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ORIGINAL PAPER

The role of automatic pollen and fungal spore monitoring across major end-user domains

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Abstract The advent of automatic pollen and fungal spore monitoring over the past few years has brought about a paradigm change. The provision of real-time information at high temporal resolution opens the door to a wide range of improvements in terms of the products and services made available to a widening

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range of end-users and stakeholders. As technology and methods mature, it is essential to properly quantify the impact automatic monitoring has on the different end-user domains to better understand the real long-term benefits to society. In this paper, we focus the main domains where such impacts are expected, using Europe as a basis to provide qualitative estimates and to describe research needs to better quantify impacts in future. This will, in part, also serve to justify further investment and help to expand monitoring networks.

Keywords Automatic monitoring · Pollen · Fungal spores · Impacts · Assessment

1 Introduction

Pollen monitoring has been routinely carried out since the late 1960s (Hyde, 1959; Emberlin et al., 1993; Gehrig & Clot, 2021), largely using volumetric traps such as that developed by Hirst in 1952 (Hirst, 1952). These measurements require manual identification and counting procedures using light microscopes carried out by trained personnel (Galán et al., 2014). While considered a significant improvement at the time, and still the most widely used sampling method worldwide (Buters et al., 2018), technology has since developed extensively towards automation as there is more and more user demand for real-time information and services (Tummon et al., 2021a). The first steps towards automation took place in the 1990s with attempts to digitise specific aspects of the process, such as light microscopy images (e.g. Treloar, 1994). Later, in the 2000s, there was more focus on automatising the classification process (e.g. Bonton et al., 2001; Boucher et al., 2002) but only a few studies used air samples (Ranzato et al., 2007; Landsmeer et al., 2009). The particular conditions in Japan—just two easily-identifiable allergenic pollen taxa present in winter—made it possible to establish an automatic monitoring and forecasting network in 2002 (Kawashima et al., 2017). Further steps

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towards automatic monitoring of a larger number of specific pollen taxa were later achieved with the Hund BAA500 device, which essentially automates the manual process using a robot and digital microscopy, first being tested in 2009 (Oteros et al., 2014). Various tests and developments were carried out over the following years, including with several other instruments based on a range of different technologies, such as flow cytometers employing digital holography and/or fluorescence (e.g. O'Connor et al., 2014; Sauliene et al., 2019; Sauvageat et al., 2020). In 2019, several of these devices were tested in parallel at the same location and showed relatively good performance compared to the conventional Hirst-trap measurements (Tummon et al., 2021b). A more comprehensive intercomparison was then carried out in Munich, Germany, over the 2021 pollen season (Maya Manzano et al., 2023). This campaign not only compared all available automatic instruments but also different identification algorithms, showing very good results for certain combinations of automatic device and algorithm. Based on these initial studies, the first use of automatic monitors to provide real-time pollen data in operational networks began in the cross-border region of Serbia and Croatia in 2019 (Tesendic et al., 2020), in the German state of Bavaria in 2020 (Oteros et al., 2020), and in the Swiss national network in 2021 (Crouzy et al., 2022). A number of other automatic measurement sites have been or are currently being installed across Europe (see Fig. 1). Although so far some of them may appear isolated by country or region, these automatic monitoring sites are potential starting points for integration into (supra-)national aerobiological networks.

Automatic pollen monitors are continually being developed and more and more instruments are coming to market as technology and methods evolve. The potential for development is particularly large in terms of the particle identification software, with a constantly growing number of pollen taxa and other particle types (e.g. pollen sub-particles, fungal pathogens, dust, or potentially even large bacteria) that can be identified. Much of the growth and development of

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automatic pollen monitoring is currently coordinated by the EUMETNET AutoPollen programme (Clot et al., 2020), which was started in 2018 to provide a framework for collaboration and cooperation across Europe. The programme continues to serve as an efficient forum for the exchange of knowledge and experience, bringing together a multidisciplinary community to develop methods, international standards, and the European real-time pollen and fungal spore monitoring network. Special attention has been given to involve currently known stakeholders to ensure that developments are in line with their needs (Tummon et al., 2021a).

This paper aims to provide an overview of the impacts of automatic pollen and fungal spore monitoring across several key sectors, including public health, agriculture, environment, and research. Quantitative estimates of the impacts of automation are provided for the monitoring itself; however, it is difficult to make accurate quantitative estimates of the impacts on other end-user domains since dedicated research and data from longer periods are not yet available. Rather, here we outline several recommendations and possible methods for future studies that could improve the accuracy in assessing the different impacts of automatic pollen and fungal spore monitoring.

2 Effects of automation on aerobiological monitoring

2.1 Impacts on measurement quality

The most recent evaluation of automatic pollen monitors was carried out over the 2021 pollen season and aimed to assess the capabilities of all devices available at the time, focusing on a range of the main allergenic pollen in Europe (Maya Manzano et al., 2023; Triviño et al., 2023). Results showed that a number of instruments perform at least as well as the manual Hirst-type traps, with the added advantage of providing data in real time (from the identification of individual particles up to several hours) and at higher temporal resolution (Crouzy et al., 2022; Maya Manzano et al., 2023; Adamov et al., 2021; Oteros et al., 2020), thus responding to current demands for real-time information (Tummon et al., 2021a). While most automatic systems are not yet capable of identifying as many pollen taxa as conventional microscopic methods, the major allergenic taxa present in Europe are well classified using algorithms that require no human intervention (Sauvageat et al., 2020; Oteros et al., 2020; Maya-Manzano et al., 2023). Furthermore, all automatic monitoring systems allow for long-term storage of raw data, meaning that any future improved algorithms can be applied retrospectively to obtain

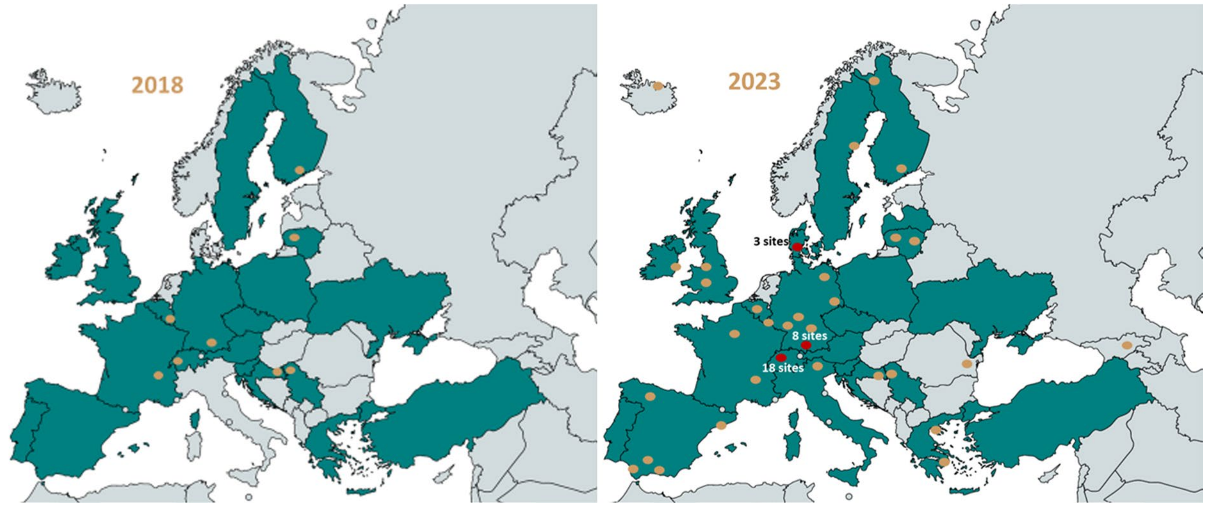

Fig. 1 EUMETNET AutoPollen programme participating countries (coloured in green) and automatic pollen monitoring sites (orange dots) in 2018 at the beginning of the programme and in 2023. Note that the red dots for 2023 indicate networks in Bavaria (8 sites), in Switzerland (15 sites), and in Denmark (3 sites). Note, what appear as white dots are very small countries, such as Monaco

homogeneous climatologically-relevant time series of additional taxa.

Accurate identification of pollen and fungal spores is a critical aspect of any aerobiological monitoring. The European standard describing the manual volumetric method using Hirst-type traps (Galan et al., 2021; EN16868:2019; Galan et al., 2014) provides a number of specific points that contribute to estimating total uncertainty of the technique. Automatic devices circumvent many of these issues, providing the possibility to notably reduce methodological uncertainty (Table 1). There are, however, different sources of uncertainty that contribute to the automatic measurements (Buters et al., 2022), which also need to be taken into account. This includes uncertainty related to the identification algorithms used or to high particle loads, the latter of which can be circumvented in certain instruments by reducing the sampling rate (see Buters et al., 2022). Nevertheless, comparisons between automatic instruments suggest that they are less uncertain than manual measurements at comparable timescales (Maya Manzano et al., 2023; Triviño et al., 2023; Adamov et al., 2021).

Not only do automatic devices provide observations with little or no human intervention, but many of the measurement techniques used lend themselves to calibration and certification similar to that carried out for air quality monitoring (e.g. Lieberherr et al., 2021), potentially paving the way for European legislation to include pollen and fungal spore monitoring. Such calibration methods are currently being tested by the metrology community, and a European standard for automatic pollen and fungal spores is being developed to describe such calibrations, as well as many other important aspects; this will ensure more homogeneous and standardised automatic observations across the continent.

