

Review



Inverse Trend Between Tree Pollen and Fungal Concentrations With Allergic Sensitization Rates in Seoul for 25 Years

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ABSTRACT

A growing number of individuals are developing allergic diseases due to pollen exposure. Seasonal variations and increased pollen concentrations have occurred with the increased rates of allergic sensitization among both children and adults. Temperature significantly influences pollination, particularly in spring- and early summer-flowering plants, with weather conditions affecting pollen allergen levels. Human activities, including agriculture and deforestation, increase carbon emissions, leading to higher atmospheric CO₂ levels that may enhance allergenic plant productivity. Climate change affects the range of allergenic plant species and length of pollen season. Studies indicate that higher CO₂ and temperature levels are linked to increased pollen concentrations and allergenicity, whereas atmospheric fungal concentrations have declined annually over the past 25 years. Despite more intense precipitation in summer and autumn, the number of rainy days has decreased across all seasons. This concentration of rainfall over shorter periods likely prolongs the dry season and shortens the period of fungal sporulation. Future climate changes, including atmospheric dryness, drought, and desertification could further decrease allergenic fungal sporulation. It remains unclear whether the inverse relationship between pollen and fungal concentrations and distributions directly results from climate change. It is crucial to evaluate the patterns of aeroallergens and their associated health risks.

Keywords: Climate change; pollen; seasons; fungi; allergens; carbon dioxide; temperature; air pollutants

INTRODUCTION

Numerous studies indicate that climate change poses a threat to health by affecting food supplies, and water and air quality. Climate, which changes constantly over time, depends on incoming solar radiation, outgoing thermal radiation, and the composition of Earth's atmosphere. Additionally, changes in the amount, intensity, and frequency of precipitation are occurring, along with more frequent extreme events such as heat waves, droughts, and hurricanes. As stated in the recent Working Group I Report of the Intergovernmental Panel on Climate Change, human-induced warming reached approximately 1°C (likely between 0.8°C and 1.2°C) above pre-industrial levels in 2017, with an increase of 0.2°C (likely between 0.1°C and 0.3°C) per decade (high confidence).¹ Significant changes in weather and climate have substantial impacts on the biosphere and human environments.

Climate fluctuations are linked to many prevalent human diseases, including cardiovascular mortality, respiratory illnesses, altered transmission of infectious diseases, and malnutrition due to crop failures.² Therefore, climate change represents a global health threat, affecting many disease factors in the twenty-first century. One of significant impacts of climate change on human health may be its effects on pollen and fungi. The ongoing process of climate change continuously affects allergies, arousing interest among both the public and the scientific community. Current knowledge is derived from experimental and epidemiological studies on the relationship between allergic respiratory diseases and environmental factors, such as meteorological variables, airborne allergens, and air pollution. However, further evaluation is needed in research on respiratory allergies triggered by climate change.^{3,4}

POLLEN AND FUNGI AS AEROALLERGEN

To qualify as a clinically significant aeroallergen, a particle must be buoyant, abundant, and possess allergenic properties, like those found in pollen. In general, insect-pollinated plants produce negligible amounts of airborne pollen, whereas wind-pollinated plants release large quantities of pollen capable of traveling miles. The size of pollen acting as an aeroallergen range from 20 to 60 μm , similar to most particulate matter. Its allergenic constituents are proteins, with molecular weights ranging from 10,000 to 40,000 Da.^{5,6}

The nasal mucosa and tracheobronchial passages have protective mechanisms to remove larger particles, allowing only those with 5 μm or smaller to reach the alveoli of the lungs. The development of asthma following pollen exposure is enigmatic because pollen grains are primarily deposited in the upper airways due to their large size. Asthma may be triggered by inhaling pollen debris small enough to access the bronchial tree. Understanding these dynamics is necessary for elucidating the pathogenesis of allergic rhinitis and asthma.^{7,8}

Fungi can be unicellular, syncytial with multiple nuclei not divided into separate cells or multicellular with nuclei separated by septa. Fungi reproduce through spore production, many of which are adapted for airborne dispersal. Spores may be produced by either meiosis or mitosis. Those produced by meiosis are associated with sexual reproduction (the teleomorphic stage) and are formed in various structures characteristic of each fungal phylum.^{9,10} Among allergenic fungi, most spores produced by mitosis are formed on differentiated hyphae or conidia. These spores are associated with the asexual (anamorphic) stage of the life cycle.⁹ Fungal spores, which are ubiquitous and highly allergenic, may outnumber pollen grains in the air. They secrete enzymes into their surroundings and absorb the resulting breakdown products, some of which are well-known allergens.¹¹ Upon inhalation, atmospheric fungal propagules may trigger IgE-mediated allergic responses in atopic individuals, leading to symptoms of allergic respiratory diseases, such as allergic rhinitis, allergic conjunctivitis and allergic asthma.¹²

