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Air quality in the era of climate change: Bioaerosols, multi-exposures, and the emerging threats of respiratory allergies and infectious diseases

Athanasios Damialis[1] and Stefanie Gilles[2,3]

With the rising global burden of allergies and asthma, bioaerosols have gained the attention of physicians and researchers over the past decades. However, bioaerosols still remain underestimated, excluded from EU Directives. This work points out that respiratory diseases, an emerging human health risk, may be predicted and appropriately managed only if the entirety of co- and multi-exposures, biogenic as well as mixed (chemical-biological) is considered, especially for vulnerable population groups. Here we present an overview of the state of the art in bioaerosol research and its challenges, and pinpoint unmet research and policy needs in a rapidly changing world.

Addresses
[1] Terrestrial Ecology and Climate Change, Department of Ecology, School of Biology, Faculty of Sciences, Aristotle University of Thessaloniki, Thessaloniki, Greece
[2] Institute of Environmental Medicine and Integrative Health, University Hospital Augsburg, Faculty of Medicine, University of Augsburg, Germany
[3] Institute of Environmental Medicine, Helmholtz Munich, German Research Center for Environmental Health, Neuherberg, Germany

Corresponding author: Gilles, Stefanie (stefanie.gilles@med.uni-augsburg.de)

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Climate change, bioaerosols, and health impacts

Air quality has been monitored by the European Union through officially and centrally administered and planned decisions [1]. The main objective of this Directive is "… to set out air quality provisions with the aim to achieve a zero-pollution objective, so that air quality within the Union is progressively improved to levels no longer considered harmful to human health, natural ecosystems or biodiversity …". While it strongly pursues the control and reduction of particle and chemical pollution, it completely lacks any reference at all to other pollutants, as of biological origin, with widely known dire effects to human and environmental health. These biogenic particles, or bioaerosols, are amongst the responsible for the number one threat for humankind in terms of emerging diseases and of mortality: the Intergovernmental Panel on Climate Change (IPCC) has provided strong to very strong evidence on the rising global burden of respiratory illnesses, among which are allergies and asthma [2]. Hence, bioaerosol monitoring is wide-spread worldwide, with allergy apps including pollen information dominating the growing market of mobile health (mHealth) apps; nevertheless, bioaerosol monitoring is still carried out mainly by university institutes, and most services depend on non-profit foundations or on research projects with limited funding, with negligible foresight in appropriate and urban planning, locally, nationally and EU-wide, as also highlighted recently by Kim and colleagues [3]**.

The study of bioaerosols, traditionally the scientific field of Aerobiology, has gained momentum as more and more data are collected daily via biomonitoring campaigns and continuously extended networks, as these provide increasing evidence on the climate change effects on plants and microbes; likewise, automation and technological advancements in aerobiological monitoring also has contributed to the development of the topic and the knowledge around it [3]**. After the recent COVID-19 pandemic, aerobiological research has gained new momentum and has improved the early detection, monitoring, and clearance of airborne viruses, mainly indoors and in transmission hot spots. In the face of climate change and growing urbanization, new zoonotic diseases, new allergen spreading, extreme events, crop failures, and epidemic livestock diseases will become increasingly frequent, with direct and indirect dire consequences for human health [4–7]. This illustrates the need for a planetary health approach in containing these risks.

While bioaerosols are relevant to climate change impacts, limited research has been comparatively conducted so far. They are relevant to climate change impacts, plant and microbial ecology, human and public health (including infectious and allergic diseases) [4–7], but also aerosol and agricultural sciences, a fact which comprises their study as an utterly interdisciplinary scientific field. Even though bioaerosols are considered locally or regionally, their importance is rather national and trans-national, which further points out the need for a collective effort. Toward this aim, the European Union could include the topic in the frame of a common EU Directive of urban planning or integrate bioaerosols into the Air Quality EU Directive. Transnational collaboration in bioaerosol monitoring is especially meaningful given the well-known fact that bioaerosols can be transferred not only from the local or regional biodiversity, but actually from sources up to thousands of kilometers away, even across oceans and between continents ([8]* and references therein).