2.2 Economic impacts

It is expected that the provision of real-time pollen and fungal spore information will reduce economic costs indirectly, for example, by reducing health care costs (see Sect. 3). Here, we make an estimate to compare cumulative costs of manual and automatic monitoring over a period of 10 years, an indicative period for which monitoring activities are typically run and the expected lifetime of many instruments. We consider a network of five instruments as this represents a reasonable number of devices for a region or a small country. Note that we only consider the first steps of the information chain, i.e. the measurements and analysis. We do not consider costs associated with the provision of information to end-users since this is assumed to be the same for the two methods. Values have been directly obtained from the manufacturers of automatic devices so provide the best available estimates at the time of publishing (even if obviously subject to change).

To calculate the cumulative costs of manual monitoring, an initial investment cost of €52′000 is assumed. This covers five Hirst-type instruments, a microscope, as well as a basic laboratory, including a fume hood, that is required for the preparation and analysis of samples. This value is based on a rough estimate for Europe, and there will obviously be country-to-country variations but this is not considered here. We also assume there is no dual usage of the facility for other tasks. Thereafter, the main costs are related to the personnel and a range of values was taken based on hourly labour costs. Two scenarios were calculated using values from EUROSTAT (https://ec.europa.eu/eurostat/web/products-eurostat-news) based on minimum and maximum values for European countries, and this corresponds to hourly rates of €7 for Bulgaria and €47 for Denmark, respectively. It was assumed that the work associated with running a manual network was equivalent to six hours per site per week, with this being carried out 50 weeks per year. The remaining two weeks would be dedicated to maintenance and quality control efforts, with 24 h being allocated for these purposes for each station. While certain sites, particularly in northern Europe, may not be operational for as many weeks of the year, this enables a fair comparison with automatic devices and for all sites. Note that certain sites in Europe carry out monitoring on a daily basis and/or count fungal spores during the relevant seasons, with both of these aspects considerably increasing the personnel costs. This is also not considered here. Site costs of €1000 per site were included as well as a value of €400 per year for consumables and shipping costs of €25 per week for four instruments. (The fifth instrument is assumed to be at the same location as

Table 1 Known uncertainties and limitations of the manual method that are reduced with automatic methods

Manual (EN16868:2020)	Currently best-performing automatic methods
Variability resulting from sample preparation	Overall, less human intervention. In digital microscopy-based approaches, a robot carries out sample preparation. For flow cytometry-based instruments, this process is eliminated entirely since each particle is analysed on-the-fly. Additionally, there is no uncertainty from the mechanical clock or cutting the impaction tape
Inter- and intra-observer variability during identification and counting	Identification is based on a computer algorithm and thus there is no counting or identification variability Uncertainty related to counting is reduced since larger sample areas or nearly all particles are counted. Nevertheless, automatic algorithms may have uncertainty related to particle identification as well as other issues
Only a small percentage (typically 10%) of the sample area is analysed	For flow cytometers all sampled particles are processed, except under very high aerosol loads when automatic down-sampling is sometimes applied. For digital microscopy-based instruments, a larger surface area is usually analysed (typically 25%)
Uncertainty related to impaction efficiency	In air flow cytometry this is completely eliminated since particles are analysed in-flight (i.e. there is no sample collection)
Uncertainty related to temporal resolution	Several automatic instruments sample larger volumes than Hirst-type traps allowing more representative sampling at low temporal resolutions. In addition, for most instruments there is no "smearing" effect over time as particles are either measured in-flight or sampling slides are changed at distinct time points (although some image-based devices have a rolling band similar to the Hirst trap). This notably reduces uncertainty, especially at high temporal resolutions
Uncertainty in flow rates	Integration of high accuracy and continuous air flow measurements limits this uncertainty by prompt detection of any deviation and variable adaption of the flow rate as required. These data, and a number of other variables, are recorded and available for later use if required (e.g. for quality assurance/control)
Uncertainty at very high concentrations (pollen may bounce off a saturated collection surface)	Some automatic monitors dynamically adjust sampling rates so they are less impacted by very high aerosol concentrations
Repeatability is typically on the order of 70–90%	The same classification algorithm run on the same sample has 100% repeatability

That no quality standard yet exists for automatic methods (although one is under development). Automatic techniques may suffer from other, different uncertainties (see Buters et al., (2022) for more details)

the laboratory.) This results in annual running costs ranging between approximately €23′000 and €89′000 (Table 2). Over the 10-year period, this results in total costs ranging from around €285′000–€942′000. The inclusion of more sites would linearly increase the costs since the personnel costs related to manual monitoring are directly related to the number of stations that need to be counted.

For automatic monitoring, a similar calculation was carried out. The range for the initial costs is based on one of the cheapest and one on the most expensive instruments currently available. Important to note is that we considered only those instruments able to identify the most important European pollen taxa (based on the work of Maya-Manzano et al., 2023). The initial investments were thus estimated to be between €285′000 and €760′000, including the price for five instruments as well as installation and training in how to use the instrument. Note that this does not include developing identification algorithms, it is assumed that the instrument is ready to run upon installation. A similar assumption is made for the manual monitoring, considering no time required for training personnel. Annual running costs are also calculated, with site and data transmission assumed to be €1′000 per site. The annual maintenance cost is estimated to be 10% of the initial instrument price, an assumption that is commonly used across this industry. The costs for data hosting are also included, as are the costs of consumables (to provide the maximum possible scenario), where a range is also taken (from €1000–€5000 per instrument). As for the manual monitoring, it was assumed that measurements are carried out 50 weeks of the year with maintenance occurring during the remaining 2 weeks. It was estimated that 5 h per week was required for running the automatic network, assuming that initial installation and supervision of instruments has been carried out. This results in annual running costs ranging from approximately €46′000–€124′000 (Table 2). Note that costs may vary also because of the geographical spread of networks, which is not taken into account here. For the 10-year period, costs range from a minimum of €752′000 to a maximum of €2′002′000 including initial investments for the automatic networks.

The initial investment costs for an automatic network are considerably more expensive. The costs for maintenance and data storage for both automatic scenarios are also higher compared to a manual network, in large part because the maintenance needs to be carried out by trained professionals. However, the personnel costs for running an automatic network are considerably cheaper compared to the manual network and depending on the country may even be cheaper in terms of annual costs after only a relatively short period of time (Fig. 2). As the number of automatic devices in a network increases, the personnel costs do not increase linearly; therefore, it is expected that for a larger network the costs of automatic monitoring will be lower than for manual monitoring. The assumption in this calculation, however, is that personnel costs are the same for both manual and automatic monitoring even if different skills are required. Another aspect to keep in mind is that as technologies evolve and the absolute value of numerical storage (€/Tb) tends to lower in the long term, it is quite possible that the initial investment costs associated with the acquisition of automatic instruments will progressively decrease. Finally, the fact that the market for automatic instruments is composed of more than a dozen manufacturers induces a competitive effect. This economic regulation contrasts with the almost monopolistic price dynamics of Hirst-type traps,

Table 2 Indicative values for the calculation of costs associated with a small monitoring network of five stations based on manual and automatic measurement systems (see text for details)

	Manual	Automatic
Initial costs		
Initial instrument cost	€5000 (per instrument)	€55′000-€150′000 (per instrument)
Other initial costs	€27′000 (Microscope, basic laboratory set-up, and installation)	€10′000 (Installation and training)
Total initial investment (5 instruments)	***€52′000***	***€285′000-€760′000***
Annual costs		
Number of hours worked per week	30 (6 h per site)	5 (for full network)
Number of hours for maintenance (per year)	120 (24 per site)	10% of annual purchase costs (costs included in “other costs” below)
Other costs	€11′000-€13′000 (Consumables, shipping, site costs)	€40′000-€112′000 (data hosting, maintenance, site costs, consumables (where relevant))
Range of total annual costs*	***€23′340-€88′980***	***€46′750-€124′225***

Values include initial investment costs as well as annual running costs

*The range is based on minimum and maximum hourly labour costs based on values from EUROSTAT (https://ec.europa.eu/eurostat/web/products-eurostat-news), with minimum values of €7/hour and maximum values of €47/hour. In all cases, it is assumed that monitoring is carried out 50 weeks a year. The range also includes the range in maintenance costs and for the maximum scenario also the range in consumable costs which have been based on only two manufacturers in the market for several decades.

It is important to note that it may be necessary for monitoring networks to maintain a minimal number of sites where manual monitoring is performed to ensure continuation of certain long-term data series for climatological and phenological reasons as well as to detect neophytes, i.e. pollen and fungal spore taxa for which automatic instruments have not yet been trained to identify. This is particularly relevant since the current generation of automatic monitors still offers a more limited list of taxa that can be identified compared to the manual method (Maya Manzano et al., 2023). An emerging alternative to precisely identify down to the species level (or even lower) is high-volume aerosol sampling followed by a metagenomic DNA analysis. This process has become feasible for regular monitoring only very recently with the third-generation DNA sequencing techniques and related analytical protocols (Núñez et al., 2017; Rojo et al., 2019; Sofiev et al., 2022).