POLLEN, FUNGI AND CO₂

The impact of climate change on the increase in allergic diseases will depend on the implementation of greenhouse gas mitigation strategies. CO₂, primarily emitted from burning fossil fuels, is the predominant greenhouse gas. Other greenhouse gasses include methane (CH₄), nitrous oxide and fluorinated gases.^{13,14} Human activities have increased the

natural concentration of CO₂ in our atmosphere, intensifying Earth's natural greenhouse effect.¹⁵ For instance, CO₂ levels were 280 parts per million (ppm) in 1870, prior to the industrial revolution, and had risen to 409.92 ppm on January 1, 2019, according to a new analysis of air samples collected by National Oceanic and Atmospheric Administration's Global Monitoring Division.¹⁶ Increasing CO₂ and air temperatures in temperate regions, where plant growing period is limited by temperature, can increase carbon uptake and prolong plant growing periods. In general, plants are expected to grow more rapidly during the period of global warming. An extended plant activity season not only increases biospheric CO₂ uptake, thereby decreasing the current rise of atmospheric CO₂ concentration and its impact on the greenhouse effect but also enhances the total annual emission of biogenic volatile organic compounds.^{16,17} These increased emissions may also contribute to the complex processes associated with global warming. Altered climate will affect the range of allergenic plant species and the length of the pollen season, while elevated atmospheric CO₂ levels may increase plant productivity and pollen production, affecting plant ecology.^{18,19}

Increased CO₂ concentration can elevate the allergen protein content in pollen grains, enhancing their allergenicity despite unchanged pollen counts. Experiments assessing tree pollen production under varying CO₂ concentrations are limited by canopy size and exposure time. Kim *et al.*²⁰ used open-top CO₂ chambers to maintain CO₂ concentrations at ambient levels (400 ppm), as well as 1.4 times ambient (560 ppm) and 1.8 times ambient (720 ppm) levels. Within these chambers, the production of pollen grains and the allergen Que a 1 in oak trees were quantitatively assessed (**Fig. 1**). Total pollen counts per tree at 560 ppm and 720 ppm increased significantly to 353% and 1,299%, respectively, compared to the ambient level. The allergenic protein content showed a significant increase by 12% and 11%, respectively. In a glass chamber study examining ragweed pollen, significant variations were observed in the concentrations of major allergen Amb a 1 across different chambers; concentrations were 1.88 ng Amb a 1/μg pollen at 400 ppm, 4.44 ng/μg pollen at 600 ppm (2.36 times vs. 400 ppm, $P < 0.032$), and 5.36 ng/μg pollen at 1,000 ppm (2.85 times vs. 400 ppm, $P < 0.025$) (**Fig. 2**).²¹

Mycorrhizal fungi form vast underground networks in soil across all continents, from forests to grasslands and croplands. These fungi, both during their lifecycle and after death, become a part of soil organic matter and play an essential role in the soil's capacity to retain carbon—roughly 75



Fig. 1. (A) Open top chambers at the National Institute of Forest Science in Suwon, Korea. (B) Internal view showing a CO₂ injection nozzle and plants. Permitted from Kim KR, Oh JW, Woo SY, Seo YA, Choi YJ, Kim HS, et al. *Int J Biometeorol* 2018;62:1587-94.²⁰

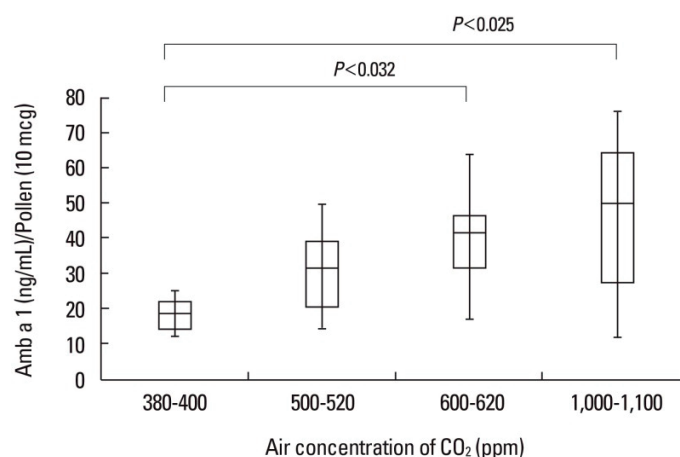


Fig. 2. Comparison of major ragweed allergen (Amb a 1) concentration in CO₂ chamber (n = 20). Concentrations were 1.88 ng Amb a 1/μg pollen at 400 ppm, 4.44 ng/μg pollen at 600–620 ppm (2.36-fold increase vs. 400 ppm, $P < 0.032$), and 5.36 ng/μg pollen at 1,000–1,100 ppm (2.85-fold increase vs. 400 ppm, $P < 0.025$). Permitted from Choi YJ, Oh HR, Oh JW, Kim KR, Kim MJ, Kim BJ, et al. Allergy Asthma Immunol Res 2018;10:278–82.²¹

percent of Earth's terrestrial carbon is stored in soil.²² Experiments have also shown that elevated levels of CO₂ increase fungal spore production. With regards to climate variables, both CO₂ and maximum temperature showed statistically significant increasing trends.^{23,24} In the San Francisco Bay area, analyses indicate a decreasing trend in the annual average concentrations of grass pollens, some frequently occurring molds and tree pollens. The average number of active weeks for trees and several molds showed a strong increasing trend over the years.²⁵

Certain rust fungi (*Uredinales* or *Pucciniales*) are negatively affected by higher temperatures and increased atmospheric CO₂ concentrations. These fungi and plants engage in a symbiotic relationship that dates back over 400 million years. The fungi colonize plant roots and extend far beyond their hosts to provide nutrients that are critical to plants' growth. Plants return the favor with sugars made from CO₂ absorbed from the atmosphere during photosynthesis.²⁶

POLLEN, FUNGI AND WEATHER

Weather changes have multiple interrelated potential consequences for plant phenology, significantly impacting pollen and fungi, which are crucial for human health. Consequently, weather change can influence the occurrence of pollen and fungal allergies. Weather conditions, including rainfall, atmospheric temperature, humidity, wind speed and direction, may alter the concentrations of pollens, fungi, and other allergens, thereby affecting the occurrence of allergic diseases.

