperature and climate are "highly likely" to occur, as determined by the IPCC.[3] In turn, these changes are expected to have a wide range of current and projected affects on human systems; indeed, the *Lancet* acknowledged that climate change represents the greatest threat to human health in the 21st century.[73] Certainly there are a myriad of acknowledged and potential effects, but the goal of the current review on CO_2/climate is to focus on allergenic pollens and spores from plants and fungi.

In this regard, to date, the data indicate that plant-based aeroallergens are likely to be significantly altered by increasing CO_2 concentrations, climate change, or both, with earlier pollen initiation, greater pollen loads, greater allergenicity and longer exposure times, and subsequent effects on aeroallergen exposure.[74] It is also clear that warmer temperatures might promote production of ground-level ozone and that interaction between this and allergen increases might further heighten the clinical expression of allergic disease.

At present, there is much that remains unknown. Although elucidation of the role of climate, CO_2 concentrations, or both on the biology of trees, grasses, ragweed, and fungi and associated aeroallergens is ongoing, critical epidemiologic studies needed to characterize and link these observations to human health are incomplete. Such studies are crucial to determine social and economic vulnerabilities among the general population. Quantitative comparisons between health care workers and plant biologists as to what constitutes pollen season and subsequent cooperation to establish a common set of plant biological indices in regard to climate would be very useful in this regard.

In addition, integration of these studies with meteorological factors and pollutant emissions could provide much needed clinical and epidemiologic information on the seasonality and incidence of allergic disease and the role of climate, CO_2 concentrations, or both. Even with the ongoing research on plants and aerobiology, there are numerous knowledge gaps related to the production and dissemination of plant- and fungus-based allergens and specific allergenic proteins, as well as potential interactions with land-use changes, urbanization, ozone, PM, and extreme weather (eg, drought and flooding) that would benefit from input and suggestions from the allergist community.[75]

Overall, there are a number of future research priorities in the context of climate change and aeroallergen exposure that can be emphasized. These include the development of global long-term (multidecadal) pollen/spore datasets, with consistent spatial and temporal methodologies for quantification and qualification of these aeroallergens at the continental and regional level; emergency department surveillance information that can elucidate the epidemiology of weather and climate in the context of aeroallergen contact; greater incorporation of changes in pollen and spore exposure into national and international assessments of climate change impacts; initiation of urban strategies that can manage known allergenic plants, minimize aeroallergen exposure, or both; development of technologies that can address climate change and air pollution; and new medical strategies for the prevention of asthma, allergic disease, or both. These are among those research priorities that can be considered in the context of climate change adaptation, responses that moderate the harmful effects of climate change.[76]

CONCLUSIONS

It is clear that anthropogenic climate change and increasing atmospheric CO_2 concentrations have the potential to transform almost all spatial and temporal aspects of plant-based aeroallergens (production, allergenicity, and distribution), with subsequent effects on aeroallergen exposure and the severity and prevalence of allergic diseases. Furthermore, there is some evidence that additional aspects of climate disruption, particularly thunderstorms, might exacerbate outbreaks of allergic illness. Yet it is also clear that there are knowledge gaps regarding the exacerbation of asthma by aeroallergens and that epidemiologic studies that link pollen and spore biology to clinical thresholds, population vulnerability, and sensitivity are sorely lacking. It is hoped that the overview presented here will serve as a means to further a scientific discussion of climate change and aeroallergen science and to derive appropriate scientific and policy solutions that can be effective on a global basis.

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