3 Impacts on key end-user sectors

Automatic devices provide data in real time and at temporal resolutions ranging from instant identification of individual particles to a couple of hours, thus meeting the needs of end-users (Maya Manzano et al., 2023; Tummon et al., 2021a). More consistent qualitative evaluations of automatic data, the possibility to accurately calibrate and certify these instruments as well as to continuously control their performance in real time, will open the door to potentially making pollen and fungal spore monitoring a legal requirement across Europe, as is the case for meteorology and air quality. Furthermore, the current location of manual sites is based on the availability of easy access to local expertise and the specific laboratory facilities required (weekly changing of the drum, samples being sent to a laboratory, etc.). An automatic device can be placed considerably more freely, at any location with the required infrastructure (power supply, Internet, and protection against damage), where the observation has the largest impact from an end-user perspective. This section discusses the various

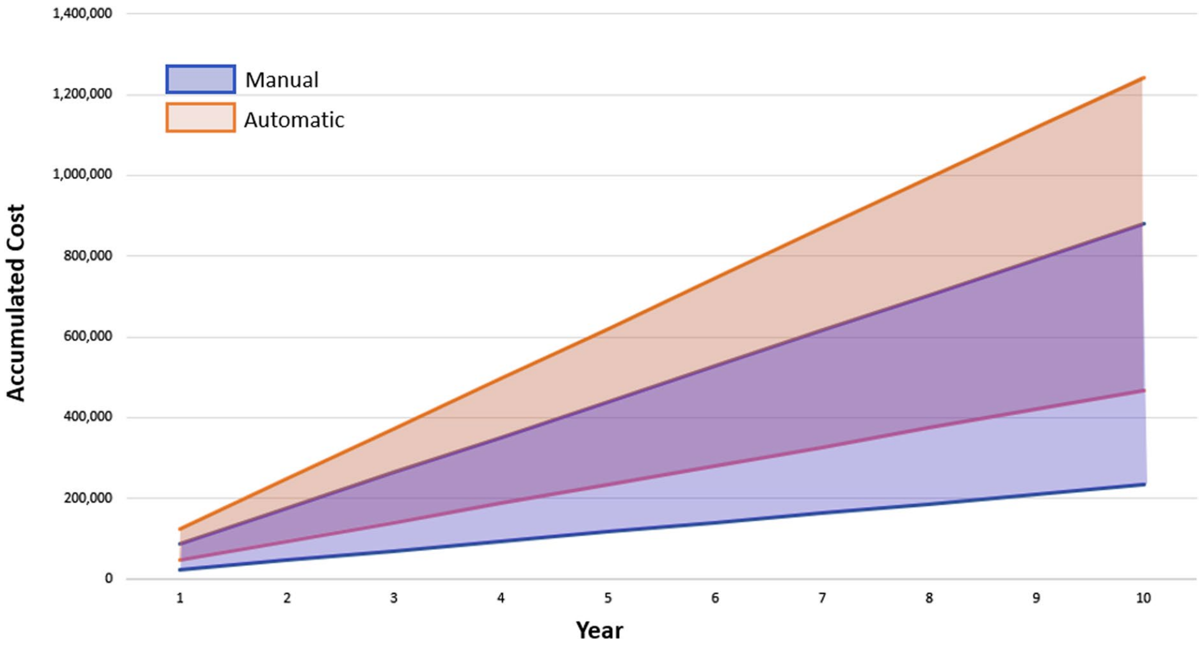

Fig. 2 Estimates of the accumulated costs for running manual and automatic pollen monitoring networks. Costs include annual network running costs, with the range for each case based on labour costs and consumables (where relevant). Initial costs are not included. See the text for full details

impacts that automatic measurements of pollen and fungal spores will have on several important end-user domains.

3.1 Impacts on forecasts

While the number of real-time pollen monitoring stations is still far from sufficient, improvements in forecast quality, similar to those seen in weather forecasts (e.g. Bauer et al., 2015), can be expected (Adamov & Pauling, 2023; Sofiev, 2019). The data from in situ automatic measurements and improved forecasts will provide end-users with information in real time and at a much higher frequency (e.g. with forecasts being generated up to 8 times a day rather than once a day). While methods to adapt numerical models to include real-time pollen data are still in their infancy, the potential for improving such forecasts using automatic measurements has already been shown to be significant (Adamov & Pauling, 2023). The first such system was recently made operational in Switzerland and has shown that real-time pollen measurements considerably improve the timing of the season and reduce the concentration bias (Adamov & Pauling, 2023).

At the European scale, other pollen forecast models exist (Maya-Manzano et al., 2020), including statistical as well as numerical models, of which there are online and offline ones (the latter being models in which the meteorology is taken from the same or another model run separately, i.e. there is no feedback from the pollen module on the meteorology and it is assumed that the offline meteorological data, e.g. at 3h resolution, is sufficient to describe pollen concentrations). Many of these models have not yet been completely adapted to integrate real-time pollen observations but large efforts by the community are expected to lead to such developments in the near future. A procedure for the fusion of observational data with numerical model predictions has been shown to bring up to a factor of 2–3 reduction in error in European-scale ensemble forecasts (Sofiev et al., 2017). These ensemble fusion methods are currently being implemented in Copernicus Atmospheric Monitoring Service (CAMS) for both pollen and air quality forecasts, with the first operational forecasts expected in 2024. Data fusion methods have quite modest requirements in terms of the density of the observational network, and therefore, a significant positive impact can be expected even with just a couple of tens of stations scattered around Europe. Another recent effort to use real-time data to produce 3-hourly forecasts with a statistical model performed well and showed the potential of providing higher temporal resolution information than is currently typically available (Muzalyova et al., 2021). Together with the provision of real-time pollen measurements, such forecasts will significantly improve the information available to end-users in terms of both spatial and temporal coverage.

Besides the study by Adamov and Pauling (2023), no systematic evaluation of the improvement to forecasts has been made. This is, however, a relatively routine exercise for model developers, and a wide range of metrics exist to quantitatively assess such improvements (WMO, 2000). We expect that over the coming years a number of studies will provide more quantitative estimates of forecast improvements. A further aspect that will need to be evaluated is the uptake of such forecasts by end-users, particularly allergy sufferers who may adapt their behaviour or medication intake, although the subsequent impacts are considerably harder to assess quantitatively. This is further discussed in the section on public health impacts below.

3.2 Public health impacts

Historically, many pollen monitoring sites were initially established to provide information to medical doctors diagnosing and treating allergic patients (Buters et al., 2021; de Weger et al., 2013; Hyde, 1972; Mitman, 2004). This situation has not changed much, and the medical community remains one of the main end-user groups that have pushed for increased availability of information and real-time monitoring of both pollen and certain fungal spores (Fuduric et al., 2021). As the number of allergy sufferers continues to increase (Holgate, 1999; Laatikainen et al., 2011; Ronmark et al., 2009), so do the associated direct and indirect health costs, which are estimated to be between €50 and 150 billion per year in Europe (Zuberbier et al., 2014). No studies have yet been carried out to quantitatively estimate the cost changes and improvement to quality of life related to the provision of real-time information about environmental levels of allergenic pollen and fungal spores. However, qualitative evaluations, from the point of view of public stakeholders, suggest that the cost of developing and running a monitoring network would be far outweighed by the potential reduction in health-related costs (Ewert, 2015; Oberpriller et al., 2017).

To provide quantitative estimates of how real-time pollen and fungal spore information affects health costs, epidemiological studies will need to be carried out. While this has never been quantitatively done for manual observations, such studies would provide key information for policy makers. Research needs to focus on various aspects such as whether allergic patients make behavioural changes based on better forecasts which in turn improve their general quality of life, or if there are changes in the use of medication that alleviates allergic symptoms (e.g. corticosteroids), amongst other things. Such investigations will require a multidisciplinary approach with input from researchers, the medical community, and the wider public. Various metrics that are relatively easy to monitor include allergy medication sales, hospitalisation rates, sick days reported during the pollen season (even if there is overlap between early flowering taxa and the typical flu season), or through patient and doctor surveys. Regions where automatic monitoring networks are already established provide the opportunity to carry out such studies.

Routine high temporal resolution data will provide an important impetus to the field of allergology, where the current standards are almost exclusively based on daily-mean concentrations (Pfaar et al., 2016). The data will allow extensive investigations of the complex relationships between symptoms, airborne pollen and fungal spore levels, weather, and air pollution at very high temporal resolution (Smith et al., 2022; Chappuis et al., 2019; Thien et al., 2018; Lake et al., 2017; D'Amato et al., 2010). For example, to study how and what symptoms are presented after short duration periods of high exposure, which are smoothed out and thus not detected in daily average values. Better understanding of exposure will help to improve new therapies (Pfaar et al., 2016). Furthermore, warnings or alert levels that are communicated to end-users will need to be adapted to reflect symptom thresholds at sub-daily scales, particularly since allergic symptoms can appear on such timescales (Damialis et al., 2019; Zuberbier et al., 2017). This will also require high temporal resolution symptom data, although not necessarily hourly data, which can then be studied together with high temporal resolution measurements of pollen and fungal spores. Major efforts will be required to obtain such data from allergy sufferers, perhaps through innovative health apps for mobile devices that encourage users to provide information several times during the day (Kvedariene et al., 2022). An incentive in return for this information is in itself the provision of real-time pollen and fungal spore measurements. The provision of nearly instantaneous information (rather than with a delay of up to 9 days) will help allergy sufferers, together with their health providers, to better understand what they are allergic, keeping in mind the complex nature of individual exposure and time lags in symptoms. Additional research will also need to focus on the spatial representativeness of the high temporal information provided by automatic monitors and how peak pollen hours are comparable in space. Studies with an installation of locally denser automatic networks, combined with numerical modelling and symptom data, will provide a much more in-depth understanding of the complex relationship between exposure and symptoms.