Numerous studies on the effect of climate change on the distribution of allergenic pollen and fungi have focused typically on the analysis of observed concentrations and their regression relationships with meteorological factors. The onset, duration, and intensity of the pollen season vary annually. Weather variables and greenhouse gases are the main factors affecting phenology and pollen production.^{27–31} Both climate and weather play a key role in the production, release, and bioavailability of allergens derived from pollen and fungi.^{32,33} In addition, weather patterns influence the production, movement and dispersion of pollen and fungi through air temperature, winds, rainfall, and precipitation depending on atmospheric stability.^{34,35}

Plant species require a certain amount of heat to complete their development; thus, air temperature plays a key role, together with other factors, such as day length, water and nutrient availability, and soil type. Increasing global evidence demonstrates that the timing of life cycle events in many species has responded to rising Earth temperature. Plants discriminate between day and night by means of photoreceptors, pigments that capture different wavelengths and can either promote or inhibit flowering. These pigments synchronize biological activities to the day-night cycle.³⁶

Weather directly determines the onset and cessation of pollination, thereby defining the duration of the pollen season. Plants may respond to day lengths exceeding a critical threshold during late spring or early summer, ensuring adequate time for seed maturation. Increasing light intensity during springtime and early summer is likely to influence flowering in summer-blooming plants and modify the effects of the photoperiod.³⁷ A recent large-scale study also demonstrates a clear positive correlation between global warming and increases in both the seasonal duration and amount of pollen for various allergenic plant species across the northern hemisphere. The atmospheric pollen concentrations collated and analyzed here reflect spatial and temporal changes in allergenic plant species, indicating that recent climatic changes, particularly temperature fluctuations, are already affecting pollen quantities as well as the duration and timing of seasons in the northern hemisphere.³⁸ Thus, climate change could lead to higher concentration of allergenic pollens and extend the pollen season (**Fig. 3, Table**).^{38,39} In turn, allergic symptoms may vary depending on the level and duration of pollen exposure. Weather conditions may influence the occurrence of allergic diseases such as asthma