Exposure to bioaerosols and associated allergies is a common public health problem of our times, with allergies being among the most frequent non-communicable diseases, showing increased global incidences because of changing environmental exposures ([9] and references therein). Consequently, allergy has been termed the "pandemic of the century", with half the global population expected to exhibit at least one form of allergy by 2050 [3]. Aeroallergens are a major cause of respiratory allergy and asthma, and a wide array of changing aeroallergen patterns have been attributed to climate change-related factors. With the aim to understand the interplay between the environment (bioaerosols) and human health, a variety of studies have been implemented: on thunderstorms and associated respiratory implications, on plant ecology and pollen production, on flowering phenology, and dispersal of pollen, including long-distance transport associated with allergic symptoms [3].

Bioaerosol trends in a world with a changing climate

Many aerobiological studies have demonstrated increasing pollen abundance and earlier-shifted pollen season starts for many taxa [3,10]. But, in contrast to a popular misunderstanding (generalized usually by non-expert clinicians), the situation, globally speaking, is much more complex, with many pollen types increasing in abundance and several plant taxa shifting towards earlier flowering onset, but with other taxa or in other locations starting later or remaining unchanged until now, and with the overall pollen season sometimes extending, sometimes shrinking or not changing at all [11]*, [12–14]. Almost all studies agree, though, that higher pollen abundance and earlier-shifted plant phenophases have been attributed to higher temperatures [14]* and rising atmospheric CO_2 concentrations, among other factors, as recently reviewed by Kim and colleagues [3].

Regarding airborne fungal spores, their sporulation also appears to be not a consistent, universal process, but varies among locations and years. This is in contrast to the more consistent trends in airborne pollen concentrations: there is evidence from independent studies and from different regions of the world that fungal spore abundance has been decreasing during the last decades [15] and could further decrease due to climate change factors [16]**.

How can this counterintuitive finding be explained? Growth-promoting greenhouse gases like CO_2, along with higher air temperatures (and if water availability is not a limiting factor), favor increased biomass production, including inflorescence production. As common allergenic fungi are endophytic, any climate change-related stress of the plant host also impacts the fungus. Given that fungi exhibit different growth strategies than their plant hosts, it seems that in response to changing climate conditions, the ratio of fungal hyphae to the spores produced is changing, with the fungi rather investing in faster hyphal growth than in producing vast quantities of spores in order to increase their probability of successful reproduction [17]. This illustrates the complexity of both biological communities and of species' interactions, as well as of ecosystems' dynamics, thus highlighting the need for thorough environmental systems research.

The unrecognized real-life situation: co- and multi-bioexposure

While the health impacts of single bioaerosol exposures may be well-studied, as for example for some pollen types or certain viruses, co- and multi-bioexposures are a virtual black box. Even the bare co-circulation of different respiratory pathogens [18,19]* aeroallergens [20], or their combinations [21] is often unappreciated, much less studied with respect to the above effects.

During the pandemic era, pollens were documented to have contributed to the increases in the infection rates, particularly in spring, when the viral infections coincided with the peaks of tree pollen seasons [21,22]. Nowadays, there is a lot of research happening on the 'pandemic preparedness' and the surveillance of respiratory viruses [23,24]**, but without any foresight, yet, on synergies with other biological (and abiotic) agents.

Chemical air pollution has long been recognized as exacerbating respiratory allergies and even as enhancing the allergenic potential of allergen carriers, such as pollen (reviewed in Ref. [25]), either via direct effects on the pollen composition [26,27] or via systemic effects on the pollen-producing plant [28]. In contrast, air pollutants like PM_{10} are only starting to be considered as a relevant co-factor in the transmission of respiratory infections, such as influenza [29]. Of note, the complex relationship between viral infections, including SARS-CoV-2, and environmental exposures and short-term meteorological variables needs further systematic research [30].