Finally, as the network of automatic pollen and fungal spore monitoring grows across Europe and forecasts provide information at higher resolution, it will be possible to produce warnings for thunderstorm asthma events. Such episodes are known to have large impacts on public health (Thien et al., 2018), and producing improved forecasts could avoid costly impacts on the lives of allergy sufferers. Likewise, it is essential to educate end-users in parallel about the improved information available. A recent study across the Netherlands showed that one quarter of the 2532 respondents thought that real-time data would contribute to better managing their allergy symptoms (Houweling et al., 2021). It is thus crucial to inform the public about how they might be able to better understand what causes their allergies using real-time information and what preventive measures they might take to relieve symptoms using this information combined with improved forecasts.

3.3 Agricultural and sylvicultural impacts

The monitoring of pollen loads from various fruiting crops, such as oak, olives, chestnut, or grapes, has been widely carried out as part of agricultural practices. Such information from the flowering season is used to produce yield forecasts (Cunha et al., 2016; Oteros et al., 2014; Garcia-Mozo et al., 2012), which are then used to organise more efficient harvests and delivery schedules, to support price negotiations, or to develop effective marketing strategies (Cunha et al., 2016). While not strictly necessary to have such data in real time, this possibility will accelerate the forecasting process and, most importantly, the high temporal resolution data will improve the quality of information used to produce the forecasts. In the latter case, the influence of meteorological factors, such as precipitation or wind speed that play an important role in the pollination process, can be used with higher temporal resolution observations (hourly or below) to enhance the accuracy of crop forecasting predictors calculated during the flowering season. Additionally, real-time monitoring will facilitate the development of digital information services and thus better serve end-user needs. Automatic pollen monitoring could also contribute to ensuring quicker responses in managing potentially unwanted gene flow (Yan et al., 2018) and unwanted cross-fertilisation in commercial crops.

Another critical aspect in the agricultural and sylvicultural sectors is plant pathogens, which are known to have massive impacts on many crops and important tree taxa, costing millions of euros in damage or yield losses per year. Many plant pathogens are spread through airborne fungal spores. For example, wheat blotch is estimated to cost up to €240 million/year to UK farmers alone (Fones & Gurr, 2015). Likewise, potato blight causes yield losses of up to €1 billion/year in Europe (Haverkort et al., 2008), while soybean rust causes losses of up to 80% in several regions of the world (Li et al., 2010). Loss is not limited to agricultural crops, with devastating tree losses being caused by airborne fungal pathogens as well (Fisher et al., 2012). One of the most well-known examples is Ash dieback (Fones et al., 2017), which has caused the death of millions of trees across a range of different environments (Fisher et al., 2012). In addition to the economic costs of such losses, further negative impacts are associated with such tree diebacks, including the loss of wood, the potential for carbon sequestration (Kurz et al., 2008), and changes in biodiversity.

The utility of early detection of airborne inoculum from pathogenic fungal spores using aerobiological monitoring has been widely demonstrated (Van der Heyden et al., 2021; Martinez-Bracero et al., 2020). However, the temporal gap between sampling and quantification that is present in manual monitoring has hampered most implementation into the agricultural system (Allen-Sader et al., 2019). The temporal delay means that the disease has likely already spread further. Real-time monitoring that provides high temporal resolution observations will allow important changes in this sector, particularly when combined with integrated forecasting frameworks. This has the potential to contribute significantly to decision analysis and disease risk management in crops (Allen-Sader et al., 2019) and forestry.

Combining real-time high-resolution observations into integrated decision support systems will require further research and collaboration. However, the breakthrough in the information provided can be expected to significantly improve how fungicide sprays are applied, particularly in terms of dose, application frequency, and overall use (Lázaro et al., 2021). This would consequently reduce environmental and human health impacts, economic costs, and the potential for such plant pathogens to develop resistant strains. Similar to the public health costs associated with allergies, even just a small percentage improvement could result in significant savings across the globe. Specific studies at local and regional levels will be required to quantify such impacts properly. Data, for example, regarding the amount of fungicides applied and crop production values, will need to be collected and compared, together with direct feedback from end-user communities.

While such measurements are still in their infancy, two real-time monitoring systems can automatically detect *Alternaria* spores at the genus level (Erb et al., 2023; Gonzalez-Alonso et al., 2022) and further developments allowing the identification of a range of other spores are expected. The potential of real-time technology for the simultaneous detection of multiple airborne pathogenic fungal spores will certainly contribute to the change of the single disease paradigm, aligned with the global strategic plan in plant pathology for a broader quantitative integrated framework to better understand when and how diseases develop (Jeger et al., 2021). As for allergy and asthma, the savings that can be expected from improved monitoring and forecasting systems hugely exceed the relatively small costs associated with developing and maintaining such an integrated system.

4 Research impacts

Interest in pollen and fungal spores has significantly grown over the past years as their importance across a range of research domains has been recognised (Fig. 3) (Ariya & Amyot, 2004; Fröhlich-Nowoisky et al., 2016). The provision of high temporal resolution data is likely to fundamentally change the research that can be carried out in all fields where pollen and fungal spores play key roles. This is particularly the case since such data have never before been available for specific taxa, allowing more in-depth studies on the impacts related to individual species, genera, or families. To date most bioaerosol research has focused on counts of fluorescent particles (e.g. Jaenicke, 2005; Markey et al., 2022) or more generalised presence/absence studies of specific taxa using high-volume sampling and genetic techniques (Brennan et al., 2019). Further questions include better understanding the spatial representativeness of high temporal resolution data and how peak pollen periods are comparable in space. While the data may not always be needed in real time, the availability of high temporal resolution observations of a range of pollen and fungal spore taxa will provide a huge impetus to scientific research possible across several fields.

A critical aspect for ensuring more research using automatic observations will be to make these data publicly available (i.e. open access). The scientific community in general is moving in this direction, and EU directives are pushing to make environmental data available, particularly for scientific purposes (Open Science), following the FAIR principles (Findable Accessible Interoperable Reusable). Relatively easy metrics exist to assess both the availability of data as well as the number of publications made using them. These should be tracked over time to ensure data are effectively used and the impact on the resultant number of research articles quantified. A final point to note is that as more and more measurements become automatic, researchers who would traditionally dedicate much of their time to counting pollen will be able to devote more of their time and expertise to carrying out aerobiological research, potentially leading to even more publications in the field.

4.1 Climate change and phenology studies

Beyond the more well-known impacts of allergenic and pathogenic pollen and fungal spores on public health and agriculture, they also play a key role in the climate system, particularly affecting cloud formation, radiative balance, and the hydrological cycle (Hoose et al., 2010; Zhang et al., 2021). Initially, it was suggested that only bacteria were able to influence the radiative balance and hydrological cycle, but recent investigations suggest that pollen and fungal spores also contribute to this important set of processes (Hassett et al., 2015; Steiner et al., 2015). With automatic monitors, it is now possible to quantify the airborne concentrations of a number of pollen

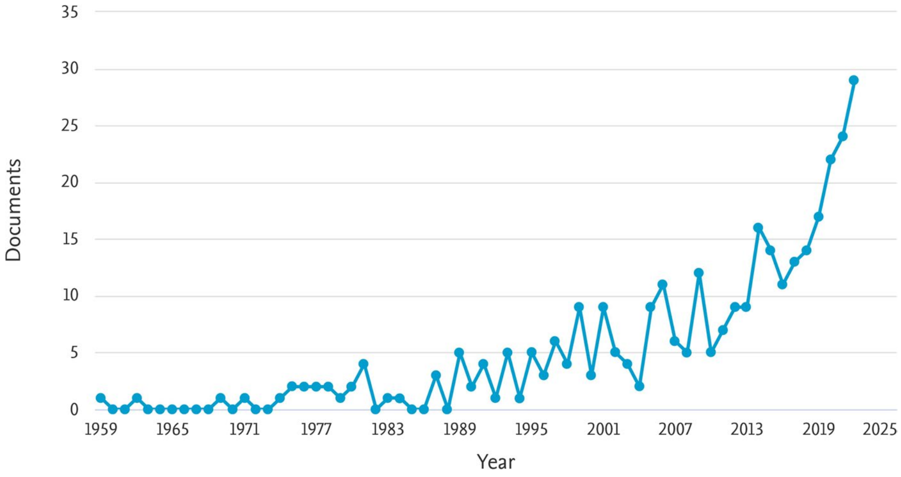

Fig. 3 Bibliometric search results extracted from the SCOPUS database for the terms “pollen” and “automat*” with the number of articles published in the scientific literature per year

and fungal spore taxa, and these observations can be used to better understand their role in the atmosphere and on climate change. Furthermore, changes in their distributions can be used to research the impacts of changing climate on biodiversity, ecosystems, and human health more generally (Norris, 2008; Rojo et al., 2021).

Phenological monitoring can be carried out using indirect methods based on airborne pollen sampling during pollination periods, which can be assimilated to identify the beginning and length of this key phenological phase for anemophilous plants (Orlandi et al., 2013; Rojo et al., 2021). To study the impact of climate change on plant phenology, the several decades-long pollen time series from several manual monitoring sites are of great value (Gehrig & Clot, 2021; Glick et al., 2021; López-Orozco et al., 2021; de Weger et al., 2021; Cebrino et al., 2016). For example, some studies have shown that certain spring-flowering taxa flower again in autumn because of extreme weather events (García-Mozo et al., 2022). Other research has focused on the taxa that contribute most to pollen concentrations, especially grasses (López-Orozco et al., 2021; Romero-Morte et al., 2018; Ghitarrini et al., 2017).