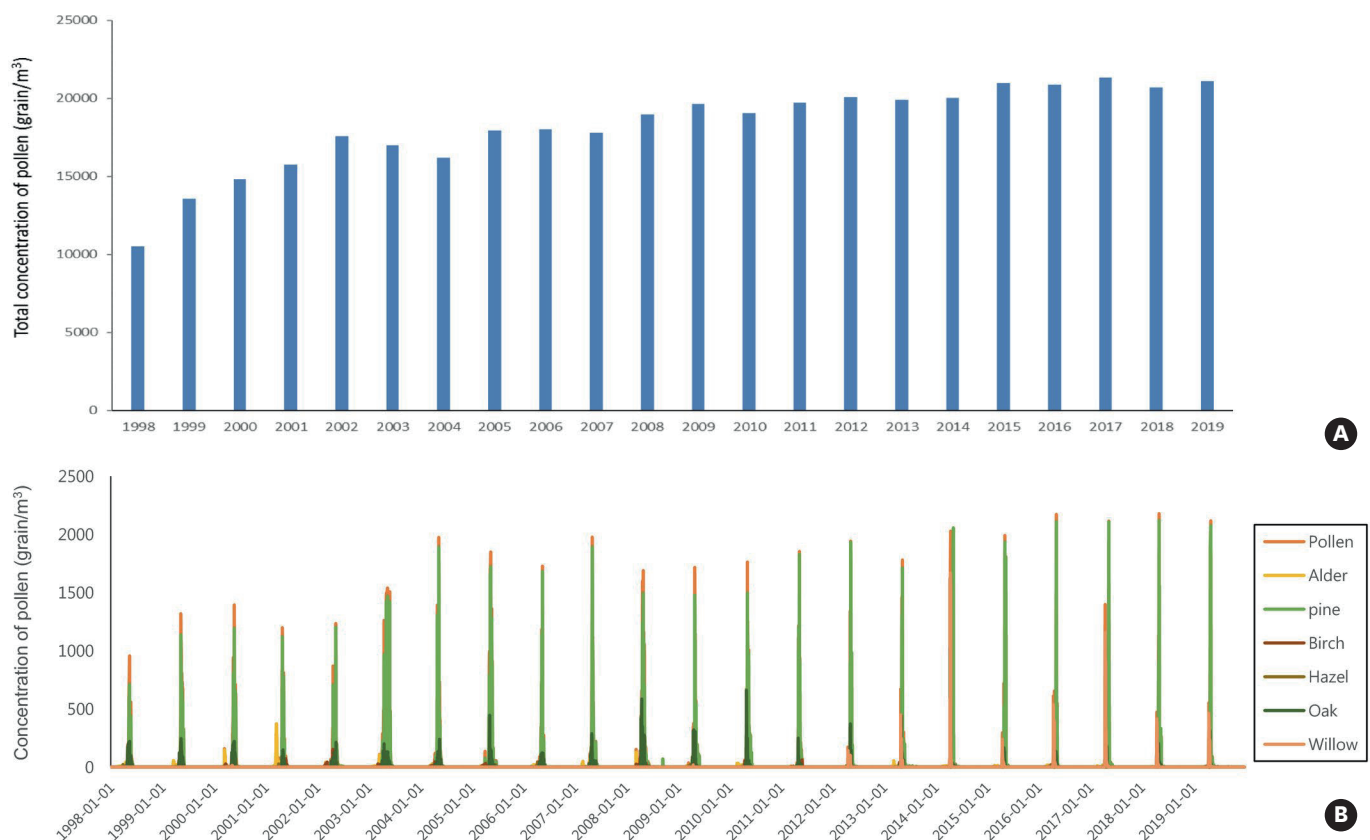


Fig. 3. Trend in the total (A) and the peak (B) pollen concentrations in the Seoul metropolitan area over the 22-year study period. Both total and peak concentrations increased gradually over time. Permitted from Lee KS, Kim K, Choi YJ, Yang S, Kim CR, Moon JH, et al. *Pediatr Allergy Immunol* 2021;32:872-9.³⁹

Table. Temporal changes in the start and end dates and duration of the pollen season across 17 locations in the northern hemisphere

Locations	Start time		End time		Season length	
	Days per year	P value	Days per year	P value	Days per year	P value
Amiens, France	-0.61	0.007	0.19	0.330	0.86	0.004
Brussels, Belgium	-0.62	0.003	0.16	0.229	0.78	0.003
Busan, Korea	-1.17	0.0004	-0.05	0.890	1.13	0.010
Fairbanks, USA	-0.68	0.129	1.68	0.005	0.92	0.124
Geneva, Switzerland	-0.45	0.204	0.74	0.010	1.64	0.014
Kevo, Finland	-0.62	0.014	0.19	0.211	0.81	0.013
Krakow, Poland	-0.47	0.542	1.04	0.009	1.50	0.065
Legnano, Italy	-0.30	0.531	-0.65	0.403	-0.36	0.710
Minneapolis, USA	-0.58	0.116	1.30	0.003	1.85	0.001
Moscow, Russia	-0.47	0.224	0.53	0.067	1.04	0.036
Papillion, USA	0.13	0.560	0.75	0.047	0.61	0.084
Reykjavik, Iceland	-1.51	0.010	0.01	0.942	1.22	< 0.0001
Saskatoon, Canada	-0.23	0.487	0.51	0.025	0.73	0.077
Seoul, Korea	-0.85	0.007	-0.12	0.844	0.74	0.224
Thessaloniki, Greece	-0.41	0.135	0.52	0.081	0.93	0.018
Turku, Finland	-0.67	0.0009	0.17	0.044	0.84	0.011
Winnipeg, Canada	-0.90	0.010	0.35	0.114	1.24	0.010

A negative value indicates an earlier start or end time, a positive value a later start or end time. Permitted from Ziska LH, Makra L, Harry SK, Bruffaerts N, Hendrickx M, Coates F, et al. *Lancet Planet Health* 2019;3:e124-31.³⁸

and allergic rhinitis.⁴⁰ These observed changes carry both immediate and future health implications, particularly for allergic diseases. Future climate projections also suggest an extended pollen season and an expected rise in sensitization rates to allergenic plants.^{39,41-44}

Atmospheric fungal spore concentrations are influenced by a wide array of environmental and meteorological factors, as well as various interspecies interactions. Seasonal variations underlie the number of allergic fungal spores, with climatic factors influencing the spectrum of fungal species and their quantities in the atmosphere.^{45,46} Atmospheric fungi are known to cause allergic reactions in late summer and early fall.^{47,48} Coupled with increasing exposure to air pollutants and other aeroallergens, weather effects also influence the distribution and concentration of allergenic fungi. The species and amounts of fungi present in the air depend on regional and seasonal variations, including changes in vegetation, air temperature, and relative humidity.^{49,50} Humidity is a crucial factor for the sporulation of fungi. However, further evaluation is needed to fully understand the determinants of spore production, seasonal dynamics, sources, and dispersion patterns. Currently, there is no convincing alternative explanations supported by observational evidence.

Over the past 25 years, Korea has recorded a long-term increase in precipitation, with annual levels rising by 17.71 mm per decade. Conversely, the number of precipitation days has decreased by 21.2 days (**Fig. 4**). During summer and autumn, the amount and intensity of precipitation have significantly increased. On the other hand, the number of days with precipitation has decreased throughout the seasons. Even though there was an increase in precipitation, it was concentrated over shorter periods. These changes in precipitation patterns may have extended the duration of dry season, shortening the sporulation period for fungi that require moisture. Eventually, the concentration of fungal spores may have declined (**Fig. 5**).⁵¹