The potentially harmful consequences of multiple bio-exposures are illustrated by the example of thunderstorm asthma, which gained a lot of attention in the last 10 years, because of the unfortunate fatalities in the Melbourne 2016 incident. Major thunderstorms are characterized by weather patterns associated with convection of air masses and strong upwards and downwards wind drifts, which lead to the resuspension of particles in the mixing layer of the atmosphere. It is hypothesized that pollen grains swell and rupture due to high osmotic pressure in the humid environment of clouds or due to voltage potentials during lightning events [31]. Downdrifts transport these pollen fragments back to the ground level atmosphere, where they may be inhaled and deposited in the lower airways, triggering severe asthma attacks in sensitive individuals. Thunderstorm asthma incidents go along with sudden increases in asthma occurrence, leading even to emergencies and fatalities [32]. It can be assumed that major thunderstorm asthma events might increase as a consequence of climate change, with thunderstorms in many regions of the world becoming stronger, more frequent, or both. Thunderstorm asthma appears to affect not only individuals with a history of pollen allergy and asthma, but also individuals previously not diagnosed with asthma [33].

Thus, the question remains whether other bioaerosols, e.g. fungal spores, chemical pollutants, or particulate matter could also play a synergistic role in this process. For instance, high stratospheric ozone levels are commonly measured during thunderstorms, which is due to the degradation of molecular oxygen by high electrical field potentials and high temperatures associated with lightnings. Ozone, known to exacerbate asthmatic symptoms, could synergize with pollen or pollen fragments in causing thunderstorm asthma. More basic research is urgently needed in the field to uncover the complex exposure mechanisms leading to thunderstorm asthma.

The future: smart environmental health services

Research on bioaerosols has rapidly developed in recent years. Automated pollen monitoring, remote sensing, and molecular techniques, such as eDNA metabarcoding, have revolutionized the detection and quantification of bioaerosols and broadened its application spectrum, e.g. for the monitoring of airborne pathogens with pandemic potential [34].

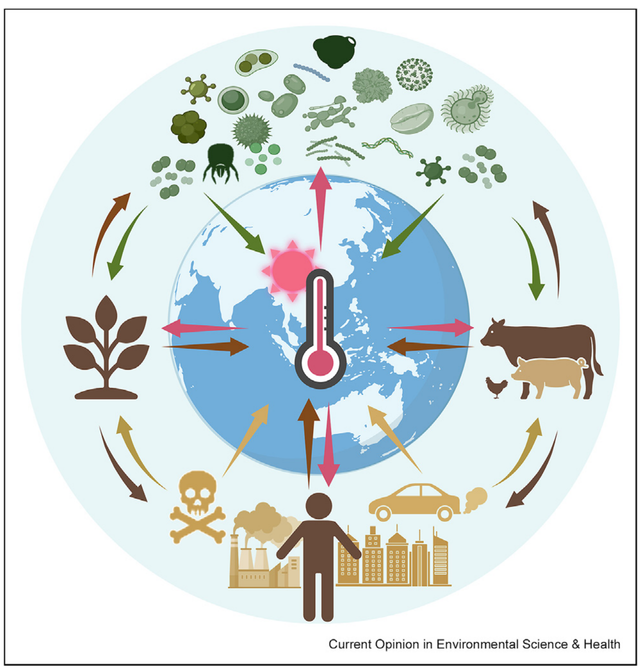
Near-physiological cell culture systems, such as the VitroCell® Cloud alpha and PowderX chambers, enable cutting-edge wet-lab research into the cellular signals induced under bioaerosol exposure [35,36], which is crucial for the development of prevention, mitigation, and treatment options. Human exposure chambers are widely used in clinical trials to test the responses of allergy patients to pollen aerosols before and after specific immunotherapy [37−39]. Aerobiologist-led initiatives, such as the current EU Horizon project 'SYLVA' and the past EU COST Action 'ADOPT', have been dedicated to the standardization and intercomparison of bioaerosol detection methods [40], and the EUMETNET-AUTOPOLLEN network has started to build up a Europe-wide automatically generated pollen concentrations (and spore) database [41,42]. Lastly, aerobiologists have generated dedicated software tools to model bioaerosol exposure in real-world populations and under climate change scenarios. Physicians treating allergy patients use this knowledge to promote the use of allergy apps [43], often equipped with local pollen information, towards efficient symptom prevention and self-management [44,45].