An important goal in the transition to automatic measurements will be the homogenisation of long time series, i.e. developing statistical procedures to combine manual and automatic data to create a continuous dataset. In this way, information about the long-term changes in pollen concentrations is retained, without endangering the scientific relevance of the long-term data. To achieve this, several years of parallel measurements are required. These automatic stations could, however, serve multiple purposes and thus also provide real-time phenological data as part of other monitoring networks, for example, the PEP725 project or the US National Phenological Network. To assess impacts, similar metrics focused on specific research branches can be quantified to better understand how high temporal resolution data about pollen and fungal spores are being used in different fields.

4.2 Urban planning impacts

Many manual aerobiological sampling sites have been placed in urban environments since pollen emissions from vegetation in urban green areas were identified as the main cause of adverse health effects on local populations (Cariñanos & Casares-Porcel, 2011). This has made it possible to characterise the main sources of allergenic pollen emission in cities and to understand which urban species have the greatest impact on health. Nevertheless, this is not true for all urban regions and reliable data about the allergenicity of pollen in polluted urban regions are still lacking (Sousa-Silva et al., 2021). The availability of automatic instruments, and particularly the nonlinear relationship between running costs and number of instruments, means that it is now possible to install a much larger number of sites. This would allow more in-depth studies of allergen exposure in urban areas or even how the pollen taxa composition and distributions change as new species are introduced in the urban environment (Cristofori et al., 2020; Sousa-Silva et al., 2021).

Cities will also face new challenges in the coming decades as populations continue to grow and as urban environments need to become greener to strengthen their resilience to the impacts of climate change. Green infrastructure provides a range of ecosystem services that benefit the well-being of urban populations but at the same time pollen emissions can be detrimental to public health. Real-time monitoring generates information that can be used to issue warnings and to adopt short-term mitigation measures that would minimise the negative impacts of pollen in urban areas. This links directly to public health, and similar epidemiological studies will need to be carried out to better understand the impact of such automatic monitoring and warning systems specifically in urban areas.

4.3 Biodiversity and ecosystem monitoring

Biodiversity studies benefit from pollen monitoring (Rojo et al., 2021). For example, the status of biodiversity conservation is typically established through monitoring programmes with standardised data collection systems that consider demographic, reproductive, and distribution parameters of different habitats and species (Elzinga et al., 2001). In this sense, automatic devices will greatly facilitate monitoring parameters of flowering plant species. The presence of automatic sampling stations in biodiversity hotspots areas such as Protected Areas or Special Conservation Areas will contribute systematically and over time, to monitor the conservation status of species and their habitats, provided appropriate identification software have been developed. Previously, this would not have been possible with manual devices that require frequent (mostly weekly) human intervention.

Pollen provides a measurable and quantifiable indicator of plant flowering, but also of the presence of new or invasive species in a territory, the latter of which is of significant value for ecosystem monitoring. Automatic sampling devices can be trained to identify new pollen taxa that may be suspected of being present in a particular region. This opens the possibility of continuous biodiversity monitoring, particularly in terms of detecting invasive species (Sauliene et al., 2021), since the high temporal resolution data together with meteorological parameters will provide a more accurate understanding of transport processes and allow the identification of the invasive plant populations that act as emission sources. Such information would improve early management practices to control further spread of invasive plants (Sommer et al., 2015). Similarly, automatic measurements of threatened species in vulnerable habitats will allow more accurate monitoring of the effectiveness of proposed recovery measures (Dbouk et al., 2022; Hornick et al., 2021; Wägele et al., 2022).

4.4 Food storage and indoor air monitoring

A set of WHO guidelines (WHO, 2010) have been established for the monitoring of gaseous and particulate pollution of indoor air, with specific recommendations for pollen and fungal spore in the context of public health and food storage. Automation of pollen and fungal spore monitoring thus also brings new opportunities for routine indoor air quality monitoring. While most instruments have so far not been used for such purposes, they could, in future be adapted to monitor various indoor environments continuously, for example, in food storage facilities, hospitals, schools, kindergartens (Sauliene et al., 2023), and renovated buildings.

The possibility to have real-time alarms for certain dangerous particles would help to reduce risks associated with crop storage, or, for example, microbiological food contamination (Avery et al., 2019). This could reduce related costs (Fisher et al., 2018). Finally, indoor air monitoring could be used to issue warnings in buildings which are either inappropriately built or renovated. Cheap construction materials, ill-repair, water damage or inappropriate usage can result in moisture accumulation with resultant development of fungal colonies. The ability to warn occupants of the airborne levels of these particles may help to reduce adverse health outcomes (Li & Yang, 2004).

5 Conclusions

Airborne monitoring of pollen and fungal spores has conventionally been carried out using manual methods but automatic measurements that provide real-time observations at high temporal resolution are becoming a reality. Although the initial costs for these instruments are currently higher than manual ones, the running costs are expected to be lower over the long term, in part because of the reduced personnel requirements, which also means that costs no longer scale linearly with the number of sites. Furthermore, because less frequent human intervention is required, instruments can be placed in remote locations where previously this was not possible. As the technology further develops, it is possible that costs will decrease further, particularly since there is more competition in the market of automatic instruments than for manual ones. In this paper, we provide estimates of the running costs for a small network to provide indicative values for the comparison between automatic and manual versions.

Quantifying the impacts of automatic pollen and fungal spore monitoring across the many end-user domains is, at present, more challenging. Automatic measurement networks have not been in place for a sufficient amount of time and, in many regions, are not yet even in place. We thus provide more qualitative indications of where impacts are expected and various methods for their quantitative assessment. While it is difficult at this point to provide quantifiable estimates of the wide range of impacts, it will be important that studies are carried out to do so. Several European research projects that are underway are expected to contribute significantly to this outcome in the coming years. To ensure as much impact as possible, it will be essential that data are made open and freely available, including historical observations which are needed for comparison and to ensure long data series.

Finally, to fully exploit the potential of real-time monitoring technologies they will also need to be further developed, for example, to monitor other airborne particles, such as large dust particles, sub-pollen particles, or a wider range of fungal spores. In addition, the establishment of standards and certification processes for these instruments will open the door to potentially making pollen and fungal spore monitoring a legal requirement across Europe, as is the case for many other air quality parameters. This will greatly facilitate the wider uptake of these technologies and enhance the potential benefits across all end-user domains.

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Declarations

Conflict of interest Fiona Tummon and Bernard Clot are guest editors for the Special Issue "Towards an European Automatic Pollen Monitoring Network-EUMETNET AutoPollen Programme". Regula Gehrig, Athanasios Damialis, F. Javier Rodríguez-Rajo, and Helena Ribeiro are associate editors, and Carmen Galán is the editor-in-chief of this journal. Délia Fernández González, Mikhail Sofiev, and Olga Sozinova are members of the journal editorial board. This article was independently handled by another member of the editorial board.

References

Adamov, S., Lemonis, N., Clot, B., Crouzy, B., Gehrig, R., Graber, M. J., Sallin, C., & Tummon, F. (2021). On the measurement uncertainty of Hirst-type volumetric pollen and spore samplers. *Aerobiologia*. https://doi.org/10.1007/s10453-021-09724-5

Adamov, S. and Pauling, A. (2023). A real-time calibration method for the numerical pollen forecast model COSMO-ART. *Aerobiologia,* in press.

Allen-Sader, C., Thurston, W., Meyer, M., Nure, E., Bacha, N., Alemyehu, Y., Stutt, R. O. J. H., Safka, D., Craig, A. P., Derso, E., Burgin, L. E., Millington, S. C., Hort, M. C., Hodson, D. P., & Gilligan, C. A. (2019). An early warning system to predict and mitigate wheat rust diseases in Ethiopia. *Environmental Research Letters, 14*, 115004.

Ariya, P. A., & Amyot, M. (2004). New Directions: The role of bioaerosols in atmospheric chemistry and physics. *Atmospheric Environment, 38*, 1231–1232.

Avery, S. V., Singleton, I., Magan, N., & Goldman, G. H. (2019). The fungal threat to global food security. *Fungal Biology, 123*, 555–557.

Bauer, P., Thorpe, A., & Brunet, G. (2015). The quiet revolution of numerical weather prediction. *Nature, 525*, 47–55.

Bonton, P., Boucher, A., Thonnat, M., Tomczak, R., Hidalgo, P. J., Belmonte, J., & Galán, C. (2001). Colour image in 2D and 3D microscopy for the automation of pollen rate measurement. *Image Analysis and Stereology, 1*, 332–527.

Boucher, A., Hidalgo, P. J., Thonnat, M., Belmonte, J., Galan, C., Bonton, P., & Tomczak, R. (2002). Development of a semi-automatic system for pollen recognition. *Aerobiologia, 18*, 195–201.

Brennan, G.L., Potter, C., de Vere, N., Griffith, G.W., Skjoth, C.A., Osborne, N.J., Wheeler, B.W., McInnes, R.N., Clewlow, Y., Barber, A., Hanlon, H.M., Hegarty, M., Jones, L., Kurganskiy, A., Rowney, F.M., Armitage, C., Adams.Groom, B., Ford, C.R., Petch, G.M., the PollerGEN Consortium, and Creer, S. (2019). Temperate airborne grass pollen defined by spatio-temporal shifts in community composition. *Nature Ecology and Evolution,* 3, 750-754

Buters, J. T. M., Antunes, C., Galveias, A., Bergmann, K. C., Thibaudon, M., Galán, C., Schmidt-Weber, C., & Oteros, J. (2018). Pollen and spore monitoring in the world. *Clinical Translational Allergy, 4*(8), 9.