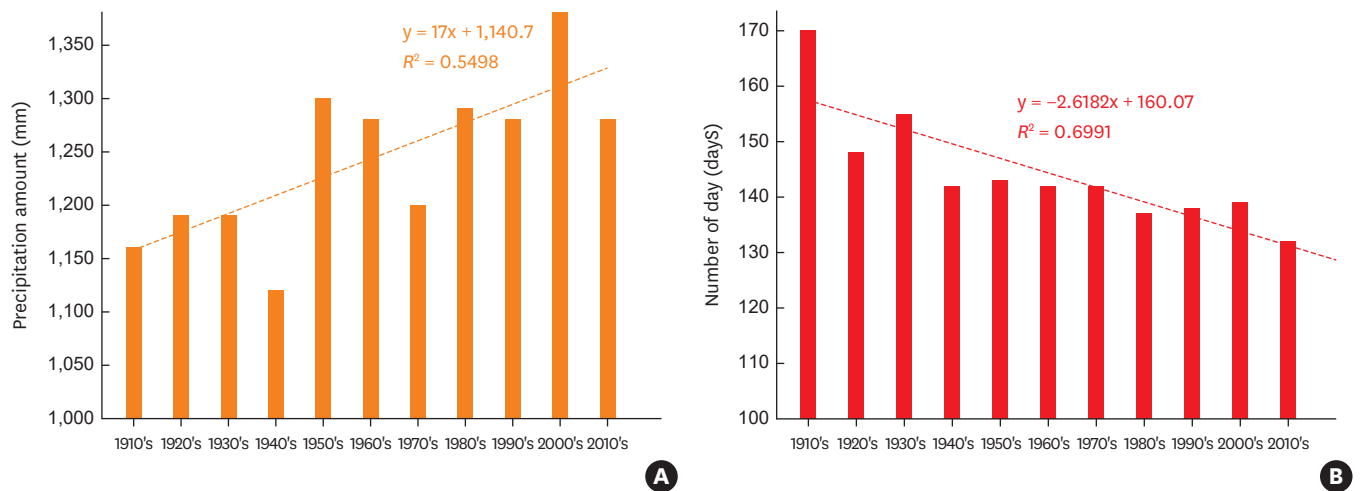


Fig. 4. Longitudinal precipitation trends of (A) precipitation amount and (B) number of precipitation days in Korea over the last 100 years. Annual precipitation increased by 135.4 mm, while the number of precipitation days decreased by 21.2 days. The annual precipitation over the last 100 years increased by +17.71 mm per decade. Permitted from Choi YJ, Lee KS, Jeong JH, Kim K, Yang S, Na JY, et al. Allergy Asthma Immunol Res 2023;15:825-36.⁵¹

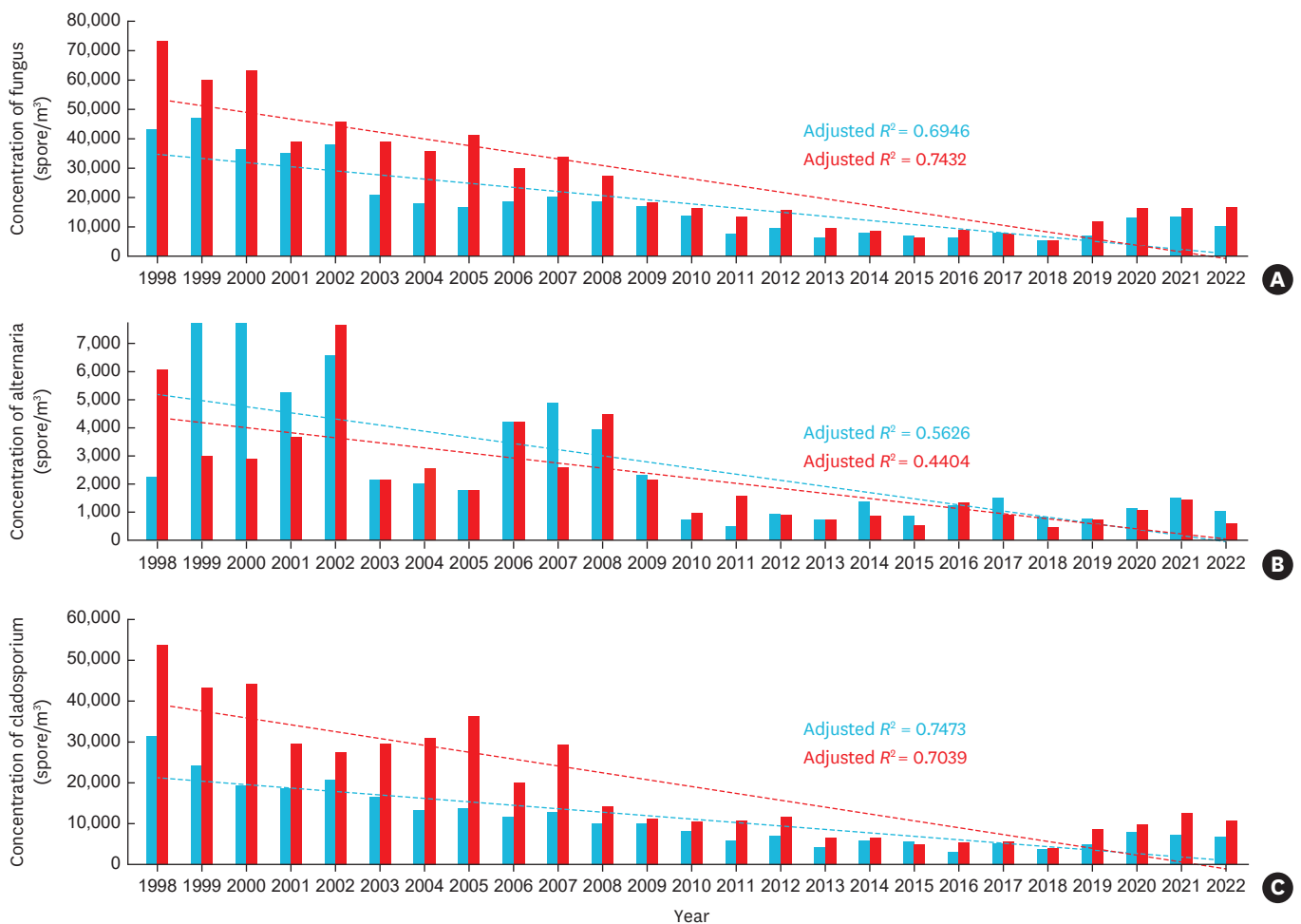


Fig. 5. Changes in the annual concentrations of fungal spores over 25 years in Seoul (blue) and Guri (red), Korea. Total concentrations decreased in both areas. Permitted from Choi YJ, Lee KS, Jeong JH, Kim K, Yang S, Na JY, et al. Allergy Asthma Immunol Res 2023;15:825-36.⁵¹