Nevertheless, there are still important requirements for the implementation of high-quality health services, which have been unmet until today. The first is the need for comprehensive information on ground-level bioaerosol sources to create reliable spatiotemporal distribution models. Pollen grains, for instance, can be transported in high altitudes for up to thousands of kilometers, and long-distance transported pollen may still cause symptoms in susceptible patients [8], which is why it is important to estimate the contribution of distant sources when modeling local exposure. Secondly, unlike for chemical air pollutants, bioaerosol monitoring networks have been unsupported by policymakers; moreover, today's urban planners still neglect the ambivalence of urban greenery in highly polluted cities [46]; even more unfortunate, there is a recent tendency of replacing such networks with dubious AI approaches, in Europe and in the USA. Finally, the most urgent unmet need is to create opportunities for long-term, reliable public funding outside the universities. Aerobiologists have contributed to the development of smart mhealth services [47], and their research is of high public interest in a rapidly changing environment characterized by global warming, biodiversity loss, and urbanization. This fact alone calls for a better recognition of aerobiological research and expertise in the future.

Beyond the anthropocentric picture: the 'Planetary health' approach

Airborne pollen is not only relevant to public health but has also been applied as an indicator of environmental change as stated by the Intergovernmental Panel on Climate Change [48]. Losses in biodiversity, a hallmark of climate change, will not only directly affect human health, but will likely also affect the health of animals and plants, which make up the human environment, across the Globe (Figure 1). A tipping ecosystem carries the risk of more frequent and dramatic crop failures or epidemic livestock diseases, with tremendous economic consequences and secondary health effects, which will mainly affect the socially disadvantaged. A 'Planetary Health' approach is therefore warranted to bring together experts from medical, biological and environmental sciences and to address all dimensions of the problem, at the scale of our planet, rather than regionally or nationally [49,50]. In the face of this environmental situation, the European Academy of Allergy and Clinical Immunology (EAACI) has been focusing on Planetary Health activities, integrating interdisciplinary panels of experts that follow a systems approach to study the complex interplay of human, animal, and environmental health in the multifactorial pathophysiology of allergic diseases. This strategic Working Group, in joint collaboration with the American Academy of Allergy, Asthma and Immunology (AAAI), aims to educate and mobilize stakeholders and to improve the health of allergy patients through interdisciplinary efforts. Bioaerosols, although harbingers of biodiversity loss, have never been incorporated in any official, centrally and permanently administered and funded, large-scale project, despite their acknowledged importance and timeliness. Policy and decision makers should be involved in creating the infrastructure of an intercontinental biomonitoring network of multiple exposures, mainly of bioaerosols. Via increased public awareness, policy and decision makers are expected to be motivated to create such networks worldwide, so as to reduce future human health risks, and to more efficiently manage challenging diseases of our era.

Figure 1



The 'Planetary Health' approach in climate change effects of bioaerosol exposure. Global warming and increased levels of atmospheric greenhouse gases influence the reproduction and health of plants, animals, and humans (red arrows), but also increase bioaerosol formation. All living organisms produce biogenic emissions, such as plant debris, seeds, pollen grains, fungal spores, fungal hyphae, bacteria, and viruses, which interact with other organisms across all kingdoms (dark brown arrows) via infectious or allergenic bioaerosols. Bioaerosols exert feedback effects on the biosphere, but they also have an impact on cloud formation and other atmospheric processes (green arrows). Urbanization, excessive farming, and agriculture lead to the accumulation of chemical pollutants and toxins, which are harmful to the health of humans, animals, and plants and thus, directly or indirectly, accelerate climate change (light-brown arrows). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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* * of outstanding interest

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