Buters, J., Gonzalez-Alonso, M., Klimek, L., Simon, J., & Treudler, R. (2021). Automatic Pollen Monitoring. *Allergology, 44*, 932–942.

Buters, J., Clot, B., Galán, C., Gehrig, R., Gilge, S., Hentges, F., O'Connor, D., Sikoparija, B., Skjoth, C., Tummon, F., Adams-Groom, B., Antunes, C. M., Bruffaerts, N., Celenk, S., Crouzy, B., Guillaud, G., Hajkova, L., Kofel Seliger, A., Oliver, G., … Stjepanovic, B. (2022). Automatic detection of airborne pollen: An overview. *Aerobiologia*. https://doi.org/10.1007/s10453-022-09750-x

Cariñanos, P., & Casares-Porcel, M. (2011). Urban green zones and related pollen allergy: A review. Some guidelines for designing space with low allergy impacts. *Landscape and Urban Planning, 101*, 205–214.

Cebrino, J., Galan, C., & Dominguez-Vilches, E. (2016). Aerobiologial and phenological study of the main Poaceae species in Cordoba city (Spain) and the surrounding hills. *Aerobiologia, 32*, 595–606.

Chappuis, C. M., Tummon, F., Clot, B., Konzelmann, T., Calpini, B., & Crouzy, B. (2019). Automatic pollen monitoring: First insights from hourly data. *Aerobiologia, 36*, 159–170.

Clot, B., Gilge, S., Hajkova, L., Magyar, D., Scheifinger, H., Sofiev, M., Bütler, F., and Tummon, F., (2020). The EUMETNET AutoPollen programme: establishing a prototype automatic pollen monitoring network in Europe. *Aerobiologia*, 1–9.

Cristofori, A., Bucher, E., Rossi, M., Cristofolini, F., Kofler, V., Prosser, F., & Gottardini, E. (2020). The late flowering of invasive species contributes to the increase of *Artemisia* allergenic pollen in autumn: An analysis of 25 years of aerobiological data (1995–2019) in Trentino-Alto Adige (Northern Italy). *Aerobiologia, 36*, 669–682.

Crouzy, B., Lieberherr, G., Tummon, F., & Clot, B. (2022). False positives: Handling them operationally for automatic pollen monitoring. *Aerobiologia, 38*, 429–432.

Cunha, M., Ribeiro, H., & Abreu, I. (2016). Pollen-based predictive modelling of wine production: Application to an arid region. *European Journal of Agronomy, 73*, 42–54.

D'Amato, G., et al. (2010). Urban air pollution and climate change as environmental risk factors of respiratory allergy: an update. *Journal of Investigational Allergology and Clinical Immunology*, *20*(2), 95–102.

Damialis, A., Häring, F., Gökkaya, G., Rauer, D., Reiger, M., Bezold, S., Bounas-Pyrros, N., Eyeich, K., Todorova, A., Hammel, G., Gilles, S., & Traidl-Hoffman, C. (2019). Human exposure to airborne pollen and relationships with symptoms and immune responses: Indoors versus outdoors, circadian patterns and meteorological effects in alpine and urban environments. *Science of the Total Environment, 653*, 190–199.

Dbouk, T., Visez, N., Ali, S., Shahrour, I., & Drikakis, D. (2022). Risk assessment of pollen allergy in urban environments. *Scientific Reports, 12*, 21076.

de Weger, L. A., Bergmann, K. C., Rantio-Lehtimäki, A., Dahl, A., Buters, J., Déchamp, C., & Belmonte, J. (2013). Impact of pollen. *Allergenic Pollen* (pp. 161–215). Springer.

Elzinga C.L., Salzer D., Willoughby J.W., and Gibbs J.P. (2001). Monitoring Plant and Animal Populations. Ed Wiley-Blackwell.

Emberlin, J., Savage, M., & Jones, S. (1993). Annual variations in grass pollen seasons in London 1961–1990: Trends and forecast models. *Clinical Experimental Allergy, 23*, 911–918.

EN16868:2019. Ambient air - Sampling and analysis of airborne pollen grains and fungal spores for networks related to allergy—Volumetric Hirst method, European Standard.

Erb, S., Berne, A., Burgdorfer, N., Clot, B., Graber, M. J., Lieberherr, G., Sallin, C., Tummon, F., & Crouzy, B. (2023). Automatic real-time monitoring of fungal spores: The case of *Alternaria spp*. *Aerobiologia*. https://doi.org/10.1007/s10453-023-09780-z

Ewert, T. (2015). Gesundheitsökonomische und arbeitsökonomische Kosten der Pollenallergie in Bayern. *Bayerisches Landesamt für Gesundheit und Lebensmittelsicherheit.* Aktenzeichen GE6-2495-06-V63-D23788/2015.

Fisher, M. C., Henk, D. A., Briggs, C. J., Brownstein, J. S., Madoff, L. C., McCraw, S. L., & Gurr, S. J. (2012). Emerging fungal threats to animal, plant, and ecosystem health. *Nature, 484*, 186–194.

Fisher, M. C., Hawkins, N. J., Sanglard, D., & Gurr, S. J. (2018). Worldwide emergence of resistance to antifungal drugs challenges human health and food security. *Science, 360*, 739–742.

Fones, H., & Gurr, S. (2015). The impact of Septoria tritici blotch disease on wheat: An EU perspective. *Fungal Genetics and Biology, 79*, 3–7.

Fones, H. N., Fisher, M. C., & Gurr, S. J. (2017). Emerging fungal threats to plants and animals challenge agriculture and ecosystem resilience. *Microbiological Species*. https://doi.org/10.1128/microbiolspec.FUNK-0027-2016

Fröhlich-Nowoisky, J., Kampf, C. J., Weber, B., Huffman, J. A., Pöhlker, C., Andreae, M. O., Lang-Yona, N., Burrows, S. M., Gunthe, S. S., Elbert, W., Su, H., Hoor, P., Thines, E., Hoffmann, T., Després, V. R., & Pöschl, U. (2016). Bioaerosols in the Earth system: Climate, health, and ecosystem interactions. *Atmospheric Research, 182*, 346–376.

Fuduric, N., Kraft, C., and Sterchi, M. (2021). CHAPo pollen needs analysis. Report by the University of Applied Sciences Northwest Switzerland (FHNW), Olten, Switzerland, pp. 60.

Galán, C., Smith, M., Damialis, A., Frenguelli, G., Gehrig, R., Grinn-gofron, A, Kasprzyk, I, Magyar, D., Oteros, J., Sauliene, I., thibaudon, M., Sikoparija, B., and the EAS QC Working Group. (2021). Airborne fungal spore monitoring: Between analyst proficiency testing. *Aerobiologia,* 37, 351–361.

Galán, C., Smith, M., Thibaudon, M. Frenguelli, G., Oteros, J., Gehrig,R., Berger, U., Clot, B., Brandao, R., and the EAS QC Working Group. (2014). Pollen monitoring: Minimum requirements and reproducibility of analysis. *Aerobiologia,* 30, 385–395.

García-Mozo, H., Dominguez-Vilches, E., & Galán, C. (2012). A model to account for variations in holm-oak (*Quercus* *ilex* subsp. *ballota*) acorn production in southern Spain. *Annals of Agricultural and Environmental Medicine, 19*, 403–408.

García-Mozo, H., López-Orozco, R., Oteros, J., & Galán, C. (2022). Factors driving autumn *Quercus* flowering in a thermo-Mediterranean area. *Agronomy, 12*, 2596.

Gehrig, R., & Clot, B. (2021). 50 years of pollen monitoring in Basel (Switzerland) demonstrate the influence of climate change on airborne pollen. *Front. Allergy, 2*, 677159.

Ghitarrini, S., Galan, C., Frenguelli, G., & Tedeschini, E. (2017). Phenological analysis of grasses (Poaceae) as a support for the dissection of their pollen season in Perugia (Central Italy). *Aerobiologia, 33*, 339–349.

Glick, S., Gehrig, R., & Eeftens, M. (2021). Multi-decade changes in pollen season onset, duration, and intensity: A concern for public health? *Science of the Total Environment, 781*, 146382.

Gonzalez-Alonso, M., Boldeanu, M., Koritnik, T., Gonçalves, J., Belzner, L., Stemmler, T., Gebauer, R., Grewling, L., Tummon, F., Maya-Manzano, J. M., Arino, A. H., Schmidt-Weber, C., & Buters, J. (2022). Alternaria spore exposure in Bavaria, Germany, measured using artificial intelligence agorithms in a network of BAA500 automatic pollen monitors. *Science of the Total Environment, 861*, 160180.

Hassett, M. O., Fischer, M. W., & Money, N. P. (2015). Mushrooms as Rainmakers: How Spores Act as Nuclei for Raindrops. *PLoS ONE, 28*, e0140407.

Haverkort, A. J., Boonekamp, P. M., Hutten, R., Jacobsen, E., Lotz, L. A. P., Kessel, G. J. T., Visser, R. G. F., & van der Vossen, E. A. G. (2008). Societal costs of late blight in potato and prospects of durable resistance through cisgenic modification. *Potato Research, 51*, 47–57.

Hirst, J. M. (1952). An automatic volumetric spore trap. *Annals of Applied Biology, 39*, 257–265.

Holgate, S. T. (1999). The epidemic of allergy and asthma. *Nature, 402*, B2–B4.