ALLERGIC SENSITIZATION RATE TO POLLEN AND FUNGI

Hypersensitivity to pollen is one of the most common aspects of allergic diseases, leading to allergic rhinitis, allergic conjunctivitis, and asthma.⁵² Research has identified an interaction between exposure to pollen and sensitization to pollen allergens; this effect was less pronounced in individuals sensitized to single type of pollen compared to those sensitized to multiple types. Plant species vary in threshold levels for allergic sensitization. Sensitization to multiple allergens, including pollen, is associated with more severe allergic symptoms and an increased risk of asthma.^{53–56} Furthermore, because different types of pollen are released at different periods of the pollen season, atopic individuals sensitized to multiple pollen types experience a prolonged exposure, potentially leading to a stronger effect on airway hyperreactivity and reduced lung function.^{57–59} Studies indicate that 10%–30% of the global population is affected by allergic rhinitis due to seasonal pollen exposure, compounded by multiple interrelated consequences of climate change.⁶⁰ A longer pollen season and greater pollen amounts may increase human exposure to allergenic pollen, potentially raising allergic sensitization rates with a recent report noting an increase in pollen sensitization among children (**Fig. 6**).³⁹

In a few studies on fungal allergies, hospitalizations or asthma symptoms were associated with exposure to fungi such as *Alternaria*, and *Cladosporium*.^{48,61–63} Associations were also reported with other species including *Coprinus*, *Aspergillus*, *Penicillium*, and *Botrytis*. These observations align with outcomes from previous studies, where increased emergency department visits for child asthma were related to *Cladosporium* and Deuteromycetes.^{64–67} *Cladosporium* spp. and *Alternaria* spp. Spores, which are ubiquitous in the environment, are 2 dominant genera among airborne spores. The threshold level of spore required to elicit allergic symptoms in atopic individuals is not precisely known and varies among species.⁶⁸

Alternaria alternata is primarily an outdoor fungus growing on vegetation, but this species can also be found indoors. Indoor concentrations of *A. alternata*, typically influenced by the outdoor levels, often produce large brown spores known to cause allergy and asthma.⁶⁹

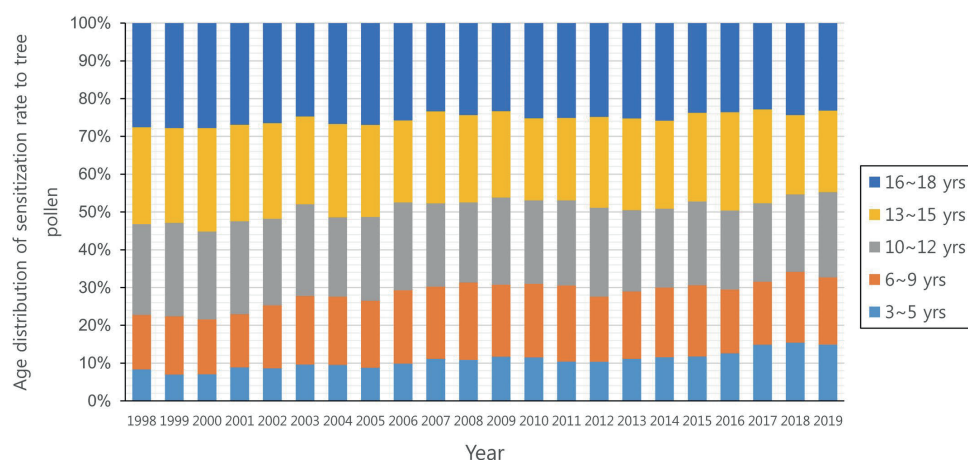


Fig. 6. Age distribution of sensitization to the major pollens in the Seoul metropolitan area from 1998 to 2019. The rates for children under 10 increased, while older age groups showed a slight decrease. Specific changes are as follows: in 1998, rates were 8.3% for ages 3–5, 14.4% for ages 6–9, 24.0% for ages 10–12, 25.4% for ages 13–15, and 27.6% for ages 16–18; in 2019, these rates became 10.7% for ages 3–5, 17.7% for ages 6–9, 22.5% for ages 10–12, 23.9% for ages 13–15, and 25.3% for ages 16–18. Permitted from Lee KS, Kim K, Choi YJ, Yang S, Kim CR, Moon JH, et al. *Pediatr Allergy Immunol* 2021;32:872–79.³⁹

Sensitization rates to fungi vary across studies; however, approximately 5% of people are allergic to *A. alternata*, which is associated with respiratory allergic diseases.^{70,71}

Cladosporium is one of the major sources of inhaled fungal allergens, which means allergic individuals sensitized to *Cladosporium herbarum* may experience symptoms upon inhaling its spores.³⁴ It ranks among the top 3 most common indoor airborne fungi, along with *Penicillium* and *Aspergillus*. A recent study showed that sensitization rates to *Alternaria* and *Cladosporium* have decreased annually over the study period. In Seoul, sensitization rates to *Alternaria* decreased from 3.5% in 1998 to 0.2% in 2022, and for *Cladosporium* they dropped from 4.4% to 0.2% over the same period (Fig. 7).⁵¹

INVERSE TREND BETWEEN POLLEN AND FUNGI CONCENTRATIONS WITH SENSITIZATION RATES

A recent study reported annual increases in allergenic tree pollen concentrations, along with rising sensitization rates to these pollens.³⁹ In contrast, both concentrations and sensitization rates to *Alternaria* and *Cladosporium* decreased annually in the Seoul metropolitan area over the past 25 years.⁵¹ Olsen *et al.*'s study,⁶⁴ spanning 26 years, demonstrated that

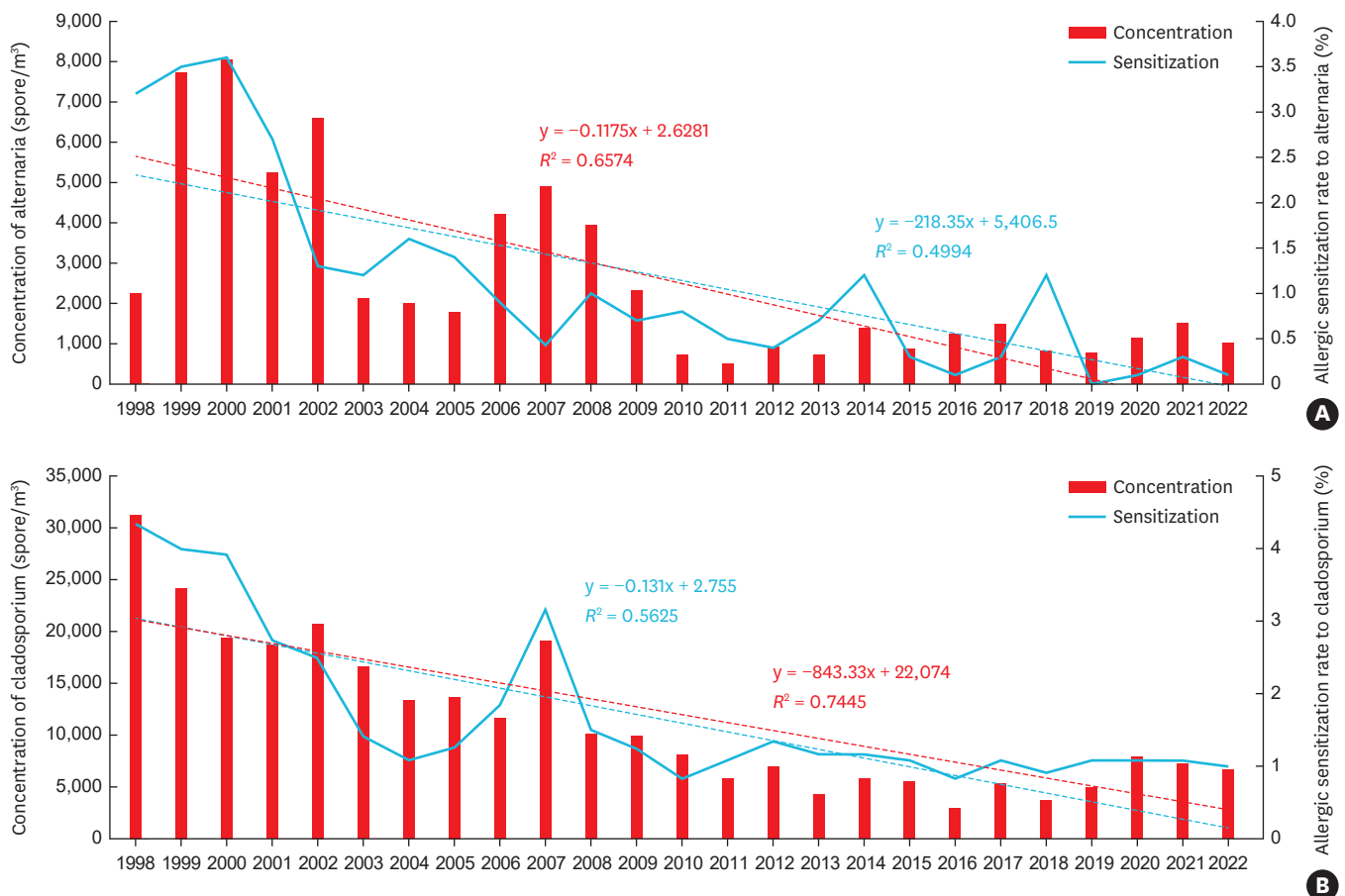


Fig. 7. Correlations between atmospheric concentrations (red bar) and allergic sensitization rates (blue line) to *Alternaria* (A) and *Cladosporium* (B) in Seoul, Korea. Permitted from Choi YJ, Lee KS, Jeong JH, Kim K, Yang S, Na JY, et al. Allergy Asthma Immunol Res 2023;15:825-36.⁵¹