Hoose, C., Kristjánsson, J. E., & Burrows, S. M. (2010). How important is biological ice nucleation in clouds on a global scale? *Environmental Research Letters, 5*, 024009.

Hornick, T., Richter, A., Harpole, W.S., Bastl, M., Bohlmann, S., Bonn, A., Bumberger, J., Dietrich, P., Gemeinholzer, B., Grote, R., Heinold, B., Keller, A., Luttkus, M.L., Mäder., P., Svara, E.M. Passoneau, S., Punyasena, S.W., Rakosy, D., Richter, R., Sickel, W., Steffan-Dewenter, I., Theodorou, P., Treudler, R., Werchan, B., Werchan, M., Wolke., R., and Dunker, S. (2021). An integrative environmental pollen diversity assessment and its importance for the sustainable development goals. *Plants People Planet*, 4, 110-121

Houweling D, van der Helm, J., Versteeg-de Jong, A., Wesseling, J. Boomsma, and C. van Wijk, S. (2021). Advies over nut en noodzaak van een pollenmeetnetwerk. www.rivm.nl/bibliotheek/rapporten/2021-0221.pdf (Retrieved 9 November 2021, in Dutch)

Hyde, H. A. (1959). Volumetric counts of pollen grains at Cardiff, 1954–1957. *Journal of Allergy, 30*, 219–234.

Hyde, H. A. (1972). Atmospheric pollen and spores in relation to allergy. *Clinical Allergy, 2*, 153–179.

Jaenicke R. (2005). Abundance of cellular material and proteins in the atmosphere. *Science*, 308(5718).

Jeger, M., Beresford, R., Bock, C., Brown, N., Fox, A., Newton, A., Vicent, A., Xu, X., & Yuen, J. (2021). Global challenges facing plant pathology: multidisciplinary approaches to meet the food security and environmental challenges in the mid-twenty-first century. *CABI Agriculture and Bioscience, 2*, 20.

Kawashima, S., Thibaudon, M., Matsuda, S., Fujita, T., Lemonis, N., Clot, B., & Oliver, G. (2017). Automated pollen monitoring system using laser optics for observing seasonal changes in the concentration of total airborne pollen. *Aerobiologia, 33*, 351–362. https://doi.org/10.1007/s10453-017-9474-6

Kurz, W. A., Dymond, C. C., Stinson, G., Rampley, G. J., Neilson Caroll, A. L., Ebata, T., & Safranyik, L. (2008). Mountain ine beetle and forest carbon feedback to climate change. *Nature, 452*, 98–990.

Kvedariene, V., Biliute, G., Didziokaitė, G., Kavaliukaite, L., Savonyte, A., Rudzikaite-Fergize, G., & Puronaite, R. (2022). Mobile health app for monitoring allergic rhinitis and asthma in real life in Lithuanian MASK-air users. *Clinical and Translational Allergy, 12*, e12192.

Laatikainen, T., von Hertzen, L., Koskinen, J.-P., et al. (2011). Allergy gap between Finnish and Russian Karelia on increase. *Allergy, 66*, 886–892.

Lake, et al. (2017). https://ehp.niehs.nih.gov/doi/10.1289/EHP173

Landsmeer, S. H., Hendriks, E. A., de Weger, L. A., Reiber, J. C., & Stoel, B. C. (2009). Detection of pollen grains in multifocal optical microscopy images of air samples. *Microscopy Research and Technique, 72*, 424–430.

Lázaro, E., Makowski, D., & Vicent, A. (2021). Decision support systems halve fungicide use compared to calendar-based strategies without increasing disease risk. *Communications Earth and Environment, 2*, 224.

Li, D., & Yang, C. S. (2004). Fungal contamination as a major contributor to sick building syndrome. *Advances in Applied Microbiology, 55*, 31–112.

Li, X., Esker, P. D., Pan, Z., Dias, A. P., Xue, L., & Yang, X. B. (2010). The uniqueness of the soybean rust pathosystem: An improved understanding of the risk in different regions of the world. *Plant Disease, 94*, 796–806.

GLieberherrKAudersetBCalpiniBClotBCrouzyMGysel-BeerTKonzelmannJManzanoAMihajlovicAMoallemiDO'ConnorBSikoparijaESauvageatFTummonKVasilatou2021Assessment of real-time bioaerosol particle counters using reference chamber experimentsAtmospheric Measurement Techniques10.5194/amt-2021-136Lieberherr, G., Auderset, K., Calpini, B., Clot, B., Crouzy, B., Gysel-Beer, M., Konzelmann, T., Manzano, J., Mihajlovic, A., Moallemi, A., O'Connor, D., Sikoparija, B., Sauvageat, E., Tummon, F., & Vasilatou, K. (2021). Assessment of real-time bioaerosol particle counters using reference chamber experiments. Atmospheric Measurement Techniques. https://doi.org/10.5194/amt-2021-136

Lopez-Orozco, R., Garcia-Mozo, H., Oteros, J., & Galan, C. (2021). Long-term trends in atmospheric *Quercus* pollen related to climate change in southern Spain: A 25-year perspective. *Atmospheric Environment, 262*, 118637.

Markey, E., Clancy, J. H., Martínez-Bracero, M., Neeson, F., Sarda-Estève, R., Baisnée, D., McGillicuddy, E. J., Sewell, G., & OConnor, D. J. (2022). A modified spectroscopic approach for the real-time detection of pollen and fungal spores at a semi-urban site using the WIBS-4+. *Part I. Sensors, 22*(22), 8747. https://doi.org/10.3390/s22228747

Maya-Manzano, J., Smith, M., Markey, E., Clancy, J. H., Sodeau, J., & O'Connor, D. J. (2020). Recent developments in monitoring and modelling airborne pollen: A review. *Grana*. https://doi.org/10.1080/00173134.2020.1769176

Maya-Manzano, J., Tummon, F., Abt, R., Allan, N., Bunderson, L., Clot, B., Crouzy, B., Daunys, G., Erb, S., Gonzalez-Alonso, M., Graf, E., Grewling, L., Haus, J., Kadantsev, E., Kawashima, S., Martinez-Bracero, M., Matavulj, P., Mills, S., Niederberger, E., … Buters, J. (2023). Towards European automatic bioaerosol monitoring: Comparison of 9 automatic pollen observational instruments with classic Hirst-type traps. *Science of the Total Environment, 866*, 161220.

Mitman, G. (2004). A history of pollen mapping and surveillance: The relations between natural history and clinical allergy. *The Allergy Archives, 114*, 1230–1235.

Muzalyova, A., Brunner, J. O., Tradil-Hoffman, C., & Damialis, A. (2021). Forecasting *Betula* and Poaceae airborne pollen concentrations on a 3-hourly resolution in Augsburg, Germany: toward automatically generated, real-time predictions. *Aerobiologia, 37*, 425–446.

Norris, K. (2008). Agriculture and biodiversity conservation: Opportunity knocks. *Conservation Letters, 1*, 2–11.

Núñez, A., Amo de Paz, G., Ferencova, Z., Rastrojo, A., Guantes, R., García, A. M., Alcamí, A., Gutiérrez-Bustillo, M., & Moreno, D. A. (2017). Validation of the Hirst-type spore trap for simultaneous monitoring of prokaryotic and 2 eukaryotic biodiversity in urban air samples. *Applied and Environmental Microbiology*. https://doi.org/10.1128/AEM.00472-17

O'Connor, D. J., Healy, D. A., Hellebust, S., Buters, J. T. M., & Sodeau, J. R. (2014). Using the WIBS-4 (Waveband Integrated Bioaerosol Sensor) Technique for the on-line detection of pollen grains. *Aerosol Science and Technology, 48*, 341–349.

Oberpriller, Q., Vettori, A., and Iten, R. (2017). Nutzen Real-Time Pollendaten. Infras und Bundesamt für Meteorologie und Klimatologie MeteoSchweiz. www.infras.ch/media/filer_public/b4/68/b468a9a4-8ce6-4b2d-9492-b72979e9d38c/b3092_nutzen_real_time_pollendaten_171221_v2.pdf . Retrieved on 19 October 2022.

Orlandi, F., García-Mozo, H., Ben Dhiab, A., Galan, C., Msallem, M., Romano, B., Abichou, M., Domínguez-Vilches, E., & Fornaciari, M. (2013). Climatic indices in the interpretation of the phenological phases of the olive in mediterranean areas during its biological cycle. *Climatic Change, 116*, 263–284.

Oteros, J., Orlandi, F., García-Mozo, H., Aguilera, F., & Dhiab, A. (2014). Better prediction of Mediterranean olive production using pollen-based models. *Agronomy for Sustainable Development, 34*, 685–694.

Oteros, J., Weber, A., Kutzora, S., Rojo, J., Heinze, S., Herr, C., Gebauer, R., Schmidt-Weber, C. B., & Buters, J. T. M. (2020). An operational robotic pollen monitoring network based on automatic image recognition. *Environmental Research, 191*, 110031. https://doi.org/10.1016/j.envres.2020.110031

Pfaar, O., Bastl, K., Berger, U., Buters, J., Calderon, M. A., Clot, B., Darsow, U., Demoly, P., Durham, S. R., Galán, C., Gehrig, R., Gerth van Wijk, R., Jacobsen, L., Klimek, L., Sofiev, M., Thibaudon, M., & Bergmann, K. C. (2016). Defining pollen exposure times for clinical trials of allergen immunotherapy for pollen-induced rhinoconjunctivitis—An EAACI Position Paper. *Allergy*. https://doi.org/10.1111/all.13092

Ranzato, M., Taylor, P., House, J., Flagan, R., LeCun, Y., & Perona, P. (2007). Automatic recognition of biological particles in microscopic images. *Pattern Recognition Letters, 28*, 31–39.