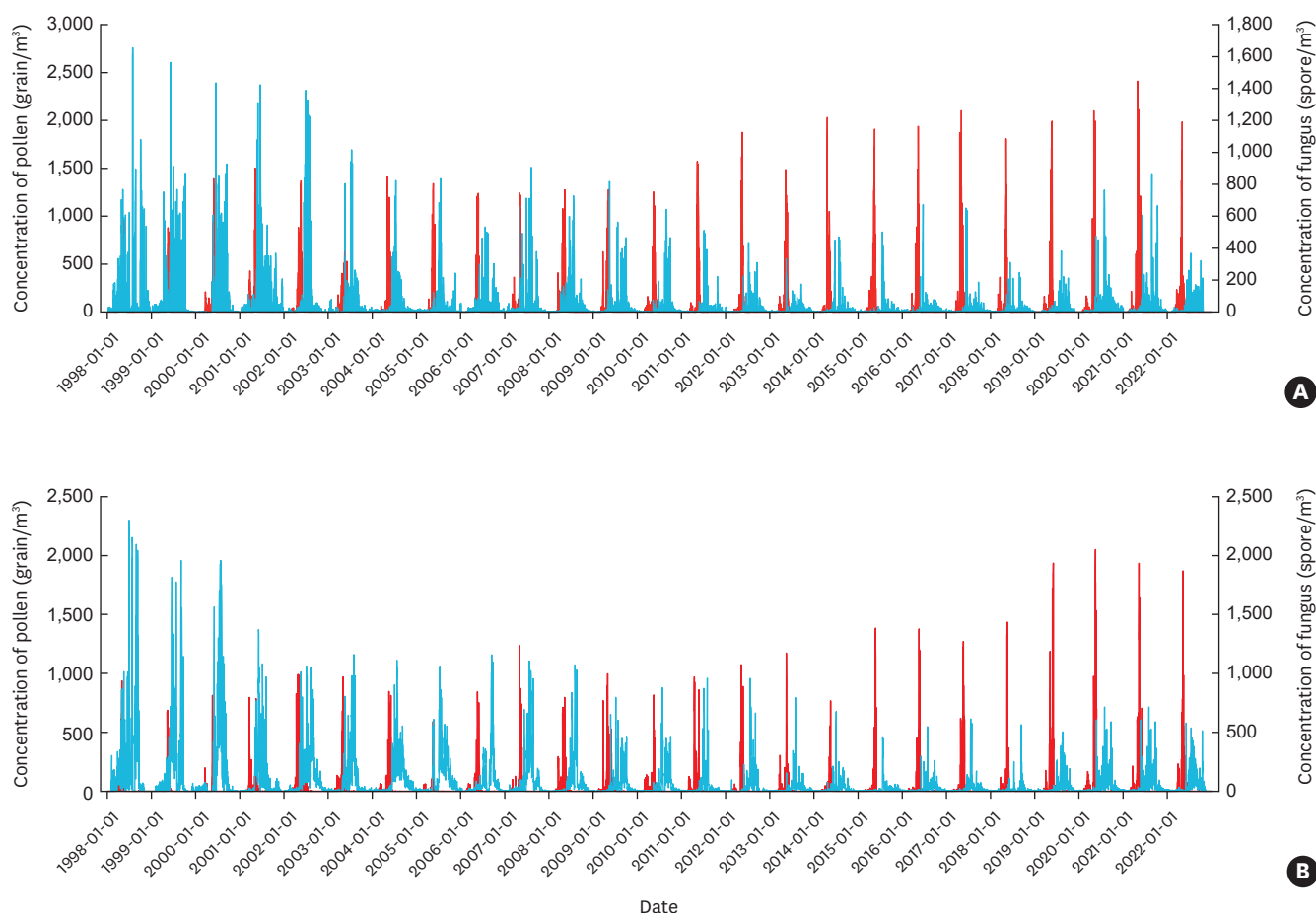


Fig. 8. Comparison of annual concentrations of pollen grains (red) and fungal spores (blue) in Seoul (A) and Guri (B) over the past 25 years. In contrast to atmospheric fungi, pollen concentrations have increased annually during this period. Permitted from Choi YJ, Lee KS, Jeong JH, Kim K, Yang S, Na JY, et al. Allergy Asthma Immunol Res 2023;15:825-36.⁵¹

despite increasing annual temperatures, there was a decreasing trend in seasonal and annual peak concentrations of *Alternaria* and *Cladosporium* with decreasing relative humidity. During this period in Korea, although the amount and intensity of precipitation during summer and autumn significantly increased, the number of days with precipitation decreased throughout the seasons. Even though there was an overall increase in precipitation, it occurred over shorter periods. These changes in precipitation patterns may have extended the duration of dry season, which in turn could have reduced the sporulation period for fungi that require moisture (Fig. 8). It is likely that the concentration and distribution of pollens and fungi are significantly affected by environmental changes due to climate change such as drought, atmospheric dryness, and prolonged dry seasons. However, it remains uncertain whether this inverse trend is directly attributable to climate change or not.

CONCLUSIONS

Climate changes may have worsened planetary environment through rising air temperatures and greenhouse gases, which in turn have elevated both the amount of allergenic pollen and the rate of sensitization. In contrast, climate change may have lengthened the dry season through desertification and drought, thereby reducing the sporulation period for fungi and decreasing

fungal amounts. It remains uncertain whether there are complex interactions among atmospheric pollen, fungi, air pollutants, and meteorological variables. Extended monitoring periods and further large-scale studies are required to confirm causality and evaluate the impact of climate change on this inverse trend. It is crucial to mitigate the associated risks to human health and take appropriate measures to reduce these risks in the future.

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