Rojo, J., Núñez, A., Lara, B., Sánchez Parra, B., Moreno, D. A., & Pérez-Badía, R. (2019). Comprehensive analysis of different adhesives in aerobiological sampling using optical microscopy and high-throughput DNA sequencing. *Journal of Environmental Management, 240*, 441–450.

Rojo, J., Fernández-González, F., Lara, B., Bouso, V., Crespo, G., Hernández-Palacios, G., Rodríguez-Rojo, M. P., Rodríguez-Torres, A., Smith, M., & Pérez-Badia, R. (2021). The effects of climate change on the flowering phenology of alder trees in southwestern Europe. *Mediterranean Botany, 42*, e67360.

Romero-Morte, J., Rojo, J., Rivero, R., Fernandez-Gonzalez, F., & Pérez-Badia, R. (2018). Standardised index for measuring atmospheric grass-pollen emission. *Science of the Total Environment, 612*, 180–191.

Ronmark, E., Bjerg, A., Perzanowski, M., Platts-Mills, T., & Lundback, B. (2009). Major increase in allergic sensitization in schoolchildren from 1996 to 2006 in northern Sweden. *Mechanisms of Allergy and Clinical Immunology, 124*, 357–363.

Sauliene, I., Sukienė, L., Daunys, G., Valiulis, G., Vaitkevicius, L., Matavulj, P., Brdar, S., Panic, M., Sikoparija, B., Clot, B., Crouzy, B., & Sofiev, M. (2019). Automatic pollen recognition with the Rapid-E particle counter: The first-level procedure, experience and next steps. *Atmospheric Measurement Techniques, 12*, 3435–3452.

Sauliene, I., Sukiene, L., Daunys, G., Valiulis, G., & Vaitkevicius, L. (2021). Automatic particle detectors lead to a new generation in plant diversity investigation. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca, 49*(3), 1–12.

Sauliene, I., Valiulis, A., Keriene, I., Sukiene, L., Dovydaityte, D., Prokopciuk, N., Valskys, V., Valskiene, R., & Damialis, A. (2023). Airborne pollen and fungi indoors: Evidence from primary schools in Lithuania. *Heliyon*. https://doi.org/10.1016/j.heliyon.2022.e12668

Sauvageat, E., Zeder, Y., Auderset, K., Calpini, B., Clot, B., Crouzy, B., et al. (2020). Real-time pollen monitoring using digital holography. *Atmospheric Measurement Techniques, 13*, 1539–1550.

Smith, M., Matavulj, P., Mimic, G., Panic, M., Grewling, L., & Sikoparija, B. (2022). Why should we care about high temporal resolution monitoring of bioaerosols in ambient air? *Science of the Total Environment, 826*, 154231. https://doi.org/10.1016/j.scitotenv.2022.154231

Sofiev, M. (2019). On possibilities of assimilation of near-real-time pollen data by atmospheric composition models. *Aerobiologia, 35*, 523–531.

Sofiev, M., Ritenberga, O., Albertini, R., Arteta, J., Belmonte, J., Bonini, M., Celenk, S., Damialis, A., Douros, J., Elbern, H., Friese, E., Galan, C., Gilles, O., Hrga, I., Kouznetsov, R., Krajsek, K., Plu, M., Prank, M., Robertson, L., … Vokou, D. (2017). Multi-model ensemble simulations of olive pollen distribution in Europe in 2014. *Atmospheric Chemistry and Physics, 17*, 12341–12360.

Sofiev, M., Sofieva, S., Palamarchuk, J., Šaulienė, I., Kadantsev, E., Atanasova, N., Fatahi, Y., Kouznetsov, R., Kuula, J., Noreikaite, A., Peltonen, M., Pihlajamäki, T., Saarto, A., Svirskaite, J., Toiviainen, L., Tyuryakov, S., Šukienė, L., Asmi, E., Bamford, D., … Karppinen, A. (2022). Bioaerosols in the atmosphere at two sites in Northern Europe in spring 2021: Outline of an experimental campaign. *Environmental Research, 214*, 113798.

Sommer, J., Smith, M., Sikoparija, B., Kasprzyk, I., Myszkowska, D., Grewling, L., & Skjoth, C. A. (2015). *Annals of Agricultural and Environmental Medicine, 22*, 625–631.

Sousa-Silva, R., Smargiassi, A., Kneeshaw, D., Dupras, J., Zinszer, K., & Paquette, A. (2021). Strong variations in urban allergenicity riskscapes due to poor knowledge of tree pollen allergenic potential. *Scientific Reports, 11*, 10196.

Steiner, A. L., Brooks, S. D., Deng, C., Thornton, D. C. O., Pendleton, M. W., & Bryant, V. (2015). Pollen as atmospheric cloud condensation nuclei. *Geophysical Research Letters, 42*, 3596–3602.

Tesendic, D., Boberic Krsticev, D., Matavlulj, P., Brdar, S., Panic, M., Minic, V., & Sikoparija, B. (2020). RealForAll: Real-time System for Automatic Detection of Airborne Pollen. *Enterprise Information Systems*. https://doi.org/10.1080/17517575.2020.1793391

Thien, et al. (2018). https://www.sciencedirect.com/science/article/pii/S2542519618301207?pes=vor

Treloar, W.J. (1994). Automation of pollen identification and counting using digital image processing techniques. INQUA Commission for the Study of the Holocene, Working Group on Data-Handling Methods Newsletter.

Triviño, M. M., Maya-Manzano, J. M., Tummon, F., Clot, B., Grewling, L., Schmidt-Weber, C., & Buters, J. (2023). Variability between Hirst-type pollen traps is reduced by resistance-free flow adjustment. *Aerobiologia*. https://doi.org/10.1007/s10453-023-09790-x

Tummon, F., Alados Arboledas, L., Bonini, M., Guinot, B., Hicke, M., Jacob, J., Kendrovski, V., McCairns, W., Petermann, E., Peuch, V.-H., Pfaar, O., Siacrd, M., Sikoparija, B., & Clot, B. (2021a). The need for Pan-European automatic pollen and fungal spore monitoring: A stakeholder workshop position paper. *Clinical Translational Allergy*. https://doi.org/10.1002/clt2.12015

Tummon, F., Adamov, S., Clot, B., Crouzy, B., Gysel Beer, M., Kawashima, S., Lieberrherr, G., Manzano, J., Markey, E., Moallemi, A., & Connor, D. O. (2021b). A first evaluation of multiple automatic pollen monitors run in parallel. *Aerobiologia*. https://doi.org/10.1007/s10453-021-09729-0

Van der Heyden, H., Dutilleul, P., Charron, J. B., Bilodeau, G. J., & Carisse, O. (2021). Monitoring airborne inoculum for improved plant disease management A Review. *Agronomy for Sustainable Development, 41*, 40.

Wägele, J. W., Bodesheim, P., Bourlat, S. J., Denzler, J., Diepenbroek, M., Fonseca, V., Frommolt, K. H., Geiger, M. F., Gemeinholzer, B., Glöckner, F. O., Haucke, T., Kirse, A., Kölpin, A., Kostadinov, I., Kühl, H. S., Kurth, F., Lasseck, M., Liedke, S., Losch, F., … Wildermann, S. (2022). Towards a multisensor station for automated biodiversity monitoring. *Basic and Applied Ecology, 59*, 105–138.

de Weger, L. A., Bruffaerts, N., Koenders, M. M. J. F., Verstraeten, W. W., Delcloo, A. W., Hentges, P., & Hentges, F. (2021). Long-term pollen monitoring in the Benelux: Evaluation of allergenic pollen levels and temporal variations of pollen seasons. *Frontiers in Allergy*. https://doi.org/10.3389/falgy.2021.676176

WMO/TD No. 1023, Geneva Switzerland (2000), https://library.wmo.int/doc_num.php?explnum_id=5301

Yan, S., Zhu, W., Zhang, B., Zhang, X., Zhu, J., Shi, J., Wu, P., Wu, F., Li, X., Zhang, Q., & Liu, X. (2018). Pollen-mediated gene flow from transgenic cotton is constrained by physical isolation measures. *Scientific Reports, 8*, 2862.

Zhang, M., Khaled, A., Amato, P., Delort, A.-M., & Ervens, B. (2021). Sensitivities to biological aerosol particle properties and ageing processes: Potential implications for aerosol–cloud interactions and optical properties. *Atmospheric Chemistry and Physics, 21*, 3699–3724.

Zuberbier, T., Lotvall, J., Simoens, S., Subramanian, S. V., & Church, M. K. (2014). Economic burden of inadequate management of allergic diseases in the European Union: A GA2LEN review. *Allergy, 69*, 1275–1279.

Zuberbier, T., Abelson, M.B., Akdis, C.A., Bachert, C., Berger, U., Bindslev-Jensen, C., Boelke, G., Bousquet, J., Canonica, G.W., Casale, T.B., Jutel, M, Kowalski, M.L., Madonini, E., Papadopoulos, N.G., Pfaar, O., Sehlinger, T., Bergmann, K.C., and the GA(2)LEN EU Network of Excellence in Allergy and Asthma. (2017). Validation of the Global Allergy and Asthma European Network (GA2LEN) chamber for trials in allergy: Innovation of a mobile allergen exposure chamber. *Journal of Allergy and Clinical Immunology*, 139, 1158-1166